

# Hazy

*a brief introduction to CLOUDY C13*

## 1. Introduction and commands

*Cloudy & Associates*

[www.nublado.org](http://www.nublado.org)

February 20, 2013

*Software:* Copyright © 1978–2013 Gary J. Ferland and others. All rights reserved.

The software described in this documentation (CLOUDY) is subject to a FreeBSD-style software license contained in the file `license.txt` in the root directory of the distributed files. The list of co-authors is given in the file `others.txt` in the same directory. Use of this program is not restricted provided each use is acknowledged upon publication. The bibliographic reference to this version of CLOUDY is “version xx.xx of the code last described [Ferland et al. \(2013\)](#).” The version number, shown here as “xx.xx”, should be given. This version number, along with a complete citation, can be found by executing the code with the **print citation** command included in the input script.

CLOUDY is an evolving code. You should confirm that you have the most recent version of the code by checking the web site [www.nublado.org](http://www.nublado.org). The code has a [discussion board](#) with emailing list. This will have announcements of any updates to the code.

Portions of the documentation have been published, and are copyrighted by, the American Astronomical Society, the Astronomical Society of the Pacific, and the Royal Astronomical Society. The remainder of the documentation is subject to the following FreeBSD format documentation license:

*Documentation:* Copyright © 1978–2013 Gary J. Ferland and others. All rights reserved.

Redistribution and use of the documentation (all parts of HAZY and the Quick Start Guide) in source (L<sup>A</sup>T<sub>E</sub>X) and ‘compiled’ forms (PDF, PostScript, HTML and so forth) with or without modification, are permitted provided that the following conditions are met:

1. Redistributions of source code (L<sup>A</sup>T<sub>E</sub>X) must retain the above copyright notice, this list of conditions and the following disclaimer as the first lines of the file `license.doc.txt` in the root directory unmodified.
2. Redistributions in compiled form (converted to PDF, PostScript, XML, HTML and other formats) must reproduce the above copyright notice, this list of conditions and the following disclaimer in the documentation and/or other materials provided with the distribution.

*This documentation is provided by the CLOUDY project “as is” and any express or implied warranties, including, but not limited to, the implied warranties of merchantability and fitness for a particular purpose are disclaimed. In no event shall the CLOUDY project be liable for any direct, indirect, incidental, special, exemplary, or consequential damages (including, but not limited to, procurement of substitute goods or services; loss of use, data, or profits; or business interruption) however caused and on any theory of liability, whether in contract, strict liability, or tort (including negligence or otherwise) arising in any way out of the use of this documentation, even if advised of the possibility of such damage.*

*Cover image: Two models of the molecular cores in Crab Nebula filaments are shown. The upper panel is a scenario where shocks or other energy sources maintain the temperature of the filament while the lower panel shows the case where the synchrotron continuum energizes the filaments. H<sub>2</sub> and CO emission lines are labeled in the lower panel. The red circles in the upper panel compares the predicted shape of the dust thermal emission peak at 70 microns with the shape found from the Herschel observations by Gomez et al. The entire spectrum, including H<sub>2</sub>, CO, and dust emission, is computed self consistently by specifying only the composition, density, and column density of the gas, and the SED and flux of ionizing photons and particles. Figure prepared by Jack Baldwin and is from [Richardson et al. \(2012\)](#).*

# CONTENTS

## LIST OF FIGURES

xxiii

## LIST OF TABLES

xxv

<b>1</b>	<b>INTRODUCTION</b>	<b>1</b>
1.1	Overview . . . . .	1
1.2	What must be specified . . . . .	1
1.2.1	Incident radiation field . . . . .	2
1.2.2	Chemical Composition . . . . .	2
1.2.3	Geometry . . . . .	2
1.2.4	Velocity Structure . . . . .	3
1.3	The input deck . . . . .	3
1.4	What is computed and reported . . . . .	4
<b>2</b>	<b>DEFINITIONS</b>	<b>5</b>
2.1	Overview . . . . .	5
2.2	Radiation fields . . . . .	5
2.2.1	Incident radiation field . . . . .	5
2.2.2	Diffuse radiation field . . . . .	5
2.2.3	Transmitted radiation field . . . . .	6
2.2.4	Reflected radiation field . . . . .	6
2.3	Geometry . . . . .	6
2.3.1	Illuminated and shielded faces of the cloud . . . . .	9
2.3.2	Depth and radius . . . . .	9
2.3.3	Covering factor . . . . .	9
2.3.4	Open vs. closed geometry . . . . .	9
2.3.5	Filling factor . . . . .	10
2.3.6	Hydrogen density . . . . .	10
2.3.7	Column densities . . . . .	10
2.3.8	Matter-bounded and radiation-bounded geometries . . . . .	11
2.4	Intensity & luminosity cases . . . . .	11
2.4.1	Luminosity case . . . . .	11
2.4.2	Intensity case . . . . .	11
2.4.3	The units of the predicted emission lines . . . . .	12

<b>3</b>	<b>INTRODUCTION TO COMMANDS</b>	<b>13</b>
3.1	Overview	13
3.2	Command format	13
3.2.1	Input and Output.	13
3.2.2	Command-line format.	13
3.2.3	Units	14
3.2.4	Number of commands.	14
3.2.5	Output as input.	15
3.2.6	Syntax used in this document	15
3.2.7	and, because nobody ever reads this document. . . .	16
3.2.8	The continue option	16
3.2.9	Numerical input	16
3.2.10	Comments	17
3.2.11	Hidden commands	17
3.2.12	⚡ Commands for experimental parts of the code	17
3.2.13	Log vs linear quantities	17
3.2.14	⚡ The <b>help</b> command	18
3.2.15	An example	18
3.3	Filenames	18
3.4	The <b>init</b> command	18
<b>4</b>	<b>THE INCIDENT RADIATION FIELD</b>	<b>21</b>
4.1	Overview	21
4.2	The coarse and fine continua	21
4.3	Defining a single component of the incident radiation field	22
4.4	Combining several radiation fields	22
4.4.1	The sum of several radiation fields	22
4.4.2	Keeping shape and intensity commands together	22
4.5	Check the incident radiation field!	23
<b>5</b>	<b>INCIDENT RADIATION FIELD LUMINOSITY</b>	<b>25</b>
5.1	Overview	25
5.2	Intensity and luminosity cases	25
5.3	The range option	25
5.4	Absolute [visual, bolometric] magnitude -2.3	26
5.5	Energy density 5e4 K [linear]	26
5.6	f(nu) = -12.456 [at .1824 Ryd]	27
5.7	Intensity 8.3 [range, linear]	27
5.8	ionization parameter = -1.984	27
5.9	L(nu) = 24.456 [at .1824 Ryd]	28
5.10	luminosity 38.3 [solar, range, linear]	28
5.11	nuF(nu) = 13.456 [at .1824 Ryd]	29
5.12	nuL(nu) = 43.456 [at .1824 Ryd]	29
5.13	phi(H) = 12.867 [range. . .]	29
5.14	Q(H) = 56.789 [range. . .]	29
5.15	ratio -3.4 0.3645 Ryd to 147 Ryd [alphaox, log]	30
5.16	xi -0.1	31

<b>6</b>	<b>INCIDENT RADIATION FIELD SHAPE</b>	<b>33</b>
6.1	Overview	33
6.2	AGN $T = 1.5e5$ K, $a(\text{ox}) = -1.4$ , $a(\text{uv}) = -0.5$ $a(x) = -1$	33
6.3	Background, $z = 1.825$ , $[f = 100; \text{no CMB}]$	35
6.4	Blackbody $t = e5$ K [linear, log, luminosity]	35
6.4.1	Blackbody, $t = 1e5$ K, $\text{disk} = 1e3$ K	36
6.4.2	Peter Martin's blackbody luminosity options	36
6.4.3	Blackbody 5, luminosity = 38.	36
6.4.4	Blackbody 5, radius = 10.	36
6.4.5	Blackbody $5e4$ K, energy density = 500K.	36
6.4.6	Blackbody, $t = 5e4$ K, STE	37
6.4.7	Blackbody, $t = 1e5$ K, dilution factor = -14	37
6.5	Bremsstrahlung, $\text{temp} = 8$	37
6.6	CMB [redshift 1000]	37
6.6.1	⌚ The time option	38
6.6.2	⌚ The density option	38
6.7	Extinguish column = 23, leak = 0.05, low = 4 Ryd	38
6.7.1	Extinguish optical depth 1.2, [options]	39
6.8	Interpolate [ $v(\text{Ryd})$ or $\log v(\text{Hz})$ ], $\log(f_v)$	39
6.9	Laser, frequency = 3.5 Ryd [rel width 0.02]	40
6.10	Power law, slope = -1.4 [hi cut = 6 Ryd low cut = .1, Kelvin]	40
6.11	Table command	41
6.11.1	Overview	41
6.11.2	Table AGN	41
6.11.3	Table akn120	42
6.11.4	Table cooling flow	42
6.11.5	Table Crab	42
6.11.6	Table Draine [factor=1.7]	43
6.11.7	Table HM96 [factor=-1]	43
6.11.8	Table HM05 redshift 2.21 [quasar; factor=-1]	43
6.11.9	Table ism [factor = 0.7]	46
6.11.10	Table power law [spectral index -1.4, low = .01, hi = 20]	46
6.11.11	Table read "contin.txt"	47
6.11.12	Table Rubin	48
6.11.13	Table XDR	48
6.12	Table stars command	49
6.12.1	Overview of available stellar SEDs	50
6.12.2	High-energy component	50
6.12.3	Starburst99 files	50
6.12.4	PopStar grids	51
<b>7</b>	<b>CHEMICAL COMPOSITION</b>	<b>53</b>
7.1	Overview	53
7.2	Absolute abundances and scale factors	53
7.3	Precedence	53
7.4	Abundances he c...	55
7.4.1	Arbitrary abundances	55
7.4.2	Setting all at once	56

7.4.3	Stored abundance sets	56
7.4.4	Grains, gas-phase depletions, and quantum heating	58
7.4.5	Interactions between the abundances and grains commands	61
7.5	Abundances starburst, Z=10	61
7.6	Element name [scale, abundance, off, log, table]	63
7.6.1	Element name scale	63
7.6.2	Element name abundance	63
7.6.3	Element name ionization	63
7.6.4	Element name off	63
7.6.5	Element limit off -12	64
7.6.6	Elements read	64
7.6.7	Element name table	66
7.7	Fluctuations abundances, period, max, min, phase	67
7.8	Grains	67
7.8.1	Using the built-in grain types	67
7.8.2	Interactions between abundances and grains commands	69
7.8.3	Creating your own grain types	71
7.8.4	PAHs	71
7.8.5	Variable grain abundances	71
7.8.6	Line intensities with grains	72
7.8.7	Extinction for point and extended sources	73
7.8.8	Grains-related commands	73
7.8.9	Effects of grains	74
7.8.10	Grain-related quantities that are printed	74
7.9	Metals 0.05 [log, linear, grains; deplete]	75
7.9.1	Scaling grains and metals together	75
7.9.2	Metals deplete—gas-phase depletion factors	76
<b>8</b>	<b>DENSITY LAWS</b>	<b>79</b>
8.1	Overview	79
8.2	Constant density, pressure, gas pressure	79
8.2.1	Constant density	79
8.2.2	Constant gas pressure [index = -1.1]	80
8.2.3	Constant pressure [no continuum, no abort]	80
8.2.4	Constant pressure set 6.5	80
8.2.5	Constant pressure timescale = 2.3e9 s, alpha=-1	81
8.2.6	The reset option	81
8.3	Gravity [options]	81
8.3.1	Gravity [spherical, plane-parallel]	81
8.3.2	Gravity external [Mass = 10 $M_{\odot}$ , extent = 3 parsecs, powerlaw = -2]	82
8.4	☞ Dark [options]	82
8.4.1	Dark NFW virial radius = 18 [characteristic radius = 17]	82
8.5	Dlaw [options]	82
8.5.1	dlaw p1, p2, p3...	82
8.5.2	☞ Dlaw wind	83
8.5.3	Dlaw table [depth, radius]	83
8.6	Fluctuations density period ...	84
8.7	Globule [density =2, depth =16, power =2]	84

8.8	hden 5.6, [proportional to $R^{-2}, \dots$ ]	85
8.8.1	Power-law dependence on radius	85
8.8.2	Clouds extending to infinity	85
8.8.3	Power-law dependence on depth	86
8.8.4	Power-law dependence on column density	86
<b>9</b>	<b>GEOMETRY</b>	<b>87</b>
9.1	Overview	87
9.2	Age 44 years [off]	87
9.3	Aperture commands	87
9.3.1	Aperture [slit, beam]	87
9.3.2	Aperture size 2.5	89
9.3.3	Aperture covering factor 0.6	89
9.4	Clumping factor = 0.05 [index = -1]	89
9.5	Covering factor 0.3	89
9.6	Cylinder log semi height = 9.12	90
9.7	Distance 3.2 linear parsecs	91
9.8	Filling factor = 0.05 [index = -1]	91
9.9	Illumination angle 45 deg [radians]	91
9.10	Radius r(inner) [r(outer), thickness; parsec; linear]	92
9.11	Sphere [options]	92
9.11.1	Sphere expanding or static	93
9.12	Stop depth...	93
9.13	Stop thickness...	93
<b>10</b>	<b>OPTICAL DEPTHS AND RADIATIVE TRANSFER</b>	<b>95</b>
10.1	Overview	95
10.2	Case A [options]	95
10.3	Case B [ $\tau_{\text{ly}} \alpha = 9$ ; options]	96
10.4	Case C [options]	97
10.5	Diffuse fields [outward, OTS]	97
10.6	Double optical depths	97
10.7	Iterate [2 times]	98
10.7.1	Number of iterations	98
10.7.2	Iterate to convergence [max = 7, error = .05]	98
10.7.3	Convergence problems	98
10.8	No scattering opacity	99
10.9	Turbulence = 100 km/s [log, dissipate]	99
10.9.1	Definitions	99
10.9.2	Turbulent pressure	100
10.9.3	Energy dissipation	100
10.9.4	Equipartition turbulent - magnetic pressures	100
10.9.5	Turbulence command heads up!	101
10.10	vlaw $\alpha = -1$	101

<b>11 THERMAL SOLUTIONS</b>	<b>103</b>
11.1 Overview	103
11.2 cextra -14.231 [temp to the 1.5 power]	103
11.3 Constant temperature, $t=1e4$ K [linear]	103
11.4 Constant grain temperature 20K [linear]	104
11.5 Coronal equilibrium, $T=1e7$ K [linear]	104
11.6 Cosmic rays [options....]	106
11.6.1 Cosmic rays background [1.2]	106
11.6.2 Cosmic ray rate -17.3	106
11.6.3 Cosmic rays density =1.2 [index, etc.]	106
11.6.4 Cosmic ray equipartition	107
11.7 Failures 100 times [ map]	107
11.8 Force temperature to 3400 K	107
11.9 Hextra -14 [depth, density, time, SS]	108
11.9.1 Hextra -14 depth 18, thickness 12	108
11.9.2 Hextra -13 density	108
11.9.3 Hextra time	108
11.9.4 Hextra SS 0.2 1e8 3e17	109
11.9.5 Notes on the hextra command	109
11.10 High temperature approach	109
11.11 Magnetic field, $\log(B) = 5$ [options]	109
11.12 Map, zone 4 [range 2000, 5000]	110
11.13 Neutrons -2 [efficiency =-2]	110
11.14 Print coolants, zone 135	111
11.15 Print heating	111
11.16 Set temperature [floor, convergence]	111
11.17 tlaw [DB96, SN99]	111
<b>12 CONTROLLING ATOMIC AND MOLECULAR MODELS</b>	<b>113</b>
12.1 Atom overview	113
12.2 The g-bar approximation	113
12.3 Atom FeII [options]	113
12.3.1 Atom FeII levels	113
12.3.2 Atom FeII trace	114
12.3.3 Atom FeII redistribution [options]	114
12.3.4 Atom FeII simulate	114
12.3.5 Atom FeII slow	114
12.3.6 Atom FeII output options	114
12.4 Atom H2 options	115
12.4.1 The <b>set H2</b> command	115
12.4.2 H <sub>2</sub> output options	115
12.4.3 Atom H2	115
12.4.4 Atom H2 chemistry [simple; full]	115
12.4.5 Atom H2 collisions [options]	115
12.4.6 Atom H2 gbar [ off; on]	116
12.4.7 Atom H2 levels	116
12.4.8 Atom H2 limit -4	116
12.4.9 Atom H2 matrix 43	116

12.4.10	Atom H2 noise [mean, standard deviation, seed]	117
12.4.11	Atom H2 thermal [simple; full]	117
12.4.12	Atom H2 trace [options]	117
12.4.13	atom H2 output options	117
12.5	Atom [H-like   He-like] [element, options]	117
12.5.1	Introduction	117
12.5.2	Structure of the model atoms	118
12.5.3	Atom H-like collisions...	119
12.5.4	Atom He-like collisions ....	120
12.5.5	Atom [H-like   He-like] continuum lowering off	120
12.5.6	Atom [H-like] damping off	121
12.5.7	Atom He-like dielectronic recombination [off]	121
12.5.8	Atom [h-like   he-like] error generation	121
12.5.9	Atom He-like FSM	121
12.5.10	Atom He-like gbar options	121
12.5.11	Atom [h-like   he-like] levels options	121
12.5.12	Atom [H-like   He-like] Lyman options	123
12.5.13	Atom [h-like   he-like] NO RECOmbination INTERp	124
12.5.14	Atom [h-like   he-like] REDI	124
12.5.15	Atom [h-like   he-like] redistribution [options]	124
12.5.16	Atom [h-like   he-like] topoff off	124
12.6	Atom Chianti [ options ]	125
12.6.1	Atom Chianti "masterlist.ini"	125
12.6.2	Atom Chianti off	125
12.6.3	Atom Chianti hybrid	125
12.6.4	Atom Chianti print	125
12.6.5	Atom Chianti Levels	125
12.6.6	Atom Chianti [experimental theoretical]	125
12.7	Atom Lamda [ON , OFF]	126
12.8	Atom Stout [on , off, no hybrid][print][levels {j, MAX}]	126
12.8.1	Atom Stout [on off]	126
12.8.2	Atom Stout "masterlist.ini"	126
12.8.3	Atom Stout hybrid	126
12.8.4	Atom Stout print	126
12.8.5	Atom Stout Levels	126
<b>13</b>	<b>DYNAMICAL &amp; TIME-DEPENDENT CALCULATIONS</b>	<b>127</b>
13.1	Overview	127
13.2	🔗 cosmology	127
13.2.1	🔗 cosmology omega	127
13.2.2	🔗 cosmology Hubble	128
13.3	🔗 A cooling or heating non-equilibrium gas	128
13.4	🔗 Time-variable incident radiation field	129
13.4.1	time command	129
13.4.2	Time-step size increment	130
13.4.3	Keywords on individual time-step entries	131
13.4.4	Varying individual continua	131
13.4.5	Controlling the number of time steps	131

13.4.6	Other commands . . . . .	131
13.5	Wind velocity=300 km/sec [mass =1.4 Msun, disk, ballistic, static] . . . . .	132
13.5.1	Ballistic solutions . . . . .	132
13.5.2	⌚ wind advection, velocity=-5 km/s . . . . .	133
13.5.3	Wind 5 km/s no continuum . . . . .	133
13.6	⌚ Miscellaneous dynamics commands . . . . .	134
13.6.1	Constant pressure time . . . . .	134
13.6.2	Set dynamics [options] . . . . .	134
13.7	Useful output options . . . . .	135
13.7.1	Print cumulative lines . . . . .	135
13.7.2	Save commands, general comments . . . . .	135
13.7.3	Save cumulative continuum . . . . .	135
13.7.4	Save time dependent . . . . .	135
13.7.5	Set save hash options . . . . .	135

## 14 STOPPING CRITERIA 137

14.1	Overview . . . . .	137
14.2	Danger! Understand why the calculation stopped! . . . . .	137
14.3	Radius inner =18 [thickness =16; parsec; linear] . . . . .	138
14.4	Stop AV 12.1 [point, extended] . . . . .	138
14.5	Stop column density = 23 [neutral; ionized; total; ...] . . . . .	138
14.5.1	Stop column density 23 . . . . .	139
14.5.2	Stop neutral column density 23 . . . . .	139
14.5.3	Stop ionized column density 23 . . . . .	139
14.5.4	Stop atomic column density 21.3 . . . . .	139
14.5.5	Stop H/TSpin column density 17.2 . . . . .	139
14.5.6	Stop H2 column density 19.2 . . . . .	140
14.5.7	Stop CO column density 19.2 . . . . .	140
14.5.8	⌚ Stop column density "OH" 19.2 . . . . .	140
14.5.9	Stop effective column density 23 . . . . .	140
14.6	Stop continuum flux 200 micron 65 Jansky . . . . .	140
14.7	Stop depth . . . . .	141
14.8	Stop eden 3 [linear] . . . . .	141
14.9	Stop efrac = 1.05 . . . . .	142
14.10	Stop line "C 2" 157.6m reaches 0.2 rel to "O 3" 5007 . . . . .	142
14.11	Stop mass 32.98 . . . . .	142
14.12	Stop mfrac = 0.5 . . . . .	143
14.13	Stop molecule depletion -2 . . . . .	143
14.14	Stop nTotalIoniz 100 . . . . .	143
14.15	Stop optical depth -1 at 2.3 Ryd . . . . .	143
14.15.1	Stop Balmer optical depth = -.3 . . . . .	144
14.15.2	Stop Lyman optical depth = 5 . . . . .	144
14.15.3	Stop 21cm optical depth = linear 3 . . . . .	144
14.16	Stop pfrac = 0.23 . . . . .	144
14.17	Stop radius 17.3 [parsec; linear; 17.6 on sec iter] . . . . .	144
14.18	Stop temperature 1e3 K [linear, exceeds] . . . . .	145
14.19	Stop thickness 9.3 [parsec; linear; 23 on sec iter] . . . . .	145
14.20	Stop velocity < 1 km/s . . . . .	145

14.21	Stop zone 123 [21 on sec iteration,...]	146
<b>15</b>	<b>CONTROLLING OUTPUT</b>	<b>147</b>
15.1	Overview	147
15.2	No buffering	147
15.3	Normalize to “O 3” 5007 [scale factor = 100]	147
15.4	Plot [type, range]	148
15.5	Plot continuum [_raw, trace, range]	148
15.5.1	Plot continuum keywords	148
15.5.2	Plot diffuse continuum	148
15.5.3	Plot emitted continuum	149
15.5.4	Plot outward continuum	149
15.5.5	Plot reflected continuum	149
15.6	Plot opacity [type, range]	149
15.6.1	Plot range options	149
15.7	Plot _map [Tmin=3e3 K, Tmax=2e4 K, linear, range]	150
15.7.1	Plot map range options	150
15.8	Print ages	150
15.9	Print arrays	150
15.10	Print citation	150
15.11	Print constants	151
15.12	Print column densities [on; off]	151
15.13	Print coolants, zone 135	151
15.14	Print continuum indices	151
15.15	Print departure coefficients	151
15.16	Print errors	152
15.17	Print every 1000 [5 37 93]	152
15.18	Print heating	152
15.19	Print populations [H-like carbon, to level 45]	152
15.20	Print last	152
15.21	Print line options	152
15.21.1	Print line all	153
15.21.2	Print line cell xx	153
15.21.3	Print line collisions	153
15.21.4	Print line column [linear]	153
15.21.5	Print line cumulative	153
15.21.6	Print line faint -2 [_off]	153
15.21.7	Print line flux at Earth	154
15.21.8	Print line heat	154
15.21.9	Print line H2 electronic	154
15.21.10	Print line inward	154
15.21.11	Print line iso collapsed	154
15.21.12	Print line optical depths [_off, faint]	154
15.21.13	Print line pump	155
15.21.14	Print line sort wavelength [range 3500A to 1.2m]	155
15.21.15	Print line sort intensity	155
15.21.16	Print line sum	155
15.21.17	Print line surface brightness [arcsec]	155

15.22	Print macros	156
15.23	Print off	156
15.24	Print on	156
15.25	Print only [header, zones]	156
15.26	Print path	156
15.27	Print quiet	156
15.28	Print recombination	157
15.29	Print short	157
15.30	Print starting at 61	157
15.31	Print version	157
15.32	Print Voigt $a=1.2e-3$	157
15.33	Print zone 1000 [5 37 93]	157
15.34	Save commands	157
15.34.1	Overview	157
15.34.2	Save vs punch commands	158
15.34.3	An output file name must appear inside double quotes	158
15.34.4	Setting a prefix for all save files	158
15.34.5	The “last iteration” option	158
15.34.6	The “no buffering” option	158
15.34.7	The “clobber/no clobber” option	158
15.34.8	The “no hash” option	159
15.34.9	The “title” option	159
15.34.10	The “separate” option	159
15.34.11	Depth versus radius	159
15.35	Save abundances	160
15.36	Save ages	160
15.37	Save agn [options]	160
15.38	Save monitors	160
15.39	Save average ...	160
15.39.1	Temperature average	160
15.39.2	Ionization average	161
15.39.3	Column density	161
15.40	Save chemistry options	161
15.40.1	Save chemistry rates “filename” species “molecule”	161
15.41	Save column density	161
15.42	Save continuum	162
15.42.1	Lines in the spectrum	162
15.42.2	Emission line - continuum contrast	162
15.42.3	Pumped contributions to the lines	164
15.42.4	The units option - changing the continuum units	164
15.42.5	Units of the save output	164
15.42.6	Save continuum predictions	164
15.42.7	What is observed	165
15.42.8	Save continuum bins	167
15.42.9	Save cumulative continuum	167
15.42.10	Save diffuse continuum	167
15.42.11	Save continuum emissivity 12 [units micron]	167
15.42.12	Save emitted continuum	167

15.42.13	Save fine continuum [range, merge]	168
15.42.14	Save grain continuum	168
15.42.15	Save incident continuum	168
15.42.16	Save interactive continuum	168
15.42.17	Save ionizing continuum [options]	168
15.42.18	Save NLTE continuum	169
15.42.19	Save outward continuum	169
15.42.20	Save raw continuum	169
15.42.21	Save reflected continuum	169
15.42.22	Save transmitted continuum	169
15.42.23	Save two photon continuum	170
15.43	Save convergence [reason, error]	170
15.43.1	Save convergence base	170
15.43.2	Save convergence error	170
15.43.3	Save convergence reason	170
15.44	Save cooling	170
15.44.1	Save cooling each	171
15.45	Save charge transfer	171
15.46	Save Chianti	171
15.47	Save dr	171
15.48	Save dynamics options	172
15.48.1	Save dynamics advection	172
15.49	Save element <i>name</i>	172
15.50	Save enthalpy	172
15.51	Save execution times	172
15.52	Save FeII [options ...]	172
15.52.1	Save FeII column densities	172
15.52.2	Save FeII continuum	173
15.52.3	Save FeII departure	173
15.52.4	Save FeII levels	173
15.52.5	Save FeII lines [faint=0.1, range 0.1 to 0.3 Ryd]	173
15.52.6	Save FeII optical depths	174
15.52.7	Save FeII populations	174
15.53	Save FITS	174
15.54	Save gammas	174
15.54.1	Save gammas element oxygen 1	174
15.55	Save gaunt factors	174
15.56	Save grains [options]	175
15.56.1	Save grain abundance	175
15.56.2	Save grain charge	175
15.56.3	Save grain continuum	175
15.56.4	Save grain D/G ratio	175
15.56.5	Save grain drift velocity	175
15.56.6	Save grain extinction	175
15.56.7	Save grain H2rate	175
15.56.8	Save grain heating	176
15.56.9	Save grain opacity	176
15.56.10	Save grain potential	176

15.56.11	Save grain qs	176
15.56.12	Save grain temperature	176
15.57	Save grid	176
15.58	Save heating	177
15.59	Save [option] history	177
15.59.1	Save pressure history	177
15.59.2	Save temperature history	177
15.60	Save H2	177
15.60.1	Save H2 column density	178
15.60.2	Save H2 cooling	178
15.60.3	Save H2 creation	178
15.60.4	Save H2 destruction	178
15.60.5	Save H2 heating	178
15.60.6	Save H2 levels	178
15.60.7	Save H2 lines	178
15.60.8	Save H2 populations	179
15.60.9	Save H2 PDR	179
15.60.10	Save H2 rates	179
15.60.11	Save H2 Solomon	180
15.60.12	Save H2 special	180
15.60.13	Save H2 temperatures	180
15.60.14	Save H2 thermal	180
15.61	Save helium [options..]	180
15.61.1	Save helium line wavelengths	180
15.62	Save hydrogen	180
15.62.1	Save hydrogen 21 cm	180
15.62.2	Save hydrogen conditions	180
15.62.3	Save hydrogen ionization	180
15.62.4	Save hydrogen lines	181
15.62.5	Save hydrogen Ly $\alpha$	181
15.62.6	Save hydrogen populations	181
15.63	Save ionization means	181
15.64	Save ionization rates carbon	181
15.65	Save ip	181
15.66	Save Leiden	181
15.67	Save lines, options	182
15.67.1	Save lines, array	182
15.67.2	Save lines, cumulative	182
15.67.3	Save line data	182
15.67.4	Save lines, emissivity	183
15.67.5	Save lines, intensity [every 5 zones]	183
15.67.6	Save line labels	184
15.67.7	Save line list [absolute]	184
15.67.8	Save line optical depths, limit=-2	186
15.67.9	Save line pressure.	186
15.67.10	Save line populations, limit= -2	186
15.67.11	Save line RT	186
15.68	Save map, zone 3 [range 3999 to 4500]	188

15.69	Save molecules	188
15.70	Save NLTE	188
15.71	Save opacities [total, grain, element]	188
15.71.1	Save total opacity	188
15.71.2	Save grain opacity	189
15.71.3	Save fine opacities range 0.7 to 1 Ryd, coadd 15 cells	189
15.71.4	Save element opacity [name]	189
15.71.5	Save opacity figure	189
15.71.6	Save opacity shell 26 5 3	190
15.72	Save optical depths	190
15.72.1	Save fine optical depths	190
15.73	Save OTS	190
15.74	Save overview	190
15.75	Save PDR	191
15.76	Save performance	191
15.77	Save pointers	191
15.78	Save physical conditions	191
15.79	Save pressure	191
15.80	Save qheat	192
15.81	Save radius	192
15.82	Save recombination [option]	192
15.82.1	Save recombination coefficients	192
15.82.2	Save recombination efficiency	192
15.83	Save results	193
15.84	Save secondaries	193
15.85	Save source function [depth, spectrum]	193
15.85.1	Save source function, spectrum	193
15.85.2	Save source function, depth	193
15.86	Save species [options]	193
15.86.1	Specifying a particular species	194
15.86.2	Save species column densities	194
15.86.3	Save species energies	194
15.86.4	Save species labels	194
15.86.5	Save species levels	194
15.86.6	Save species populations	194
15.87	Save special	194
15.88	Save tegrid	195
15.89	Save temperature	195
15.90	Save time dependent	195
15.91	Save TPredictor	195
15.92	Save XSPEC [atable/mtable]	195
15.93	Save wind	196
15.94	State [get; put] “filename”	196
15.95	Title “This is a title”	196
15.96	Trace zone 94 [iteration 2; options . .]	197
15.96.1	Trace convergence level	197
15.96.2	Trace H-like [element name, full]	197
15.96.3	Trace He-like [element name, full]	197

<b>16 THE OPTIMIZE COMMAND</b>	<b>199</b>
16.1 Running the optimizer	199
16.2 Overview	199
16.3 What must be specified	201
16.4 Observed quantities	201
16.4.1 Optimize column density	201
16.4.2 Optimize, [intensity, luminosity]=36.425 [error =0.1]	202
16.4.3 Optimize continuum flux 350 micron 126 Jansky [error =0.1]	203
16.4.4 Optimize lines	204
16.4.5 Optimize temperature	204
16.4.6 Optimize diameter	205
16.5 Optimization methods	205
16.5.1 Optimize phymir [sequential mode] [8 cpu]	205
16.5.2 Optimize Subplex	205
16.6 Controlling the optimizer	205
16.6.1 Optimize file= "best.in"	205
16.6.2 Optimize increment = 0.5 dex	206
16.6.3 Optimize, iterations = 1200	206
16.6.4 Optimize range -2.3 to 3.9	206
16.6.5 Optimize tolerance = 0.02	207
16.6.6 Optimize continue	207
16.7 Convergence criteria	207
16.8 Other optimizer commands	208
16.8.1 No vary	208
16.8.2 Optimize, trace start 4	208
16.8.3 Optimize, trace flow	208
16.9 Notes concerning commands with vary option	208
16.9.1 Cosmic rays	208
16.9.2 Dlaw	208
16.9.3 Element	208
16.9.4 Fudge	208
16.9.5 Illuminate	209
16.9.6 Metals	209
16.9.7 Power law	209
16.9.8 Save output	209
16.9.9 Radius	209
16.9.10 Ratio alphox	209
16.9.11 Stop thickness	210
16.9.12 Stop radius	210
16.9.13 Table star ...	210
16.10 Notes concerning the optimization process	210
16.10.1 Use physically motivated initial conditions	210
16.10.2 Change the increment size	210
16.10.3 Set physically motivated limits to the variable quantities	210
16.10.4 Don't give up!	211
16.11 Other optimization methods	211
16.12 The optimizer test cases	211

<b>17 THE GRID COMMAND</b>	<b>213</b>
17.1 Grid start point, end point, increment [ linear ]	213
17.2 Beware the grid command treatment of temperatures!!	214
17.3 Grid output options	215
17.4 Other grid options	215
17.5 Notes on various commands	215
17.5.1 Constant temperature	215
<b>18 MISCELLANEOUS COMMANDS</b>	<b>217</b>
18.1 Overview	217
18.2 Introduction to the compile commands	217
18.3 Compile stars	217
18.4 Compile opacities	218
18.5 Compile gaunt factors	218
18.6 Compile recombination coefficients [H-like; He-like]	218
18.7 Compile grains	218
18.7.1 Compile grains	219
18.7.2 Compile grain 10 bins, [filename, ism graphite]	219
18.7.3 Some caveats	220
18.7.4 Examples	220
18.8 Crash [keywords]	221
18.8.1 crash zero	221
18.8.2 crash overflow	221
18.8.3 crash long overflow	221
18.8.4 crash NaN	221
18.8.5 crash setnan [float, double]	221
18.8.6 crash isnan [float, double]	221
18.8.7 crash monitor	221
18.8.8 crash bounds	222
18.8.9 crash exception	222
18.8.10 crash undefined	222
18.9 Drive fread, gaunts, pointers,...	222
18.9.1 Drive Case B	223
18.9.2 Drive cdLine	223
18.9.3 Drive E1	223
18.9.4 Drive escape probabilities	223
18.9.5 Drive fread	223
18.9.6 Drive gaunts	223
18.9.7 Drive HyAs	223
18.9.8 Drive pointers	223
18.9.9 Drive pumping	224
18.9.10 Drive starburst	224
18.9.11 Drive Voigt	224
18.10 Eden -2	224
18.11 Fudge factors 4.59678 [12.3 34.5 958 ...]	224
18.11.1 Init ["c84.ini", path]	225
18.12 No ...	225
18.12.1 No advection [H-like, He-like, ...]	225

18.12.2	No Auger effect	225
18.12.3	No buffering	225
18.12.4	No charge transfer	226
18.12.5	No collisional ionization	226
18.12.6	No Compton effect	226
18.12.7	No CHeat	226
18.12.8	No diffuse line pumping	226
18.12.9	No FeII pumping	226
18.12.10	No file opacity	226
18.12.11	No fine structure line optical depths	226
18.12.12	No fine opacities	227
18.12.13	No free free	227
18.12.14	No grain [process]	227
18.12.15	No induced processes	228
18.12.16	No ionization reevaluation	228
18.12.17	No line transfer	228
18.12.18	No Lya 21cm pumping	228
18.12.19	No OTS [options]	228
18.12.20	No level 2 lines	228
18.12.21	No molecules[H2 CO]	228
18.12.22	No on the spot	228
18.12.23	No opacity reevaluation	229
18.12.24	No outward [options]	229
18.12.25	No photoionization	229
18.12.26	No radiation pressure	229
18.12.27	No recoil ionization	229
18.12.28	No scattering opacity	229
18.12.29	No secondary ionizations	229
18.12.30	No Stark broadening	230
18.12.31	No TePredictor	230
18.12.32	No static opacities	230
18.12.33	No three body recombination	230
18.12.34	No times	230
18.12.35	No UTA ionization	230
18.12.36	No vary	230
18.13	Monitor commands	230
18.13.1	Monitor set error 0.1	231
18.13.2	Monitor Case B [H-like, He-like] element error	231
18.13.3	Monitor column “species” 18.9	231
18.13.4	Monitor csupra -17.09	232
18.13.5	Monitor Ctot -12.5	232
18.13.6	Monitor departure coefficients mean=1, error=0.04	232
18.13.7	Monitor depth 13.2	233
18.13.8	Monitor eden 9	233
18.13.9	Monitor grain potential	233
18.13.10	Monitor H2 grain rate -16.5	233
18.13.11	Monitor H2 ortho/para ratio 2.02	233
18.13.12	Monitor Htot -13.2	233

18.13.13	Monitor HHeicf -0.013	233
18.13.14	Monitor ionization fraction oxygen 3 -3.45, error 0.1, weight = radius	233
18.13.15	Monitor molecular fraction H2 -3.45, error 0.1	234
18.13.16	Monitor mpi	234
18.13.17	Monitor itrzn < 3.5	234
18.13.18	Monitor line "TOTL" 4861 < 1.01	234
18.13.19	Monitor line [luminosity intensity] "Q(H)" 4861 38.91	234
18.13.20	Monitor niter < 4	234
18.13.21	Monitor nothing 0	234
18.13.22	Monitor nzone < 135	234
18.13.23	Monitor pressure error < 0.01	235
18.13.24	Monitor PRadMax 0.34	235
18.13.25	Monitor temperature hydrogen 2, 4.02 volume, error 0.01	235
18.13.26	Monitor grain temperature index 2, temperature 234	235
18.13.27	Monitor temperature at face 11400K	235
18.13.28	Monitor radius 18.2	235
18.13.29	Monitor thickness 13.2	235
18.13.30	Monitor velocity 7.6 km/s	236
18.13.31	Table lines "LineList_PDR.dat"	236
18.14	Set commands	236
18.14.1	Set 12C13C -3.2	236
18.14.2	Set assert abort	236
18.14.3	Set atomic data [options ...]	236
18.14.4	Set charge transfer -11.5	237
18.14.5	Set chemistry	237
18.14.6	Set check energy every zone	238
18.14.7	Set collisional ionization [Dima, Hybrid]	238
18.14.8	Set collision strength averaging on	238
18.14.9	Set continuum options	238
18.14.10	Set convergence ...	239
18.14.11	Set coverage [fast]	239
18.14.12	Set csupra = -12.34	239
18.14.13	Set D/H -3.2	240
18.14.14	Set didz 0.05	240
18.14.15	Set dr 11.2	240
18.14.16	Set drmax 11.2	240
18.14.17	Set drmin 11.2	240
18.14.18	Set dynamics commands	241
18.14.19	Set eden [options ....]	241
18.14.20	Set flxfnt -20	241
18.14.21	Set gbar off	241
18.14.22	Set grain heating factor 2.	241
18.14.23	Set H2 ...	242
18.14.24	Set HCORR	243
18.14.25	Set HO charge transfer [chemistry; ionization]	243
18.14.26	Set ind2 [on, off]	243
18.14.27	Set ionization tolerance 0.01	243
18.14.28	Set isotopes [ALL]	243

18.14.29	Set kshell energy 1e6	243
18.14.30	Set Leiden hack	243
18.14.31	Set line precision [4, 5, or 6]	244
18.14.32	set monitor scientific notation	244
18.14.33	Set nchrg 3	244
18.14.34	Set negopc	244
18.14.35	Set nend 500	244
18.14.36	Set nFnu [options]	245
18.14.37	Set nFnu add 300 micron	245
18.14.38	Set nmaps 50	245
18.14.39	Set numerical derivatives	246
18.14.40	Set PAH option	246
18.14.41	Set phfit [1995, 1996]	246
18.14.42	Set presioniz 50	246
18.14.43	Set pressure convergence 0.01	246
18.14.44	Set save commands	246
18.14.45	Set recombination keywords	248
18.14.46	Set species gbar 0.01	248
18.14.47	Set temperature [floor, convergence]	249
18.14.48	Set test	249
18.14.49	Set trimming -9 [upper lower, off]	249
18.14.50	Set tsqden 8	249
18.14.51	set update couplings every ion	250
18.14.52	Set UTA	250
18.14.53	Set WeakHeatCool 0.02	250
18.15	Table lines “name.dat”	250
18.16	Test	250
18.16.1	Test FeII	251
18.16.2	Test large	251
18.16.3	Test H2	251
18.16.4	Test molecular	251
18.17	Performance speedups	251
18.17.1	Turn off minor elements	251
18.17.2	Turn off the chemistry	251
18.17.3	Turn off grain physics	252
18.17.4	Turn off line transfer	252
18.17.5	Turn off level 2 lines	252
18.17.6	Don’t reevaluate the ionization or opacities	253
18.17.7	Turn off fine opacities.	253
18.17.8	Degrade the continuum resolution	253
18.17.9	Make the iso-sequence model atoms as small as possible	253
<b>A</b>	<b>USING THE GRAIN CODE IN CLOUDY</b>	<b>255</b>
A.1	Introduction	255
A.2	Using the grain model	256
A.3	Description of the refractive index files	257
A.3.1	rfl.tbl	258
A.3.2	opc.tbl	260

A.4	Description of the mixed medium files . . . . .	261
A.5	Description of the size distribution files . . . . .	262
A.5.1	ssize . . . . .	263
A.5.2	ncarb . . . . .	263
A.5.3	power . . . . .	263
A.5.4	exp1, exp2, exp3 . . . . .	263
A.5.5	normal . . . . .	264
A.5.6	lognormal . . . . .	264
A.5.7	table . . . . .	264
<b>B</b>	<b>INCLUDING USER-DEFINED ATMOSPHERE GRIDS IN CLOUDY</b>	<b>265</b>
B.1	Introduction . . . . .	265
B.2	The ascii file . . . . .	265
B.3	Compiling the grid . . . . .	268
B.4	Runtime behavior . . . . .	268
<b>C</b>	<b>LATEX STYLE AND MACROS</b>	<b>269</b>
C.1	Cross references . . . . .	269
C.2	Blocks of verbatim text . . . . .	269
C.3	Macros . . . . .	269
	<b>REFERENCES</b>	<b>271</b>



# LIST OF FIGURES

2.1	Contributors to total radiation field . . . . .	6
2.2	Incident and reflected radiation field . . . . .	7
2.3	Cloudy_3D simulation of a planetary nebula . . . . .	8
2.4	Open and closed geometries . . . . .	9
6.1	AGN SED . . . . .	34
6.2	Crab Nebula SED . . . . .	44
6.3	ISM radiation field . . . . .	45
6.4	Stellar radiation fields . . . . .	49
7.1	Quantum heating . . . . .	62
9.1	Cylindrical geometry . . . . .	90
11.1	X-ray emission spectrum . . . . .	105
12.1	Resolved and collapsed levels . . . . .	118
15.1	Incident and net emission . . . . .	163
15.2	Radiation field components . . . . .	166
15.3	Save line ratio example . . . . .	187



# LIST OF TABLES

3.1	Default Conditions . . . . .	14
3.2	Interpretation of Numerical Input . . . . .	17
4.1	Commands specifying both shape <i>and</i> intensity . . . . .	23
6.1	AGN Continuum . . . . .	41
6.2	Akn 120 Continuum . . . . .	42
6.3	ISM Radiation Field . . . . .	46
6.4	Power Law Continuum . . . . .	47
7.1	Solar Composition . . . . .	54
7.2	Stored Abundance Sets . . . . .	57
7.3	Old Solar Composition . . . . .	59
7.4	2010 Solar Composition . . . . .	60
7.5	Solar composition sorted by abundance . . . . .	65
7.6	Standard Grain Types . . . . .	68
7.7	Depletions . . . . .	77
15.1	Trace convergence keywords and routines . . . . .	197
15.2	Trace Keywords and Effects . . . . .	198
16.1	Commands with vary option. Entries “var” are explained in Section 16.9. . . . .	200
16.2	Optimizer results . . . . .	211
18.1	Grain keywords for size distribution (*.szd files) . . . . .	219
18.2	Grain keywords for refractive index data (*.rfi files) . . . . .	220
A.1	The definition of each of the material types hardwired into Cloudy. . . . .	258
A.2	The various choices for the enthalpy function hardwired in Cloudy. . . . .	259
A.3	The various choices for the minimum charge hardwired in Cloudy. . . . .	259
A.4	The various expressions for the electron affinity hardwired in Cloudy. . . . .	259
A.5	The various choices for the inverse attenuation length. . . . .	259
A.6	The various expressions for the photoelectric yield hardwired in Cloudy. . . . .	259
A.7	The various choices for splitting up the grain emissions. . . . .	259
A.8	The expressions for the ro-vibrational distribution of H <sub>2</sub> formed on various grain surfaces. . . . .	259
A.9	Example of a mixed medium file for fluffy silicate. . . . .	261
A.10	Allowed choices for the mixing law. . . . .	262
B.1	Example of an ascii file, derived from the kwerner.ascii file. . . . .	267

---

C.1	Naming convention for labels . . . . .	269
C.2	Macros defined in <code>macros.tex</code> . . . . .	270

# Chapter 1

## INTRODUCTION

### 1.1 Overview

CLOUDY is a microphysics code. It is designed to simulate physical conditions within clouds ranging from the intergalactic medium to the high-density LTE and STE limits. The range of temperatures extends from the CMB temperature up to  $1.001 \times 10^{10}$  K and the physical state ranges between fully molecular to bare nuclei. It predicts the thermal, ionization, and chemical structure of a cloud which lies within these limits, and predicts its observed spectrum.

This document describes the input, output, and assumptions for the code. It fully defines the commands used to drive the program. Part 2 gives details about the program structure, its output, the computational environment, and how to call CLOUDY as a sub-program of other programs. The methods, approximations, and assumptions used by CLOUDY are outlined in Part 3 of this document, although this part, like CLOUDY itself, is still under construction. The *Quick Start Guide* summarizes these three volumes and gives a general overview of the simulations.

Many environments are encountered in which dilute gas is heated and ionized by the radiation field striking the gas. Under these circumstances it is possible to predict the physical conditions (that is, the distribution of ionization, density, and temperature) across the cloud, and its resulting spectrum, in a unique and self-consistent manner. This is done by simultaneously solving the equations of statistical and thermal equilibrium, equations that balance ionization-neutralization processes, and heating-cooling processes, respectively. The graduate text [Osterbrock and Ferland \(2006\)](#), hereafter AGN3) describe the physics governing such environments and [Ferland \(2003\)](#) provides additional details on current research topics.

The instructions for downloading and setting up the code are on the web site [www.nublado.org](http://www.nublado.org). We maintain a discussion board at [tech.groups.yahoo.com/group/cloudy\\_simulations](http://tech.groups.yahoo.com/group/cloudy_simulations) where questions can be posted.

### 1.2 What must be specified

One powerful asset of photoionization analysis is the large number of observables resulting from only a few input parameters. Intensities of a very large number of spectral lines<sup>1</sup> are predicted by CLOUDY. These result from the specification of only a) the shape and intensity of the external radiation field striking a cloud, b) the chemical composition and grain content of the gas, and c) the geometry of the gas, including its radial

---

<sup>1</sup> There is no limit to the number of spectral lines that the code can compute because there is no limit to the number of levels of atoms of the H-like ( $H^0$ ,  $He^+$ , etc) and He-like ( $He^0$ ,  $Li^+$ , etc) isoelectronic sequences. Processor speed and memory limit the simulation to a few million lines in most applications with today's computers, however.

extent and the dependence of density on radius. The following subsections describe the general philosophy of the specification of each.

### 1.2.1 Incident radiation field

Both the shape and intensity of the external radiation field striking the cloud must be specified. Often this is the region's only source of heat and ionization. Different commands are usually used to specify the external radiation field shape and intensity, although a few commands specify both.

**Shape of the external radiation field** The shape of the spectral energy distribution (SED) should be fully specified between an energy of  $1.001 \times 10^{-8}$  Ryd ( $\lambda \approx 10$  m – this is roughly the plasma frequency of the Earth's ionosphere) and an energy of  $7.354 \times 10^6$  Ryd ( $h\nu \approx 100$  MeV) if possible.<sup>2</sup> A physically-motivated radiation field spanning the full energy range should be specified if possible. This can be specified as a fundamental form (such as blackbody emission, optically thin bremsstrahlung emission, or a power law with optional exponential cutoff), interpolated from tables of points, or as the radiation field transmitted through a cloud and predicted by previous calculations. Additionally, a set of built-in radiation fields (for instance, emission from many model atmospheres, the observed Crab Nebula spectral energy distribution (SED), or several typical AGN SEDs) can be specified as look-up tables.

**Intensity or luminosity of the external radiation field** The intensity of the external radiation field striking the cloud must be specified. This can be given either as the flux striking a unit surface area of cloud or as luminosity radiated by the central object into  $4\pi$  sr. The code must be able to derive the flux of photons ( $\text{cm}^{-2} \text{s}^{-1}$ ) striking the illuminated face of the cloud. There are many commands that set these. Two cases, the intensity and luminosity cases, can be used to set the strength of the radiation field. These are described in the next Chapter.

**Combining several radiation fields** Up to 100 different radiation fields can be included as part of the total field striking the cloud. There must be exactly the same number of shape and luminosity specifications. The code will stop if there are not.

### 1.2.2 Chemical Composition

The program considers the lightest 30 elements in detail. Grains are not part of the default composition but can be included. All stages of ionization are treated, and all published charge exchange, radiative recombination, and dielectronic recombination processes are included as recombination mechanisms. Photoionization from valence and inner shells and many excited states, as well as collisional ionization by both thermal and supra-thermal electrons, and charge transfer, are included as ionization mechanisms. The chemistry includes many molecules and will go to the fully molecular limit (H in  $\text{H}_2$  and C or O in CO). Although the default composition is solar several other standard mixtures can easily be specified and an arbitrary composition can be entered.

### 1.2.3 Geometry

The geometry is always 1D spherical but can be made effectively plane parallel by making the inner radius much larger than the thickness of the cloud. The default is for the gas to have constant density and to fully

<sup>2</sup> In much of the following discussion photon energies will be given in Rydbergs. The ionization potential of hydrogen is nearly 1 Rydberg. See the discussion in Part 2 of this document for an exact definition and how to convert the Rydberg to other units.

fill its volume. Other pressure laws and strongly clumped clouds can be computed as well.

CLOUDY normally assumes an *open geometry*, or one in which the gas has a very small *covering factor* (these terms are defined in the following chapter and in section 5.9 of AGN3). This can be changed with the **sphere** command which sets the covering factor to a large enough value for light escaping the cloud in the direction towards the central object to always interact gas on the other side. This is a *closed geometry*. Line photons which cross the central hole interact with line-absorbing gas on the far side if **sphere static** is set but do not interact (because of a Doppler shift due to expansion) if **sphere expanding** is set. This case is the default when **sphere** is specified.

### 1.2.4 Velocity Structure

CLOUDY normally assumes that only thermal motions broaden spectral lines and that there is no internal velocity structure. These assumptions can be changed. A component of microturbulence can be added with the **turbulence** command. A flow can be computed with the **wind** command.

## 1.3 The input deck

CLOUDY is driven by a set of command lines. These normally reside in a small input file which the code reads when it starts. The commands are four-letter keywords (either upper or lower case) followed by free-format numbers that may be mixed with letters. When CLOUDY is executed as a stand-alone program standard input (stdin) is read for input and standard output (stdout) is used for output.

As an example, create a small file (say, called `simple.in`) containing the following lines:

```
title example input
hden 5 // log of hydrogen density, cm-3
blackbody 5e4 K // spectral shape is a 50000K blackbody
// intensity of blackbody is set with
// ionization parameter so starting radius is not needed
ionization parameter -2
```

Suppose that the code has been compiled to create the executable `cloudy.exe`. Then, the model described by the parameters in this input file could be computed by typing the following at the command prompt:

```
cloudy.exe -r simple
```

Note that on many Linux systems the command will have to be written as

```
./cloudy.exe -r simple
```

for system security. The file `simple.in` will be read for input and the output will be in the file `simple.out`.

The [www.nublado.org](http://www.nublado.org) web site has many more details about running this version of CLOUDY in the page [RunCode](#).

It is also possible for a larger program to drive CLOUDY directly by treating it as a subroutine. See [RunCode](#) for more details.

## 1.4 What is computed and reported

The code creates an output file as the model is computed. The program begins by echoing the input commands, except for comment lines beginning with a #, %, //, or c\_ (a space after the leading c). Comments are ignored. The input stream ends with either a blank line or the end-of-file. Some properties of the incident radiation field, such as luminosity and number of photons in certain frequency ranges, are then printed.

CLOUDY works by dividing a cloud into a set of thin concentric shells referred to as zones. The zones are chosen to have thicknesses that are small enough for the physical conditions across them to be nearly constant. Adaptive logic continuously adjusts the physical thicknesses of these shells to ensure this. Typically  $\sim 100$  to 200 zones are computed in an optically thick model of an H II region. The physical conditions in the first and last zones are always printed and intermediate zones may be printed if needed (this is governed by the **print every** command). The output for each zone begins with a line giving the zone number, its electron temperature, the distance from the center of the spherical nebula to the center of the zone, and some other properties of the solution. The next line gives the relative contributions of various emission lines to the radiation pressure if this amounts to more than 5% of the gas pressure. The remaining lines of output give the relative populations of ionization stages of the other elements. Many details about the conditions within the zone are intermixed with these relative populations.

After the zone calculations are complete and the model is finished the code will explain why the calculation stopped. It is very important to confirm that the calculation stopped for the intended reason. Some warnings, cautions, or notes about the calculation may also be printed. The code is designed to be autonomous and self aware. This self checking will ensure that its range of validity is not exceeded. It will complain if it goes outside its range of validity, if it feels that some parameter has been incorrectly set, or if something surprising has happened during the calculation. This is an essential core feature of the code since it is now often used to generate grids of thousands of models, making it impossible to validate individual models by hand.

The final print out begins with a recapitulation of the entered commands followed by the predicted emission-line spectrum. The first two columns of the emission-line spectrum give an identifying label and wavelength for each spectral line. The third column is the log of the luminosity [ $\text{erg s}^{-1}$ ] or intensity [ $\text{erg cm}^{-2} \text{s}^{-1}$ ] of the emission line, and the last column gives its intensity relative to the reference line. The reference line is  $\text{H}\beta$  by default and other emission lines can be chosen with the **normalize** command. The third column will be either the luminosity or intensity. The luminosity (energy radiated by a shell of gas covering  $\Omega$  sr of the central object) is predicted if the incident radiation field is specified as a luminosity. The line intensity  $4\pi J$  (the energy emitted per square centimeter of the gas slab) is predicted if the incident radiation field is specified as an intensity. If the geometry is spherical but the incident radiation field is specified as an intensity then the line intensities will be expressed per unit area at the inner radius. Only the strongest emission lines are printed; the relative intensity of the weakest line to print is adjusted with the **print faint** command.

The last pages of the output gives some averages of the ionization fractions over the slab, the optical depths in various lines and continua, and other properties of the nebula.


There is a vast amount of information that is computed but not given in the standard output file. Special output files are created with the **save** commands described below.

# Chapter 2

## DEFINITIONS

### 2.1 Overview

This section defines many of the quantities used by CLOUDY. I try to follow standard notation, such as that used by [Mihalas \(1978\)](#) or AGN3. Other parts of this document goes into many of these quantities in greater detail.

This document has the following typographic conventions; `filename`, *variable*, **command**, *jargon*, , experimental commands, *variable name*, and *routine name*.

### 2.2 Radiation fields

Figure [2.1](#) shows several of the radiation fields computed in the calculation.

#### 2.2.1 Incident radiation field

The *incident radiation field* is the external radiation field emitted by the central object that strikes the *illuminated face* of the cloud. It is specified in the commands that set up the calculation. Often the incident field is the only energy source for the cloud. As the incident radiation field is transmitted through the cloud it is diminished by extinction.

#### 2.2.2 Diffuse radiation field

The *diffuse radiation field* (often referred to as the diffuse fields) is the radiation field emitted by gas and grains within the nebula. Examples include the Lyman, Balmer, or two-photon continua emitted by hydrogen. These fields are very nearly isotropic and can be significant sources of ionizing radiation under some circumstances.

The main difference between the calculation of a stellar atmosphere and a photoionized cloud is in the treatment of the diffuse fields. The gas albedo, which gives the relative probability of a photon being scattered versus being absorbed, is generally small in a nebula. As a result, the diffuse fields must be far weaker than the attenuated incident continuum since the second is usually the cloud's only real energy source. The total radiation field is usually dominated by the attenuated incident radiation field. By contrast in a stellar atmosphere the nearly isotropic diffuse field usually dominates the local intensity. As a result the diffuse fields can be treated by lower order approximations in a photoionized cloud than in a stellar atmosphere.

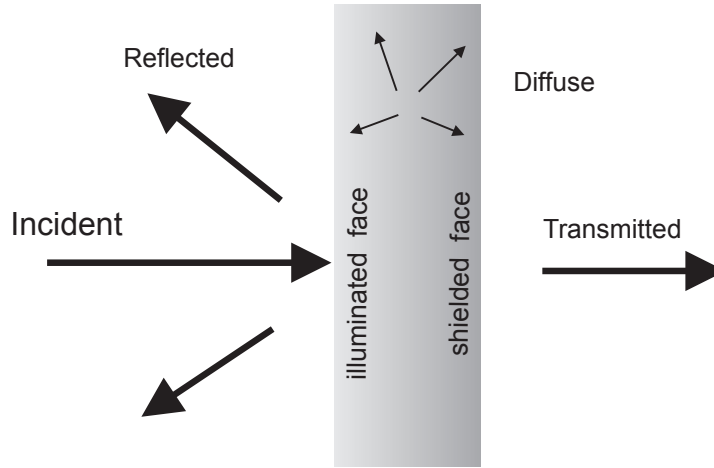


Figure 2.1: Several of the radiation fields that enter in the calculations.

### 2.2.3 Transmitted radiation field

The *transmitted radiation field* is the net emission emergent from the shielded face of the cloud. It includes both the *attenuated incident* and the *diffuse* radiation fields.

### 2.2.4 Reflected radiation field

The *reflected radiation field* is the emission from the illuminated face of the cloud back into the direction towards (i.e., within  $2\pi$  sr of) the source of the external field. The reflected field is the result of both backscattered incident radiation and diffuse emission emitted from the cloud towards the source of ionizing radiation. This component is only computed for an *open geometry* (defined below).

Figure 2.2 shows a plot of the incident and reflected radiation fields for the Compton reflector in an AGN. This is a large column-density cloud,  $N(\text{H}) = 10^{23.75} \text{ cm}^{-2}$ , illuminated by a  $f_\nu \propto \nu^{-1}$  power law. The incident radiation field is shown as a dashed line and the reflected radiation field, obtained from the **save continuum** command), is the solid line. The Compton reflector's peak at X-ray energies is clearly shown.

## 2.3 Geometry

In the simplest case the geometry is spherical, or plane parallel if the inner radius is much larger than the thickness of the cloud. The summary at the end of the calculation will say whether the geometry was plane parallel (the ratio of the thickness to the inner radius,  $\Delta r/r_o < 0.1$ ), a thick shell ( $\Delta r/r_o < 3$ ), or spherical ( $\Delta r/r_o \geq 3$ ).

Complex geometries are done by using Cloudy to compute volume elements within a much larger cloud. An example is the Cloudy\_3D code, available from [sites.google.com/site/cloudy3d](https://sites.google.com/site/cloudy3d) and described in Morisset (2006) and Morisset and Stasinska (2008). Cloudy\_3D was used to compute the images shown on the cover and in Figure 2.3. The RAINY3D code is another example (Moraes and Diaz, 2009).

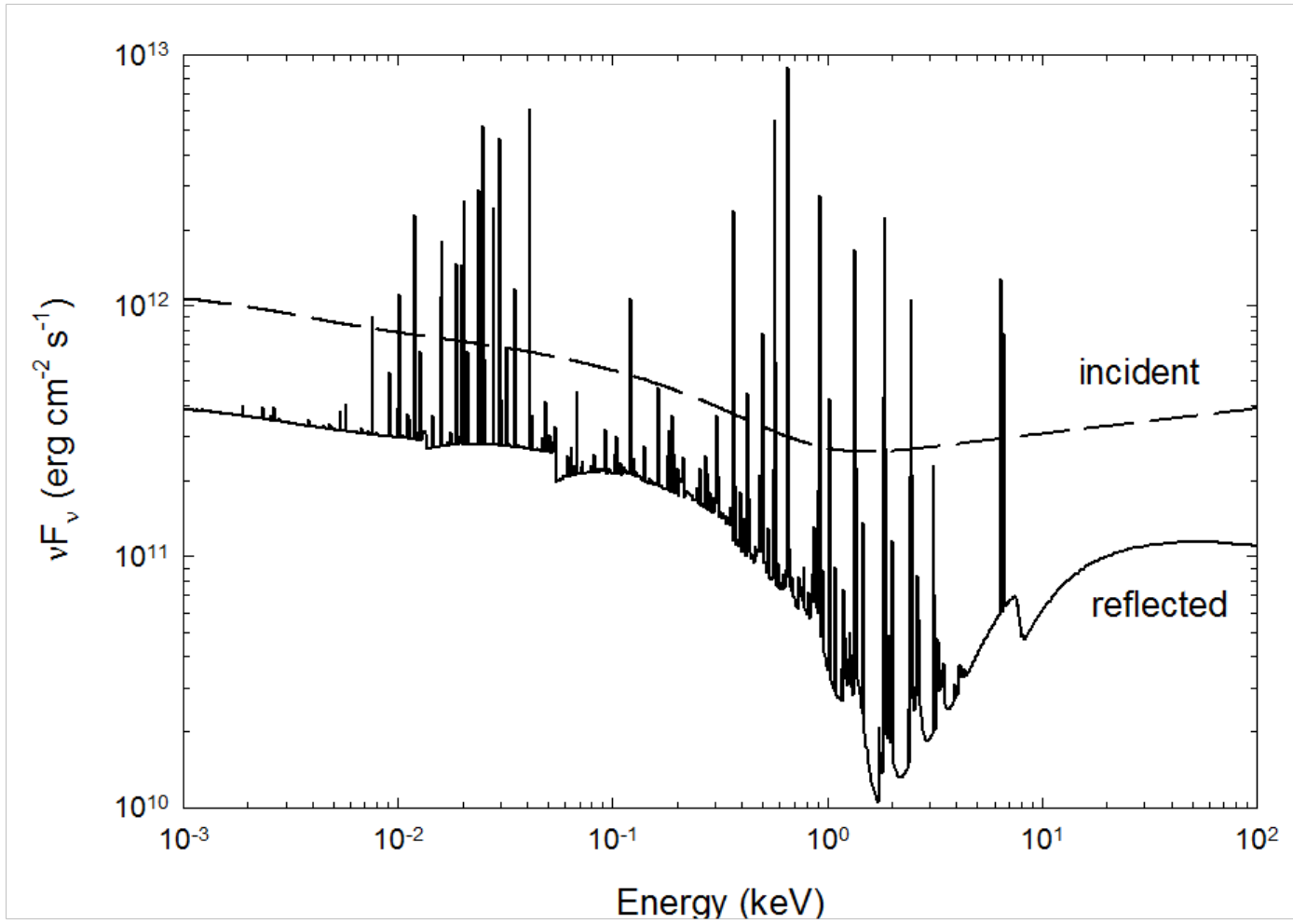
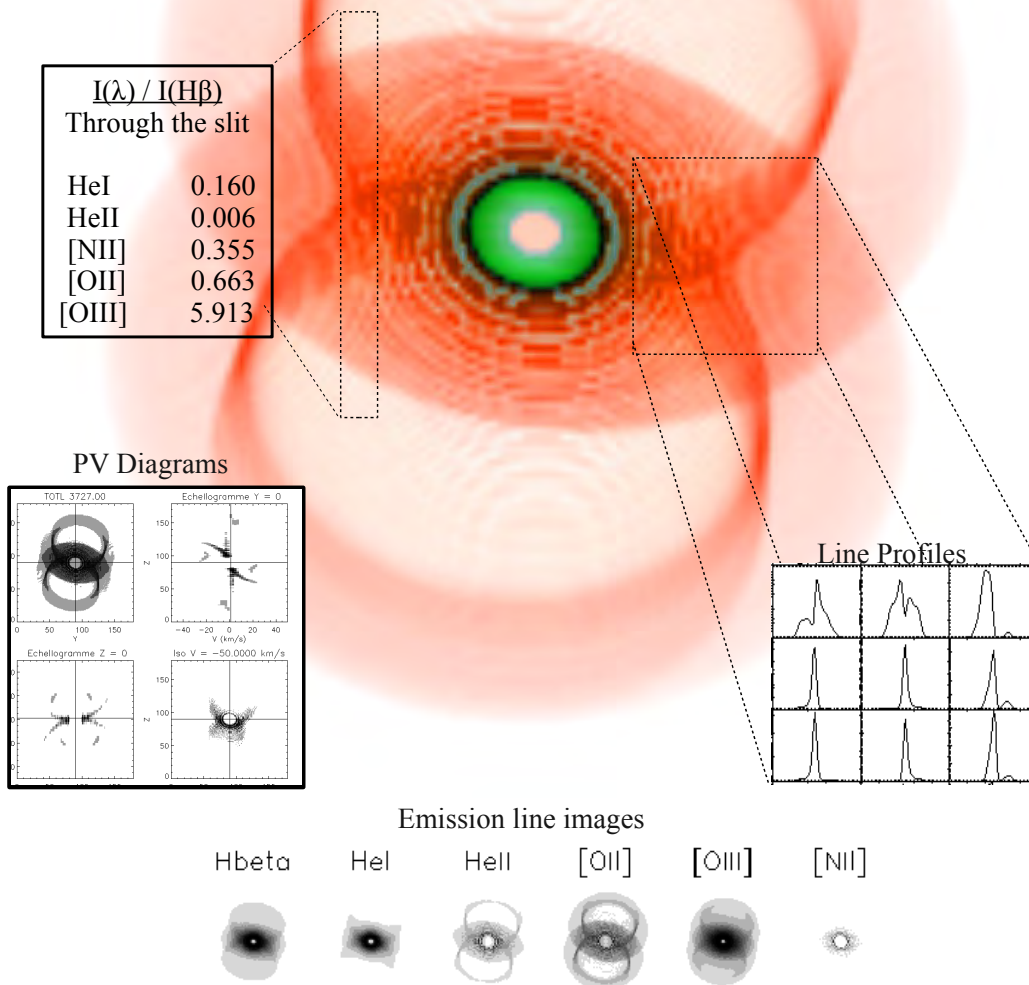


Figure 2.2: This incident (dashed) and reflected (solid) radiation fields, as computed by `agn_blr_albedo.in` in the test suite.

# Cloudy\_3D



<http://sites.google.com/site/cloudy3d/>

Image by: Nahiel Flores, Jonnathan Reyes, Juan Venancio Hernández & Christophe Morisset

Figure 2.3: A 3-color image of a Hourglass-type nebula, obtained by running Cloudy 3D. Colors are [N II] (orange) and [O III] (green) emission. Emission line profiles are shown for [N II] lines. Intensities through any given slit can be obtained. Position-velocity diagrams are obtained as well as channel maps, for any line. Emission line surface brightness maps are also available for any line computed by CLOUDY. Statistical tools to analyze emission line properties are also provided.

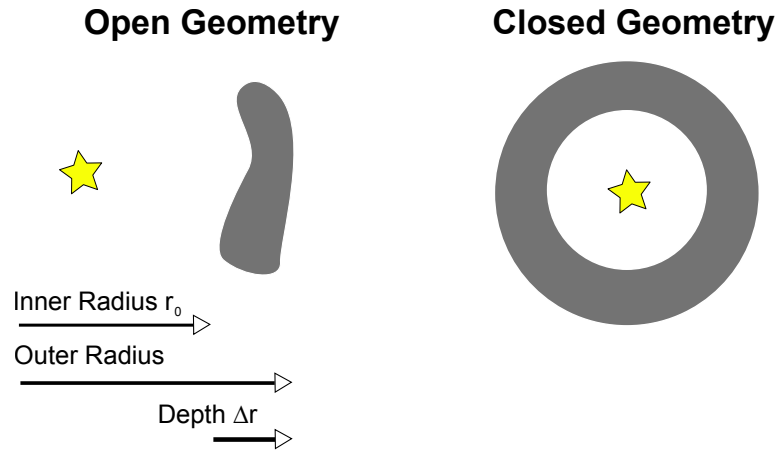


Figure 2.4: This figure shows the two limiting cases that can be assumed. The star is the source of ionizing radiation and the shaded area represents the cloud. An open geometry is the default, and a closed geometry will be computed if the **sphere** command is entered.

### 2.3.1 Illuminated and shielded faces of the cloud

The side of the cloud facing the source of the external radiation field is the *illuminated face* of the cloud. The opposite side, in shadow, is the *shielded face* of the cloud. The illuminated face is generally hotter and more highly ionized than the shielded face. In nearly all cases the calculation starts at the illuminated face and stops at the shielded face.

### 2.3.2 Depth and radius

Figure 2.4 shows two possible geometries and some terms used to describe them. The *radius* is the distance from the center of symmetry, usually the center of the central object, to a given point. The *depth* is the distance between the illuminated face of the cloud and a point within the cloud. The *inner radius* is referred to as  $r_o$ , the depth is  $\Delta r$ , and the *current radius* is  $r$ . The depth or radius for a zone is the distance to the center of the zone.

### 2.3.3 Covering factor

The *covering factor* is the fraction of  $4\pi$  sr covered by gas, as viewed from the central source of radiation. It is normally written as  $\Omega/4\pi$  (AGN3 Section 5.9), has the limits  $0 \leq \Omega/4\pi \leq 1$ , and is the fraction of the radiation field emitted by the central object that actually strikes nebular gas. *Line luminosities* give the total energy emitted by a shell covering  $\Omega$  sr while *line intensities* give the energy emitted per unit area of cloud. Line luminosities scale nearly linearly with increasing covering factor while line intensities are only weakly dependent on it.

### 2.3.4 Open vs. closed geometry

Two limiting cases, referred to as *open* and *closed*, can be identified for the geometry and its influence upon the calculations. Figure 2.4 shows examples of both. The covering factor determines which is the best approximation. The choice mainly affects the transfer of the diffuse fields and has only second-order effects on predicted quantities.

**Open geometry.** An *open* geometry is one in which the covering factor of the gas is small. All radiation that escapes from the illuminated face of the cloud, towards the source of continuous radiation, then escapes from the system without further interaction with gas. This is thought to be the case in, for example, the broad-line region of active nuclei or a blister H II region. In this case  $L\beta$  and higher hydrogen Lyman lines and ionizing radiation produced by recombinations can escape from the nebula. This geometry is the default and will be assumed if the **sphere** command is not specified.

**Closed geometry.** Emission-line gas covers  $\sim 4\pi$  sr as seen by the central object in a *closed* geometry. The central object is small relative to the nebula then all diffuse fields which escape from the illuminated face of the cloud in the direction towards the central object will go on to strike the far side of the nebula. This geometry is implicitly assumed in most calculations of planetary nebulae and H II regions. This geometry will be assumed if the **sphere** command is entered.

**Static vs. expanding.** The sphere command has two optional arguments, **static** and **expanding**. This determines how emission-line photons which cross the central hole and strike the far side of the shell interact with the gas. The **static** option says to assume that the shell is stationary so that all lines interact across the nebula. In this case hydrogen Lyman line interaction should ensure that Case B is reached (AGN3 Section 4.2). If the nebula is expanding then the continuum photons that cross the central hole will interact with gas on the far side but the expansion velocity of the shell ensures that diffuse line photons do not. In this case the **expanding** option should be set. This second case is the default when **sphere** is specified with no options.

*Don't panic!* These geometrical considerations (open vs closed, static vs expanding) make only second-order differences in the predicted emission-line spectrum, generally at the  $\approx 10\%$  level, largely because of the different treatments of the radiative transfer of the diffuse fields. If you are concerned about which geometry to use, try both, and compare the results. The differences are usually small.

### 2.3.5 Filling factor

The *filling factor*  $f(r)$  accounts for clumping of emission-line gas. When a filling factor is set the hydrogen density is the density within regions containing gas while surrounding regions are assumed to be a vacuum. The specific effects of a filling factor are described by [Osterbrock and Flather \(1959\)](#) and in AGN3 section 5.9.

### 2.3.6 Hydrogen density

The *hydrogen density*  $n(\text{H})$  is the total hydrogen density given by

$$n(\text{H}) = n(\text{H}^0) + n(\text{H}^+) + 2n(\text{H}_2) + \sum_{\text{other}} n(\text{H}_{\text{other}}) [\text{cm}^{-3}] \quad (2.1)$$

where  $n(\text{H}_{\text{other}})$  represents H in all other hydrogen-bearing molecules.

### 2.3.7 Column densities

The *hydrogen column density*  $N(\text{H})$  is given by

$$N(\text{H}) = \int n(\text{H}) f(r) dr [\text{cm}^{-2}] \quad (2.2)$$

where  $f(r)$  is the filling factor. I try to consistently use lower case  $n$  for a volume density ( $\text{cm}^{-3}$ ) and an upper case  $N$  for a column density ( $\text{cm}^{-2}$ ).

### 2.3.8 Matter-bounded and radiation-bounded geometries

Two limiting cases for the hydrogen-ionization structure of a cloud exist.

**Matter-bounded geometry.** The cloud is said to be matter bounded if the outer limit to the  $H^+$  region is marked by the outer edge of the cloud. In this case the cloud is ionized throughout and is optically thin to the incident radiation field. In a matter-bounded cloud the intensity or luminosity of an optically thin recombination line is set by the product of volume and density (called the emission measure  $n^2V$ , AGN3, Section 8.1) and is not directly related to the luminosity of the ionizing continuum.

**Radiation-bounded geometry.** The cloud is said to be radiation bounded if the outer limit to the  $H^+$  region is defined by a hydrogen ionization front so both warm ionized and cold neutral regions exist. The  $H^+$  region is optically thick to the hydrogen-ionizing radiation and has absorbed nearly all of it. In this case the intensity or luminosity of a recombination line is set by the luminosity of the ionizing continuum with relatively little dependence on cloud properties.

## 2.4 Intensity & luminosity cases

The external radiation field is usually specified with two different commands. One specifies the shape of the incident radiation field. A second command will set the brightness of the light. CLOUDY must be able to deduce the flux of photons [ $\text{cm}^{-2} \text{s}^{-1}$ ] striking the illuminated face of the cloud. There are two ways to specify the brightness of the external radiation field.

### 2.4.1 Luminosity case

If the brightness of the external radiation field is specified as a “luminosity”, the light radiated by the central object into  $4\pi$  sr, then it is also necessary to specify an inner or starting radius so that the flux of photons can be derived.

The emission lines will be predicted as luminosities. A covering factor will linearly change the luminosity of the entire spectrum but will have only second order effects on relative intensities.

### 2.4.2 Intensity case

The external radiation field can be specified as an “intensity”, the energy incident upon a unit area of cloud, with units something like  $\text{photons cm}^{-2} \text{s}^{-1}$ . It is not necessary to specify a starting radius in the intensity case although it is possible to do so. Line intensities (energy emitted per unit area of cloud, related to  $4\pi J$ ), are predicted in this case.

If the “intensity” of the external radiation field is set then a starting radius does not need to be specified. If the starting radius is not specified then an inner radius of  $10^{30}$  cm is assumed. A plane-parallel geometry usually results. The predicted emission-line spectrum is then given in intensity units. A starting radius may be specified and, if it is, then the resulting geometry may be spherical, plane parallel, or a thick shell, depending on the ratio of the outer to inner radii. Both absolute and relative intensities of lines have only second-order dependencies on the covering factor.

The word “intensity” appears in quotes since it is not the  $I$  or  $J$  defined in radiative transfer texts, but rather the photon or energy equivalent of  $4\pi J$ .

### 2.4.3 The units of the predicted emission lines

The units of the predicted emission-line spectrum are determined by the units of the incident radiation field. If the incident field is specified as a luminosity then the spectrum will be given as the luminosity radiated by a shell covering  $\Omega$  sr of the central object ( $L_{line}, \text{erg s}^{-1}$ ). Here  $\Omega$  is the angular coverage of the nebula so that  $\Omega/4\pi$  (with a default value of unity) is the covering factor (AGN3, Section 5.9). If the continuum is specified as an intensity then the spectrum will be the energy radiated by a unit area of cloud into  $4\pi$  sr ( $4\pi J_{line}, \text{erg cm}^{-2} \text{s}^{-1}$ ).

# Chapter 3

## INTRODUCTION TO COMMANDS

### 3.1 Overview

This section introduces the commands that drive CLOUDY. The following chapters group the commands together by purpose. Individual commands are discussed after examples of their use. This section begins by outlining conditions that are assumed by default and then goes on to discuss the various classes of commands (i.e., those that set the incident radiation field, composition, or the geometry).

Keeping this document parallel with the code is a very high priority. In case of any confusion, please consult the original source. The commands are parsed by the series of routines that have names beginning with “*parse*”. The list of routines can be seen by listing the files `parse*.cpp`. The second half of the name indicates the command that is parsed by that routine.

CLOUDY is designed so that a reasonable set of initial conditions to be assumed by default so that a minimum number of commands are needed to drive it. These default conditions are summarized in Table 3.1, which also lists the commands that change each assumption.

The code is also designed to check that its assumptions are not violated. It should complain if problems occur, if its limits are exceeded, or if the input parameters are unphysical. It may print a series of warnings, cautions, or notes if some limit was exceeded or physical assumption violated.

### 3.2 Command format

#### 3.2.1 Input and Output.

When executed as a stand-alone program CLOUDY reads `stdin` for input and produces output on `stdout`. From a command prompt, this would be done as **cloudy.exe < input > output** or **cloudy.exe -r prefix** (the latter form will read its input from `prefix.in` and write its main output to `prefix.out`). The code is also designed to be used as a subroutine of other, much larger, programs. In this case the input stream is entered using the subroutine calls described in a section of Part 2 of this document. In either case, this input stream must contain all the commands needed to drive the program. The command format is the same whether used as a stand-alone program or as a subroutine.

#### 3.2.2 Command-line format.

Commands are entered as lines that start with a left-aligned four-character keyword in columns 1 to 4, except where more characters are required to prevent ambiguity. This keyword specifies the purpose of the

Table 3.1: Default Conditions

Quantity	Value	Command
Default inner radius	$10^{30}$ cm	<b>radius</b>
Default outer radius	$10^{31}$ cm	<b>radius</b>
Highest allowed temperature	$1.001 \times 10^{10}$ K	
Stop calculation when $T$ falls below this value	4000 K	<b>stop temperature</b>
Relative error in heating-cooling balance	0.005	<b>set temperature convergence</b>
Relative error in electron density	0.0	<b>set eden convergence</b>
Relative intensity of faintest line to print	$10^{-3}$	<b>print line faint</b>
Low-energy limit to continuum	$1.001 \times 10^{-8}$ Ryd	
High-energy limit to continuum	$7.354 \times 10^6$ Ryd	
Limiting number of zones	1400	<b>set nend</b>
Total hydrogen column density	$10^{30}$ cm $^{-2}$	<b>stop column density</b>
H $^+$ column density	$10^{30}$ cm $^{-2}$	<b>stop column density</b>
H $^0$ column density	$10^{30}$ cm $^{-2}$	<b>stop column density</b>
Grains	No grains	<b>grains</b>
Spectral resolution	mesh resolution	<b>set save line width</b>
Background cosmic rays	No	<b>cosmic rays</b>
Cosmic background	No	<b>background</b>

command and is usually followed by one or more numbers or keywords. The keywords can be either lower or upper case. In the following examples the individual command keywords are shown extending beyond column 4. These extra characters are usually ignored.

The end of each command line is marked<sup>1</sup> by the end-of-line, a semi-colon “;”, a pair of forward slashes “//”, a sharp sign “#”, or a percentage sign “%”.

The command lines can be in any order and each can be up to 200 characters long<sup>2</sup>. The input stream ends with a blank line, the end-of-file, or a field of stars (“\*\*\*\*\*”).

### 3.2.3 Units

Most commands use cgs units. In a few cases common astronomical nomenclature can be entered (i.e., the luminosity can be specified as erg s $^{-1}$ , in solar units, or even magnitudes). This syntax varies from command to command so it is important that the units be checked carefully.

### 3.2.4 Number of commands.

Up to 4000 separate commands may be entered.

<sup>1</sup>Before version 92 a colon (“:”) could also mark an end of line. This character is needed to specify a path in the Windows environment and is no longer an end-of-line indicator.

<sup>2</sup>This limit is set by the length of the variable *INPUT\_LINE\_LENGTH* which occurs in a header file. Increase this variable and recompile the entire code if longer lines are needed.

### 3.2.5 Output as input.

CLOUDY can read its own output as an input stream. As described in the section *Output* in Part 2 of this document, the code echoes the input command lines as a header before the calculation begins. These lines are centered on the page and surrounded by asterisks.

Sometimes a particular model will need to be recomputed. You can do this by making a copy of the printed command lines and using this copy as an input file. The input parser will handle removal of the leading spaces and asterisk. This is mainly a debugging aid.

### 3.2.6 Syntax used in this document

Sections describing each of the commands are introduced by examples of their use.

Square brackets indicate optional parameters. Optional parameters are shown surrounded by square brackets (“[” and “]”). The examples shown below use the format given in this document.

```
// following needs flux density, but frequency is optional
f(nu) = -12.456 [at .1824 Ryd]
//
// the luminosity command has several optional keywords
luminosity 38.3 [solar, range, linear]
//
// the phi(h) command has the range option
phi(h) = 12.867 [range ...]
```

These square brackets indicate only that the parameters are optional. The brackets should not be placed on the command line. They will be totally ignored if they occur. The above example would actually be entered as follows:

```
// following gives flux density at energy of 0.1824 Ryd
f(nu) = -12.456 at .1824 Ryd
//
// the luminosity command with linear keyword
luminosity 2e38 solar linear
//
// the phi(h) command with the range option
phi(h) = 12.867 range 0.1 to 0.2 Ryd
```

Underscores indicate a space. Most commands and keywords require four character matches to be recognized. Keywords which start with a letter (i.e. A—Z) must start following a space (or other non-alphabetic character) in order to be recognized. Only one space is needed between words.

The following is an example with the commands written as they are shown in this document:

```
// blackbody with T=5e4 K, in strict TE
blackbody 5e4 K lte
//
// use ISM radiation field
table ism
```

The following is how the commands should actually be entered:

```
// blackbody with T=5e4 K, in strict TE
blackbody 5e4 K lte
//
// use ISM radiation field
table ism
```

The space must occur where the underscore is written.

### 3.2.7 and, because nobody ever reads this document....

The examples of commands that follow show the square brackets and underscores for optional parameters and required spaces. Many people put these characters into the input stream because they don't read documentation. As a service to the user, the command-line parser will usually replace any square brackets or underscores with the space character when the command lines are initially read. The exception is any part of a string that is surrounded by double quotes. The string between double quotes is likely to be a file name and an underscore can occur in such a name.

### 3.2.8 The continue option

It may not be possible to enter all the required values on a single line for the **interpolate** and **abundances** commands. In these two cases the original command line can be continued on following lines with a series of lines beginning with the keyword **continue**. The format on a **continue** line is unchanged. There is no limit to the number of **continue** lines that can be included other than the limit of a total of 4000 input lines. The following is an example with the abundances command

```
abundances he ==-1 li=-9 be=-11 b=-9 c=-4.3 n=-5 o=-2.3
continue f=-7 ne ==-1.2 na ==-3 mg ==-8
continue al ==-8 si ==-8 p=-6 s=-8 cl=-9 ar ==-8 k=-6
continue ca ==-8 sc=-9 ti=-7 v=-8 cr=-6.3 mn=-6 fe ==-8
continue co ==-9 ni ==-8 cu=-7 zn=-7
```

### 3.2.9 Numerical input

Numerical parameters are entered on the command line as free-format numbers. Exponential notation can be used.<sup>3</sup> Numbers may be preceded or followed by characters to increase readability. The strings "T=1000000K", "1000000", and "T=1E6" are equivalent. A period or full stop (".") by itself is interpreted as a character, not numeral or number.

At present, commas can be freely embedded in input numbers and they are completely ignored. This behaviour is in the process of being deprecated, so in future versions of Cloudy will lead to warnings and in due course fail. Exponential notation can generally be used instead to improve clarity.

Default values are often available. As an example, the **power law** command has three parameters, the last two being optional. The following are all acceptable (but not equivalent) forms of the command;

```
power law, slope=-1.4, cutoffs at 9 Ryd and 0.01 Ryd
powe -1.0 5
power law, slope=-1.4 .
```

The last version uses the default cutoffs, i.e., none. If optional parameters are omitted they must be omitted from right to left; numbers must appear in the expected order.

Note that implicit negative signs (for instance, for the slope of the power law) *do not* occur in any of the following commands.

Table 3.2 shows how various typed input numbers will be interpreted. The first column gives the typed quantity, the second its interpretation, and the third the explanation.

The last two examples illustrate why it is intended in the future to no longer allow commas to be used as mark up within numbers, but instead as a separator character.

<sup>3</sup>Exponential notation could not be used in versions 07 and before.

Table 3.2: Interpretation of Numerical Input

Typed Quantity	Interpreted as	Why
1e2	100	Exponential notation is OK
1.2.3	two numbers 1.2 0.3	1.2 is parsed, then .3
.3 3	0.3 and 3.0	
10^3	1000	$\wedge$ acts as exponentiation operator
1,000	1000	Commas are removed before parsing (deprecated usage)
\$temp	variable value	set by \$temp = 1000 previously in input
1e2,1e4	two numbers, 1e21 and 4	',' is removed (deprecated usage)
100,3.141516	1 number, 1003.141516	',' is removed (deprecated usage)


### 3.2.10 Comments

Comments may be entered among the input data in several ways. Comments can be entered at the end of a command line after a semi-colon (“;”), double slash (“//”), a sharp sign (“#”), or a percentage sign (“%”). Anything on a line after one of these characters is completely ignored. This can be used to document parameters on a line. Any line beginning with a #, %, //, or a \* is totally ignored; it is not even printed. A line beginning with **c** is ignored, but printed (note a space is required after the ‘c’ to distinguish it from other commands). There is also a **title** command, to enter a title for the simulation.

### 3.2.11 Hidden commands

A command will be parsed and used by the code but not printed in the output if the keyword **hide** occurs somewhere on the command line. This provides a way to not print extensive sets of commands, like the **continue** option on the **continuum** command, or the **print off** command in an initialization file.

### 3.2.12 Commands for experimental parts of the code

The code is in continuous development. When new versions are released there will be new or experimental parts of the code that are still being developed or which have not been fully debugged. The newly-developed physics is not included in a calculation which uses the default conditions. The commands which exercise these new features are included in this document and are indicated in two ways. First by the  symbol in the section header, and second by a grey background. You are welcome to give these commands a try but should not expect robust results.

### 3.2.13 Log vs linear quantities

Most quantities are entered as the log of the number but some are linear. The following outlines some systematics of how these are entered.

**Temperature.** CLOUDY will interpret a temperature as a log if the number is less than or equal to 10 and the linear temperature if it is greater than 10. Many commands have the optional keyword **linear** to force numbers below 10 to be interpreted as the linear temperature rather than the log.

**Other parameters.** The pattern for other quantities is not as clear as for the case of temperature. Often quantities are interpreted as logs if negative, but may be linear or logs if positive (depending on the command). Many commands have the keywords **log** and **linear** to force one or the other interpretation to be used.

Using the new notation  $10^{3.5}$  as a linear number is equivalent to the form **3.5 log**, and will be required to replace the **log** keyword in future versions of CLOUDY.

### 3.2.14 The help command

This command prints helpful information about Cloudy and exits. Don't expect much as yet, beyond a recommendation to read this document!

### 3.2.15 An example

Specific commands to set boundary conditions for a simulation are discussed in the following sections. As a minimum, the hydrogen density, the shape and intensity of the incident radiation field, and possibly the starting radius, must be specified to compute a model. As an example, a simple model of a planetary nebula could be computed by entering the following input stream.

```
title "this is the input stream for a planetary nebula"
//
// set the temperature of the central star
blackbody, temperature = 1e5 K
//
// set the total luminosity of the central star
luminosity total 38 // log(Ltot)- ergs/s
radius 17 // log of starting radius in cm
hden 4 // log of hydrogen density - cm^-3
sphere // this is a sphere with large covering factor
```

## 3.3 Filenames

It is sometimes necessary to read or write external files whose names are specified on a command line. File names are entered inside pairs of double quotes, as in "name.txt".

The command parser first checks whether a quote occurs anywhere on the command line. If one does occur then the parser will search for a second pair of quotes and use whatever text lies between as a filename. The code will stop with an error condition if the second of the pair of quotes is not found or if the file cannot be opened for reading or writing.

## 3.4 The init command

This is a special command that tells the code to read a set of commands stored in an ancillary file. This allows frequently-used commands to be stored in a single file. The **init** command will automatically find

initialization files that are located in the code's data directory, allowing them to be easily accessed from other directories. The code will first search for the file in the local directory and then in the data directory. The **init** command is fully described in later sections below.

The filename can be specified within a pair of double quotes, as in "ism.ini". The default name for the initialization file is cloudy.ini. There is no limit to the number of commands that can be in this initialization file other than the total limit of 4000 command lines that is intrinsic to the code.

This provides an easy way to change the default behavior of the code. For instance, many of the elements now included in CLOUDY have negligible abundances and the code will run a bit faster if they are turned off with the **element off** command. Also, only about half of these elements were included before version 86 of the code. The file c84.ini in the CLOUDY data directory which will turn off many of these elements. The c84.ini file contains the following commands:

```
print off hide
elements read
helium
carbon
nitrogen
oxygen
neon
sodium
magnesium
aluminium
silicon
sulphur
argon
calcium
iron
nickel
end of elements
element Lithium off
element Beryllium off
element Boron off
element Fluorine off
element Phosphor off
element Chlorine off
element Potassium off
element Scandium off
element Titanium off
element Vanadium off
element Chromium off
element Manganese off
element Cobalt off
element Copper off
element Zinc off
print on
```

The current version of the code would only include those elements present in version 84 if the command

```
init "c84.ini"
```

were entered in the input stream.

A series of \*.ini files are included in the data directory included in the CLOUDY distribution. Do an `ls *.ini` within the data directory to list the available files. Comments at the start of the files describe their purpose.



# Chapter 4

## THE INCIDENT RADIATION FIELD

### 4.1 Overview

The incident radiation field should be defined between the low-energy limit to the code,  $1.001 \times 10^{-8}$  Ryd, corresponding to a wavelengths of 10 m, and the high-energy limit of  $7.354 \times 10^6$  Ryd, corresponding to an energy of 100 MeV. The shape and its intensity or luminosity are usually specified independently. There are many ways to do this.

### 4.2 The coarse and fine continua

The spectral resolving power is defined as  $E/\delta E$ , where  $E$  is the photon energy and  $\delta E$  the width of the resolution element. The number of energy bins needed to store the radiation field is proportional to the resolving power. This number is a major pace setter for the code since it must continuously reevaluate various integrals over the radiation field.

The code uses multi-grid methods to compute interactions among the many millions of spectral lines (Shaw et al., 2005). The *coarse continuum* is used to define the incident and diffuse continua and is output with various **save continuum** commands. The resolving power of the coarse continuum is defined in the file `continuum_mesh.ini` in the data directory. This file is designed to be changed by the user and can be changed to much higher resolving power if need be. This is all described in the Chapter *The Continuum Mesh* in Part 2 of this document.

The resolution of the coarse continuum for a particular model can be changed with the **set continuum resolution** command described on page 238. The resolution of particular parts of the continuum can be changed by changing the file `continuum_mesh.ini` in the data directory. If you change the continuum resolution either way you will need to recompile the stellar continua and grain opacities so that their energy grid agrees with that used by the code.

A second *fine continuum* has much higher spectral resolving power and is far more expensive to evaluate. It is used to resolve overlapping spectral lines and define blocking coefficients for the coarse continuum. This permits the effects of line overlap and velocity shear to be treated automatically.

The fine continuum, which does resolve all spectral features, is not normally reported. There are some options on the **save continuum** command (page 162) which do give this fine continuum.

### 4.3 Defining a single component of the incident radiation field

Two quantities, the *shape* and *intensity*, specify a single component of the incident radiation field. The shape gives the form of the spectral energy distribution but not its intensity. The intensity can be specified as either the energy striking the illuminated face of the cloud, referred to as the intensity case, or both the source luminosity and the distance separating the source and the cloud. The latter is referred to as the luminosity case. The shape and intensity are specified independently in most cases, although some commands specify both (the command specifying the cosmic microwave background is an example of the latter).

In much of the following discussion we will refer to both luminosity and intensity commands as simply intensity commands. The distinction between the luminosity and intensity cases is discussed further on page 11.

## 4.4 Combining several radiation fields

### 4.4.1 The sum of several radiation fields

It is possible to combine up to 100 incident radiation fields.<sup>1</sup> CLOUDY will stop if more than 100 continua are entered. This limit is set by the variable *LIMSPC* that occurs in one of the included header files.

When more than one radiation field is entered the series of luminosity and shape commands must be in the same order (i.e., map one to one). There must always be exactly the same number of luminosity and shape specifications; CLOUDY will stop if there are not.

As an example, the following would be a rough approximation of an accretion disk and boundary layer around a white dwarf:

```
// this is the black body associated with the boundary layer
// this is a shape command
black body, temperature =5e5 K
// this gives its total luminosity
luminosity (total) 37.3
// the following shape is a rising power law,
// a simple approximation to the disk
power law, slope = 1.333, cutoff = 0.6 Ryd
// the total luminosity of this power law component
luminosity (total) 37.2
```

The  $5 \times 10^5$  K blackbody has a total luminosity of  $10^{37.3} \text{ erg s}^{-1}$  while the power-law has a total luminosity of  $10^{37.2} \text{ erg s}^{-1}$ .

### 4.4.2 Keeping shape and intensity commands together

It is not absolutely necessary to keep the ordered pairs of shape and intensity commands together but this is a good practice since some commands (those given in Table 4.1) specify *both* the shape *and* intensity of the incident radiation field. Problems arise if one of the commands giving both shape and intensity is entered between another pair of shape and intensity commands. For instance, the following will produce unintended results:

<sup>1</sup> Restrictions on the number of tables that could be entered existed in CLOUDY versions 73 and before, but have been lifted. Restrictions on which types of continua could be combined existed in CLOUDY versions 67 and before, but have been lifted.

Table 4.1: Commands specifying both shape *and* intensity

---

background
blackbody, energy density
blackbody, LTE
blackbody, luminosity
blackbody, radius
CMB
table Draine
table HM96, HM05
table ISM

---

```
black body, temp = 5e5 K
CMB, z=2
luminosity (total) 37
```

because the **CMB** command enters both the shape and intensity of the cosmic microwave background. In this example it comes after the **blackbody** command specifies a shape, but before the **luminosity** command specifies the luminosity of the blackbody. As a result the intensity implicitly entered by the **CMB** command will apply to the hot blackbody rather than the cosmic microwave background and the **luminosity** command will then incorrectly set the intensity of the cosmic background blackbody shape. This problem cannot occur if the shape and intensity commands are always kept together as in the previous example. The code should produce a warning if shape and luminosity commands are mixed together with a command that enters both.

## 4.5 Check the incident radiation field!

It is important to check that the incident radiation field has been entered correctly. First set up the commands to do a simulation and include the **save continuum** command (described on page 162). Do the simulation and examine the file produced by the **save continuum** command. The first column gives the photon energy and the second gives the incident radiation field (as  $\nu J_\nu$ ,  $\text{erg cm}^{-2} \text{s}^{-1}$ ) at the illuminated face of the cloud. Plot this radiation field and check that it is correct.



# Chapter 5

## INCIDENT RADIATION FIELD LUMINOSITY

### 5.1 Overview

All commands setting the intensity or luminosity of the incident radiation field are defined in this Chapter.

### 5.2 Intensity and luminosity cases

The brightness of the incident radiation field can be specified as either an intensity, the energy per unit area of cloud, or as a luminosity, the power emitted by the central source of radiation into  $4\pi$  sr. The *intensity case* and *luminosity case* are described on page 11. Each of the following commands is listed as an intensity or luminosity command. This distinction is important because the inner radius of the cloud must also be specified in the luminosity case.

### 5.3 The range option

Many of the intensity/luminosity commands specify the number of photons or integrated energy *in hydrogen-ionizing radiation* ( $1 \text{ Ryd} \leq h\nu \leq 7.354 \times 10^6 \text{ Ryd}$ ). Other energy intervals can be specified with the **range** option, an optional keyword that can appear on most intensity / luminosity commands.

When the keyword **range** appears there are an additional two parameters, the low- and high-energy limits to the energy range in Rydbergs. These appear as the second and third numbers on the line (the first number gives the intensity or luminosity). The position of the keyword **range** on the command line does not matter but the order of the numbers on the line does matter. If both range parameters are omitted then the low ( $1.001 \times 10^{-8} \text{ Ryd}$ ) and high ( $7.354 \times 10^6 \text{ Ryd}$ ) energy limit of the incident radiation field will be substituted. If both energies are specified then the second number must be larger than the first. If only one parameter appears then only the lower limit of the range will be changed and the high-energy limit will be left at its default of  $7.354 \times 10^6 \text{ Ryd}$ . If the first optional number is negative or the keyword **log** appears then *both* of the extra numbers are interpreted as logs. If you want to set the lower limit of the range to the low energy limit  $1.001 \times 10^{-8} \text{ Ryd}$  of the incident radiation field, but want to supply your own upper limit, you can enter 0 followed by the upper limit if you use linear numbers, or  $-10$  followed by the upper limit if you use log numbers ( $-10$  is actually any number  $\leq \log(1.001 \times 10^{-8} \text{ Ryd})$ ).

If **range total**, or simply **range** or **total**, appears with no parameters then the full energy range considered by the program,  $1.001 \times 10^{-8}$  Ryd to  $7.354 \times 10^6$  Ryd, will be used. In this case the number is the total integrated (bolometric) intensity or luminosity.

The following shows examples of the range option for the **luminosity** command. By default the **luminosity** command has a single parameter, the log of the luminosity [ $\text{erg s}^{-1}$ ] in hydrogen-ionizing radiation ( $1 \text{ Ryd} \leq h\nu < 7.354 \times 10^6 \text{ Ryd}$ ). The “;” symbol is used to terminate the line in one case.

```
// this will use the default range, only ionizing radiation
luminosity 38 ;the log of the luminosity in erg s^-1

// either will be the total luminosity
luminosity total 38
luminosity 33.4 range
luminosity 33.4 range total

// this will be the luminosity in visible light
luminosity 37.8 range .15 to .23 Ryd

// the luminosity in radiation more energetic than 0.1 Ryd
luminosity 38.1 range -1

// this will be the luminosity in non-ionizing radiation
luminosity 39.8 range 0 1
```

## 5.4 Absolute [visual, bolometric] magnitude -2.3

It is possible to specify the integrated or monochromatic luminosity in “magnitudes,” a quaint unit of historical interest. One of the keywords **bolometric** or **visual** must also appear. The absolute bolometric magnitude  $M_{bol}$  is related to the total luminosity by (Allen, 1976, page 197)

$$L_{total} = 3.826 \times 10^{33} \times 10^{(4.75 - M_{bol})/2.5} [\text{erg s}^{-1}]. \quad (5.1)$$

The absolute visual magnitude  $M_V$  is approximately related to the monochromatic luminosity per octave at  $5550 \text{ \AA}$  by (Allen, 1976, page 197)

$$\nu L_\nu (5500\text{\AA}) \approx 2.44 \times 10^{35} \times 10^{-M_V/2.5} [\text{erg s}^{-1}]. \quad (5.2)$$

The conversion between monochromatic luminosity per octave  $\nu L_\nu$  and absolute visual magnitude  $M_V$  is approximate, with typical errors of roughly a percent. This is because CLOUDY assumes that the V filter has an isophotal wavelength of  $5550 \text{ \AA}$  and does not actually integrate over the incident radiation field using a V-filter transmission function.

This is a luminosity command.

## 5.5 Energy density 5e4 K [linear]

This specifies the energy density [K] of the incident radiation field. The number is the equivalent energy-density temperature, defined as  $T_u = (u/a)^{1/4}$  K where  $u$  is the total energy density in all radiation [ $\text{erg cm}^{-3}$ ] and  $a$  is the Stefan radiation-density constant. The number is interpreted as the log of the temperature if it is less than or equal to 10 or the keyword **log** is present, and as a linear number otherwise. The optional keyword **linear** forces the number to always be interpreted as a linear temperature.

This is an intensity command.

## 5.6 $f(\text{nu}) = -12.456$ [at .1824 Ryd]

This specifies the monochromatic intensity at an arbitrary energy. The first number is the log of the monochromatic mean intensity at the illuminated face of the cloud,  $4\pi J_\nu$  (with units  $\text{erg s}^{-1}\text{Hz}^{-1}\text{cm}^{-2}$ ), where  $J_\nu$  is the mean intensity of the incident radiation field per unit solid angle.

The optional second number is the frequency in Rydbergs where  $4\pi J_\nu$  is specified. The default is 1 Ryd. In the example above the incident radiation field is specified at  $0.1824 \text{ Ryd} = 5000\text{\AA}$ . The frequency can be any within the energy band considered by the code, presently  $1.001 \times 10^{-8} \text{ Ryd}$  to  $7.354 \times 10^6 \text{ Ryd}$ . If the energy is less than or equal to zero then it is interpreted as the log of the energy in Rydbergs, and as the linear energy itself if positive.

This is an intensity command.

## 5.7 Intensity 8.3 [range, linear]

This specifies the integrated mean intensity,  $4\pi J$ , [ $\text{erg cm}^{-2}\text{s}^{-1}$ ] at the illuminated face of the cloud

$$4\pi J = \int_{\nu_1}^{\nu_2} 4\pi J_\nu d\nu [\text{erg cm}^{-2} \text{s}^{-1}]. \quad (5.3)$$

This is the per unit area equivalent of the **luminosity** command. The number is the log of the intensity unless the optional keyword **linear** appears. Unlike the majority of the commands, the first five characters of the line must be entered.

The default range is over hydrogen-ionizing energies ( $1 \text{ Ryd} \leq h\nu \leq 7.354 \times 10^6 \text{ Ryd}$ ). The range option can be used to adjust the values of  $\nu_1$  and  $\nu_2$ .

Some of the interstellar medium and photo-dissociation region (PDR) literature specifies the incident radiation field in units of the [Habing \(1968\)](#) field (see, for instance, [Tielens and Hollenbach, 1985a](#), [Tielens and Hollenbach, 1985b](#)). This radiation field has an integrated intensity of  $1.6 \times 10^{-3} \text{ erg cm}^{-2} \text{s}^{-1}$  between the limits of 6 and 13.6 eV ([Tielens and Hollenbach, 1985a](#); [Hollenbach et al., 1991](#)). This integrated intensity is sometimes referred to as *Go*. The incident radiation field described by Tielens and Hollenbach, but with an intensity of 1 *Go*, could be generated with the commands:

```
// a B star with an intensity roughly the Habing 1968 radiation field
blackbody 3e4 K
intensity -2.8, range 0.44 to 1 Ryd
// remove all H-ionizing radiation
extinguish by 24, leakage = 0
```

This set of commands sets the shape of the Balmer continuum to that of a hot blackbody, sets the intensity to the Habing value, and then extinguishes all hydrogen-ionizing radiation, as is assumed in the PDR literature.

This is an intensity command.

## 5.8 ionization parameter = -1.984

The ionization parameter is the dimensionless ratio of hydrogen-ionizing photon to total-hydrogen densities. It is defined as

$$U \equiv \frac{Q(\text{H})}{4\pi r_o^2 n(\text{H}) c} \equiv \frac{\Phi(\text{H})}{n(\text{H}) c} \quad (5.4)$$

(AGN3, equation 14.7, page 357). Here  $r_o$  is the separation [cm] between the center of the source of ionizing radiation and the illuminated face of the cloud,  $n(\text{H})$  [ $\text{cm}^{-3}$ ] is the total<sup>1</sup> hydrogen density (ionized, neutral, and molecular),  $c$  is the speed of light,  $Q(\text{H})$  [ $\text{s}^{-1}$ ] is the number of hydrogen-ionizing photons emitted by the central object, and  $\Phi(\text{H})$  [ $\text{cm}^{-2} \text{s}^{-1}$ ] is the surface flux of ionizing photons. The number is interpreted as the log of  $U$  unless the keyword **linear** appears. The ionization parameter is a useful quantity in plane-parallel, low-density, constant-density, models, because of homology relations between models with different photon and gas densities but the same ionization parameter (see [Davidson, 1977](#)).

This is an intensity command.

## 5.9 L(nu) = 24.456 [at .1824 Ryd]

This sets the monochromatic luminosity  $L_\nu$  [ $\text{erg s}^{-1} \text{Hz}^{-1}$ ] of the central object. The first number is the log of the luminosity. The optional second number is the frequency in Rydbergs where  $L_\nu$  is specified. The default is 1 Ryd. In the example above the incident radiation field is specified at  $0.1824 \text{ Ryd} = 5000 \text{ \AA}$ . The frequency can be any within the energy band considered by the code, presently  $1.001 \times 10^{-8} \text{ Ryd}$  to  $7.354 \times 10^6 \text{ Ryd}$ . If the energy is less than or equal to zero then it is interpreted as the log of the energy in Rydbergs, and the linear energy itself if positive.

This is a luminosity command.

## 5.10 luminosity 38.3 [solar, range, linear]

The number is the log of the integrated luminosity<sup>2</sup> emitted by the central object into  $4\pi$  sr,

$$L = 4\pi R_{star}^2 \int_{\nu_1}^{\nu_2} \pi F_\nu d\nu [\text{erg s}^{-1}]. \quad (5.5)$$

The default range is over hydrogen-ionizing energies ( $1 \text{ Ryd} \leq h\nu \leq 7.354 \times 10^6 \text{ Ryd}$ ). The **range** option can be used to adjust the values of  $\nu_1$  and  $\nu_2$ .

If the optional keyword **solar** appears the number is the log of the *total* luminosity relative to the sun. It is the log of the total luminosity if the keyword **total** appears. If the **linear** keyword is also used then the quantity will be the luminosity itself and not the log. The **range** option cannot be used if the luminosity is the total luminosity or it is specified in solar units. It will be ignored if it appears.

The following are examples of the luminosity command.

```
// log of luminosity (erg/s) in ionizing radiation
luminosity 36

// roughly the Eddington limit for one solar mass
luminosity total 38

// both are a total luminosity 1000 times solar since
// solar specifies the total luminosity relative to the sun
luminosity solar 3
```

<sup>1</sup>Before version 65 of the code the electron density was used rather than the hydrogen density. Before version 75  $n(\text{H})$  was the atomic/ionic hydrogen density, and did not include molecules.

<sup>2</sup>Before version 83 of the code, the luminosity command was used to enter both luminosity and intensity. The code decided between the two by checking on the resulting ionization parameter. There are now separate intensity and luminosity commands.

```

luminosity linear solar 1000

// this will be the luminosity in visible light
luminosity 37.8 range .15 to .23 Ryd

```

This is a luminosity command.

## 5.11 $\text{nuF}(\text{nu}) = 13.456 [\text{at} .1824 \text{ Ryd}]$

This command specifies the log of the monochromatic mean intensity per octave  $4\pi\nu J_\nu$  [ $\text{erg s}^{-1} \text{cm}^{-2}$ ] at the illuminated face of the cloud. Here  $J_\nu$  is the mean intensity of the incident radiation field.

The optional second number is the energy (Ryd) where  $4\pi\nu J_\nu$  is specified. The default is 1 Ryd. In the example above the incident radiation field is specified at 0.1824 Ryd = 5000Å. The energy can be any within the energy band considered by the code, presently  $1.001 \times 10^{-8}$  Ryd to  $7.354 \times 10^6$  Ryd. If the energy is less than or equal to zero it is interpreted as the log of the energy in Rydbergs. It is the linear energy if it is positive.

This is an intensity command.

## 5.12 $\text{nuL}(\text{nu}) = 43.456 [\text{at} .1824 \text{ Ryd}]$

This command specifies the monochromatic luminosity per octave  $\nu L_\nu$  [ $\text{erg s}^{-1}$ ]. The first number is the log of the luminosity radiated by the central object into  $4\pi$  sr. It can be expressed at an arbitrary photon energy but the default is 1 Ryd.

The optional second number is the energy (Ryd) where  $L_\nu$  is specified. In the example above the incident radiation field is specified at 0.1824 Ryd = 5000Å. The frequency can be any within the energy band considered by the code, presently  $1.001 \times 10^{-8}$  Ryd to  $7.354 \times 10^6$  Ryd. If the energy is less than or equal to zero, it is interpreted as the log of the energy in Rydbergs, and the linear energy if positive.

This is a luminosity command.

## 5.13 $\text{phi}(\text{H}) = 12.867 [\text{range} \dots]$

This command specifies the log of  $\Phi(\text{H})$ , the surface flux of hydrogen-ionizing photons [ $\text{cm}^{-2} \text{s}^{-1}$ ] striking the illuminated face of the cloud. It is defined as

$$\Phi(\text{H}) \equiv \frac{Q(\text{H})}{4\pi r_o^2} \equiv \frac{R_{star}^2}{r_o^2} \int_{\nu_1}^{\nu_2} \frac{\pi F_\nu}{h\nu} d\nu [\text{cm}^{-2} \text{s}^{-1}] \quad (5.6)$$

and is proportional to the optical depth in excited lines, such as the Balmer lines (Ferland et al., 1979; AGN3). The range option can be used to change the default energy range, given by the values of  $\nu_1$  and  $\nu_2$ .

This is an intensity command.

## 5.14 $Q(\text{H}) = 56.789 [\text{range} \dots]$

This is the log of the total number of ionizing photons emitted by the central object [ $\text{s}^{-1}$ ]

$$Q(\text{H}) = 4\pi R_{star}^2 \int_{\nu_1}^{\nu_2} \frac{\pi F_\nu}{h\nu} d\nu. \quad (5.7)$$

The default energy range is 1 Ryd to  $7.354 \times 10^6$  Ryd and the **range** option can be used to change the energy bounds  $\nu_1$  and  $\nu_2$ . The photon flux (the number of photons per unit area of cloud surface) can be specified with the **phi(H)** command<sup>3</sup>.

This is a luminosity command.

## 5.15 ratio -3.4 0.3645 Ryd to 147 Ryd [alphaox, log]

This specifies the intensity of a second radiation field (referred to as the current radiation field) relative to the intensity of the previous radiation field. The ratio of the intensities  $4\pi J_\nu$  ( $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$ ) of the current to the previous radiation field is given by the first number on the command line. It is assumed to be the linear ratio unless it is less than or equal to zero, in which case it is interpreted as a log. If the keyword **log** appears then the positive number is interpreted as the log of the ratio.

The second parameter is the energy in Rydbergs where the previous radiation field is evaluated and the optional third parameter is the energy where the current radiation field is evaluated. If the second energy is not entered then the same energy is used for both. The following is an example of using the **ratio** command to simulate the spectral energy distribution of a typical quasar.

```
blackbody 5e4 K          // the big blue bump
ionization parameter -2 // its ionization parameter
table power law          // an alpha = -1 power law
// now set intensity of power law relative to bump at 1 Ryd
ratio 0.001 at 1 Ryd;
```

This command was introduced to provide a mechanism to specify the optical to X-ray spectral index  $\alpha_{ox}$ . This is defined here as in [Zamorani et al. \(1981\)](#), except for a difference in sign convention. Here  $\alpha_{ox}$  is the spectral index which would describe the continuum between 2 keV (147 Ryd) and 2500Å (0.3645 Ryd) if the continuum could be described as a single power-law, that is,

$$\frac{f_\nu(2 \text{ keV})}{f_\nu(2500 \text{ Å})} = \left( \frac{\nu_{2 \text{ keV}}}{\nu_{2500 \text{ Å}}} \right)^{\alpha_{ox}} = 403.3^{\alpha_{ox}}. \quad (5.8)$$

The definition of  $\alpha_{ox}$  used here is slightly different from that of Zamorani et al. since implicit negative signs are never used by CLOUDY. Typical AGN have  $\alpha_{ox} \sim -1.4$ . If X-rays are not present then  $\alpha_{ox} = 0$ .

The **ratio** command has an optional keyword, **alphaox**, which allows  $\alpha_{ox}$  to be specified directly. If the keyword appears then only one parameter is read, the value of  $\alpha_{ox}$ . A generic AGN spectral energy distribution could be produced with the following,

```
blackbody 5e4 K          // the big blue bump
ionization parameter -2
table power law          // an alpha = -1 power law
ratio alphaox -1.4 // set alpha_ox of the X-ray and UV continua
```

Note that  $\alpha_{ox}$  may (or may not) depend on the luminosity of the quasar, as described by [Avni and Tananbaum \(1986\)](#). The solid line in their Figure 8 corresponds to

$$\alpha_{ox} = -1.32 - 0.088 \times \log \left( \frac{L_o}{10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (5.9)$$

<sup>3</sup>Before version 83 of the code the **phi(H)** and **Q(H)** commands were the same. The code decided which was specified by checking the order of magnitude of the resulting ionization parameter. These are now two different commands.

where they define  $L_o$  as the monochromatic optical luminosity at 2500Å in the source rest frame, and we assume  $H_0 = 50$  and  $q_0 = 0$ . Other fits are given by [Worrall et al. \(1987\)](#):

$$\alpha_{ox} = -1.11 - 0.111 \times \log \left( \frac{L_o}{10^{27} \text{ erg s}^{-1} \text{ Hz}^{-1}} \right) \quad (5.10)$$

and by [Wilkes et al. \(1994\)](#):

$$\alpha_{ox} = -1.53 - 0.11 \times \log \left( \frac{L_o}{10^{30.5} \text{ erg s}^{-1} \text{ Hz}^{-1}} \right). \quad (5.11)$$

However, [La Franca et al. \(1995\)](#) find no dependence of  $\alpha_{ox}$  on luminosity. [Avni et al. \(1995\)](#) find a complicated luminosity dependence. Clearly this is an area of active research.

*N.B.* The net incident radiation field may have a smaller than specified ratio of current to total incident radiation field, since the command specifies the ratio of the current to the previous incident radiation fields, not the ratio of current to total incident radiation field. The ionization parameter will be slightly larger than specified for the same reason.

In general, it is probably better to use the **AGN** command rather than this command.

This is neither a luminosity nor intensity command—the units of the previous radiation field carry over to this command.

## 5.16 xi -0.1

[Tarter et al. \(1969\)](#) defined an ionization parameter  $\xi$  given by

$$\xi = \frac{L_{ion}}{n(H)r^2} = (4\pi)^2 \int_{1R}^{1000R} J_\nu d\nu / n(H) [\text{erg cm s}^{-1}] \quad (5.12)$$

where  $n(H)$  is the hydrogen density at the illuminated face of the cloud,  $r$  is the source - cloud separation, and  $L_{ion}$  is the luminosity between 1 and  $10^3$  Ryd. The number is the log of  $\xi$ . Only the first two characters on the line are checked to match **xi**, unlike the majority of commands where the first four characters on the line must match.



# Chapter 6

## INCIDENT RADIATION FIELD SHAPE

### 6.1 Overview

The spectral energy distribution (SED) of the incident radiation field should be specified between the energies of  $1.001 \times 10^{-8}$  Ryd ( $\lambda \approx 10$  m) and  $100 \text{ MeV} \approx 7.354 \times 10^6$  Ryd. The low-energy region is important for Compton cooling, photoionization from excited states of the elements, free-free heating,  $\text{H}^-$  heating, and grain heating. The high-energy portion is important for Auger and secondary ionization, Compton heating, and pair production. Energies greater than 100 MeV are not generally important since the Klein - Nishina electron-scattering cross section is small. CLOUDY will complain, but compute the model if possible, if the incident radiation field is not specified over the full energy range. An intensity of zero will be assumed for missing portions of the incident radiation field.

The *plasma frequency*, given by

$$\nu_{pl} = \left( \frac{n_e q_e^2}{\pi m_e} \right)^{1/2} = 8.978 \times 10^3 n_e^{1/2} \text{ s}^{-1} = 2.729 \times 10^{-12} n_e^{1/2} \text{ Ryd}, \quad (6.1)$$

will move into the energy range considered by the code if the electron density is higher than  $\sim 10^7 \text{ cm}^{-3}$ . The incident radiation field below the plasma frequency is totally reflected and does not enter the slab. The code will generate a comment if the plasma frequency occurs within the energy grid.

It is a good idea to plot the incident radiation field using the output of the **save continuum** command.

Most radiation fields are assumed to strike the cloud as a single-directional beam. The beam is assumed to enter the slab normal to the surface, unless this is changed with the **illumination angle** command. The **background**, **CMB**, **table Drain**, **table HM96**, **table HM05**, and **table ISM** commands all generate continua that are isotropic.

### 6.2 AGN T =1.5e5 k, a(ox) = -1.4, a(uv)=-0.5 a(x)=-1

This produces a multi-component continuum similar to that observed in typical Active Galactic Nucleus (AGN). An example is shown in Figure 6.1. The “Big Bump” component, peaking at  $\approx 1$  Ryd, is a rising power law with a high-energy exponential cutoff. It is parameterized by the temperature of the bump, the first argument on the command line. It is interpreted as the log of the temperature if it is less than or equal to 10 and the linear temperature otherwise. The second parameter is the X-ray to UV ratio  $\alpha_{ox}$ . Note that there is no implicit negative sign in this exponent; typical AGN have  $\alpha_{ox} \sim -1.4$ , (Zamorani et al., 1981). The third (optional) argument is the low-energy slope of the Big Bump continuum, with the default

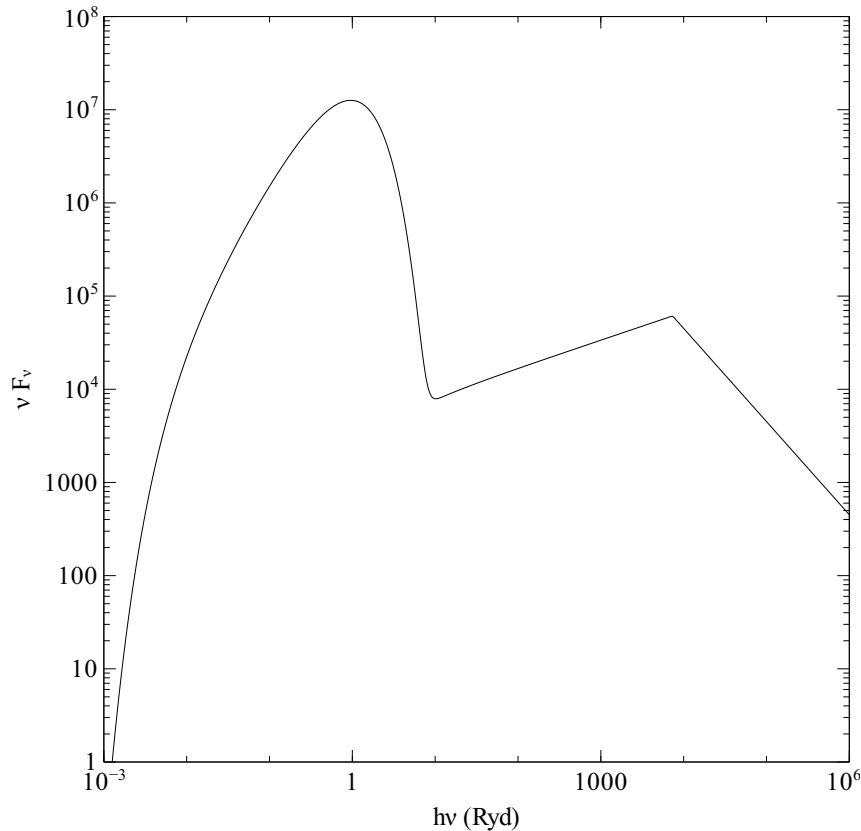


Figure 6.1: The continuum produced by the **AGN** continuum command. The Big Bump peaks at  $\approx 1$  Ryd, while the X-ray power law dominates at high energies. The two components are normalized by the second parameter, the value of  $\alpha_{ox}$ .

$\alpha_{uv} = -0.5$  (Elvis et al., 1994; Francis, 1993). The last argument is the slope of the X-ray component with the default  $\alpha_x = -1$ . Optional parameters can be omitted from right to left.

The full continuum is the sum of two components, as in equation 6.2:

$$f_v = v^{\alpha_{uv}} \exp(-hv/kT_{BB}) \exp(-kT_{IR}/hv) + av^{\alpha_x}. \quad (6.2)$$

The coefficient  $a$  is adjusted to produce the correct  $\alpha_{ox}$  for the case where the Big Bump does not contribute to the emission at 2 keV. If the bump is very hot then it may contribute to the X-rays as well and the resulting continuum will have a more negative  $\alpha_{ox}$  than specified. The X-ray power law is only added for energies greater than 0.1 Ryd to prevent it from extending into the infrared, where a power law of this slope would produce *very* strong free-free heating. The Big Bump component is assumed to have an infrared exponential cutoff at  $kT_{IR} = 0.01$  Ryd.

The last term in equation 6.2 is not extrapolated below 1.36 eV or above 100 keV. Below 1.36 eV the last term is simply set to zero (the bump dominates for these energies). Above 100 keV the continuum is assumed to fall off as  $v^{-2}$ .

The exponential cutoff in the low-energy end of the Big Bump will cause the incident continuum to have zero intensity at very long wavelengths. The code will complain since a zero incident continuum is unphysical, but the model will be computed. You can prevent the continuum from going to zero by including the cosmic background with the **background** command or with the **CMB** command.

We used this command to generate the continuum used in a large atlas of BLR line intensities (Korista et al., 1997a). The specific parameters needed to reproduce that continuum are **AGN 6.00 -1.40 -0.50 -1.0**. Only Kirk Korista can remember all these numbers and the parameters were not explicitly given in the original paper in the format used by the code. The **kirk** option on the **AGN** command will generate that continuum. It is fairly similar to the Mathews and Ferland (1987) continuum but there is much greater flexibility in changing its details.

### 6.3 Background, z=1.825, [f=100; no CMB]

This specifies a radiation field shape and intensity chosen to mimic the cosmic radio to X-ray background (Ostriker and Ikeuchi, 1983, Ikeuchi and Ostriker, 1986, and Vedel et al., 1994). Their ultraviolet continuum shape is an  $\alpha = -1$  power-law, with a mean intensity  $J_\nu$  at 912Å given by

$$4\pi J_\nu(912\text{\AA}) = 4\pi \times 10^{-21} \left( \frac{1+z}{3.5} \right)^4 f [\text{erg Hz}^{-1} \text{cm}^{-2} \text{s}^{-1}] \quad (6.3)$$

where  $z$  is the redshift and  $f$  an optional scale factor entered as the second parameter. Its default value is  $f = 1$ , and  $z = 0$  (i.e., now) is assumed if no redshift is entered. Judging from Bechtold et al. (1987), Bajtlik et al. (1988), and Vedel et al. (1994),  $f$  is confidently known to be within an order of magnitude of unity.

This command specifies *both* the shape and intensity of the incident radiation field. It is important that any previously occurring ordered pairs of shape and intensity commands be complete before this command is given.

Cosmic microwave background radiation is included in the generated background. This radiation field is assumed to be a blackbody radiation field, in strict thermodynamic equilibrium, with temperature given by

$$T_{CMB} = T_o (1+z) [\text{K}] \quad (6.4)$$

where the redshift dependence is from Peebles (1971) and the present temperature of the background is assumed to be  $T_o = 2.725 \pm 0.002 \text{K}$  (Mather et al., 1999; Wilkinson, 1987). This background can be an important source of Compton cooling for low-density clouds. If the optional keyword **no CMB** appears on the line then the CMB background will not be included. The CMB can be specified independently with the **CMB** command.

The **table HM96** command uses a more sophisticated form of the energetic continuum, but only at a redshift of  $z = 2$ . The **table HM05** command works at any redshift.

This command does not add the cosmic-ray background. This should be included if the simulation is to extend into molecular gas and is done separately with the **cosmic ray** command.

This radiation field is assumed to be isotropic rather than beamed.

### 6.4 Blackbody t=e5 K [linear, log, luminosity]

The continuum will be a blackbody with temperature (K) given by the number. The temperature may be entered directly or as a log. The number is assumed to be a log if it is less than or equal to 10 and linear if greater than 10. The keywords **log** and **linear** will override this default and force the interpretation of the numbers to be either a log or linear. Embedded commas can improve readability, such as

```
black body, Temp = 1e6 K
```

which is equivalent to

```
black 1000000
```

```
or
```

```
black body t=6 .
```

### 6.4.1 Blackbody, t = 1e5 K, disk = 1e3 K

This command produces a multi-color blackbody as if due to an accretion disk with inner and outer temperatures  $T_{in}$  and  $T_{out}$  as in [Mitsuda et al. \(1984\)](#). The temperatures can be in either order; the code will automatically take the greater temperature as  $T_{in}$ .

Neither the luminosity nor the intensity is set by this command.

### 6.4.2 Peter Martin's blackbody luminosity options

The luminosity of the black body can be specified with command-line options added by P.G. Martin. If the luminosity is specified with any of these options then it must not also be specified with another luminosity command for this radiation field. The keywords that can appear on the line are given in the following subsections.

### 6.4.3 Blackbody 5, luminosity = 38.

If the keyword **luminosity** appears then the second number is the log of the *total* luminosity ( $\text{erg s}^{-1}$ ) of the black body,  $4\pi R_{star}^2 \sigma T_{eff}^4$  (this number is interpreted as a log even when the keyword **linear** appears on the line). This example would be a  $10^5$  K planetary nebula nucleus at the Eddington limit.

This is a luminosity command.

### 6.4.4 Blackbody 5, radius = 10.

The log of the radius (in cm) of the blackbody  $R_{star}$  is used to set the total luminosity when the keyword **radius** appears (this number is interpreted as a log even when the keyword **linear** appears on the line). The total luminosity is  $4\pi R_{star}^2 \sigma T_{eff}^4$ . This example is also typical of a planetary nebula nucleus.

This is a luminosity command.

### 6.4.5 Blackbody 5e4 K, energy density = 500K.

The energy density of the blackbody radiation field, expressed as the equivalent blackbody temperature  $T_u$  in degrees Kelvin, is used to set the luminosity when the **energy density** keyword appears anywhere on the line. The energy-density temperature is defined from Stefan's law and the energy density of the radiation field  $u$  [ $\text{erg cm}^{-3}$ ]:

$$T_u \equiv \left(\frac{u}{a}\right)^{1/4} [\text{K}] \quad (6.5)$$

where  $a$  is the Stefan's radiation density constant.

Both temperatures are interpreted as logs if they are less than or equal to 10 or the keyword **log** appears, and linear otherwise. They will be interpreted as the linear temperature rather than as a log if the keyword **linear** appears. Note that if the **linear** key is used then both temperatures are interpreted as linear. Similarly, if the keyword **log** appears, both temperatures are interpreted as log. Note also that the cosmic background radiation should also be included if  $T_u \leq 2.725(1+z)K$ . CLOUDY will complain, but compute

the model, if the energy density of the incident continuum corresponds to a temperature less than the present energy-density temperature of the universe.

This is an intensity command.

### 6.4.6 Blackbody, t = 5e4 K, STE

The keyword **STE**<sup>1</sup> (note that a space must appear before “STE”) with no second number is equivalent to the **energy density** option with  $T_u$  set to the color temperature of the radiation field. This is a quick way to check that ionization and level populations go to strict thermodynamic equilibrium in the high radiation-density limit.

This is an intensity command.

### 6.4.7 Blackbody, t = 1e5 K, dilution factor = -14

Here the second parameter is the *dilution factor*  $W$  defined as

$$W \equiv \frac{J_\nu}{B_\nu} \approx \frac{\pi R_{star}^2}{4 \pi r_o^2}, \quad (6.6)$$

where  $R_{star}$  is the radius of the star and  $r_o$  is the separation between the illuminated face of the cloud and the center of the star. The approximation on the RHS assumes that  $R_{star} \ll r_o$ . The dilution factor can be entered either directly or as a log. Any number  $> 0$  will be interpreted as linear, while any number  $\leq 0$  will be interpreted as log. The example above is a rough approximation of the radiation field within a typical planetary nebula.

This is an intensity command.

## 6.5 Bremsstrahlung, temp = 8

The incident radiation field will be optically thin pure hydrogen bremsstrahlung emission. The shape is given by

$$f_\nu \propto \nu^{-0.2} \exp(-h\nu/kT) \quad [\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}]. \quad (6.7)$$

The argument is assumed to be the log of the temperature if it is less than or equal to 10 or the keyword **log** is present, and linear otherwise. The form of the continuum is approximate since a simple power-law gaunt factor is assumed and the emission from an optically thin gas with cosmic abundances is actually characterized by hundreds of overlapping emission lines (see, for example, Kato, 1976).

A more realistic radiation field could be produced by combining the **coronal equilibrium** command with the **save transmitted continuum** command to generate a continuum which can be read in with the **table read** command.

## 6.6 CMB [redshift 1000]

This command generates a blackbody radiation field in strict thermodynamic equilibrium (that is,  $T_{color} = T_u$ , where  $T_u$  is the energy-density temperature). The optional argument is the redshift  $z$ . If it is not

<sup>1</sup>The keyword was **LTE** before version 96 of the code. It was changed to **STE** to better reflect the fact that this condition corresponds to strict thermodynamic equilibrium. The code will continue to accept the **LTE** keyword for the foreseeable future.

entered then  $z = 0$  is assumed. The temperature of the blackbody is given by

$$T_{CMB} = T_o (1 + z) \quad [\text{K}] \quad (6.8)$$

where the redshift dependence is from [Peebles \(1971\)](#) and the present temperature of the background is assumed to be  $T_o = 2.725 \pm 0.002\text{K}$  ([Mather et al., 1999](#); [Wilkinson, 1987](#)). This command specifies *both* the shape and intensity of the radiation field. A starting radius of  $10^{30}$  cm will be assumed if no starting radius is specified.

### 6.6.1 The time option

The keyword **time** will follow the time-dependent recombination of an evolving universe. This is now being developed by Ryan Porter and will be described in Porter et al. (in preparation).

### 6.6.2 The density option

The keyword **density** will also specify the density at the redshift.

This CMB radiation field is assumed to be isotropic rather than beamed.

## 6.7 Extinguish column = 23, leak = 0.05, low =4 Ryd

This command will modify the shape of the incident SED by extinction due to photoelectric absorption by a cold neutral slab with column density given by the first argument (entered as a log,  $\text{cm}^{-2}$ ). This extinction is applied *after* the radiation field has been fully generated and normalized to the correct intensity. The form of the extinction is a simple power-law fit to the absorption curves calculated by [Cruddace et al. \(1974\)](#).

The extinguished continuum  $f'_\nu$  is related to the initial continuum  $f_\nu$  by

$$f'_\nu (\nu \geq 1 \text{ Ryd}) = f_\nu \left\{ \eta + (1 - \eta) \exp \left( -6.22 \times 10^{-18} \nu_{\text{Ryd}}^{-2.43} N(\text{H}) \right) \right\} \quad (6.9)$$

where  $N(\text{H})$  is the total hydrogen column density ( $\text{cm}^{-2}$ ),  $\nu_{\text{Ryd}}$  is the frequency in Rydbergs, and  $\eta$  is the leakage.

The optional second number is the fractional leakage  $\eta$  through the absorber (see [Ferland and Mushotzky, 1982](#)). This has a default value of 0, i.e., no leakage. The leakage is interpreted as a log if it is negative and linear otherwise. If unexpected or unphysical results occur when the **extinguish** command is given then it is likely that nearly all ionizing radiation has been attenuated. A plot of the generated continuum (with the **plot continuum** command) may prove interesting. The code will stop if the leakage is greater than 1.0 (100%).

The optional third number is the lowest energy for the absorption to occur. The default is 1 Ryd and is appropriate if the absorption is mainly due to atomic hydrogen. The number is interpreted as linear Rydbergs if positive and the log of the energy if less than or equal to zero. The continuum with energies below this cutoff energy will be unaffected by the absorption. The non-ionizing ( $h\nu < 1\text{Ryd}$ ) continuum can be extinguished by this command but extrapolating the power law to these energies is nonsense.

The second two arguments are optional and may be omitted from right to left. The cutoff energy can only be changed if the leakage is specified.

The command acts by first generating the continuum shape with extinction neglected. The continuum is then normalized using any of the luminosity or intensity commands (i.e., **Q(H)**, **ionization parameter**, **luminosity**, etc.). Only *then* is the continuum extinguished. The continuum that actually strikes the illuminated face of the cloud *does not* have the intensity or luminosity actually entered. (These values would be correct were the extinction not present.) Physically, the luminosity of the central object is not changed by the presence of an absorbing cloud along the line of sight.

This command should only be used as a quick test. A more physical way to extinguish the continuum would be to actually transmit it through a model of the absorbing slab, save that continuum with the **save transmitted continuum** command, then use this filtered continuum with the **table read** command.

### 6.7.1 Extinguish optical depth 1.2, [options]

If **optical depth** appears rather than **column** then the first number is the log of the Lyman continuum optical depth. All other options are the same as the **extinguish column** command. *N.B.* It really is the log of the optical depth, not the linear optical depth.

## 6.8 Interpolate [ $\nu$ (Ryd) or log $\nu$ (Hz)], log( $f_\nu$ )

The shape of the incident radiation field will be interpolated from the table of points given by this command. The interpolation uses straight lines in log-log space. Up to 130000 ordered pairs of points can be entered. This limit is set by the variable **NCELL**, which also sets the size of several continuum arrays. **continue** lines can be used to continue entering values after the initial **interpolate** line is filled.

Unlike the majority of the commands the first five characters of the command must be entered.

The numbers are ordered pairs giving the energy and intensity. The first number within each ordered pair of points is *either* the energy in Rydbergs (linear *or* as a log) or the log of the frequency (in Hertz). CLOUDY assumes that the log of the energy in Rydbergs was entered if the first number is negative; that the log of the frequency (Hz) was entered if the first number is greater than 5; and linear Rydbergs otherwise. Any of the three styles can be chosen but it must be used consistently within the command. If the first energy is entered as zero then it is interpreted as the low-energy limit of the code. In this case the remaining energies will be interpreted as linear Rydbergs if the second number is positive and the log of the energies in Rydbergs if it is negative. An energy of zero Rydbergs is not allowed (except for the first), and the energies must be in increasing order.

The second number in each ordered pair is the log of the relative flux density per unit energy interval [ $\log_{10}(J_\nu) + \text{constant}$ ] at that energy. These numbers are only used to set the shape of the continuum. The constant in the equation is set by one of the intensity or luminosity commands.

The **interpolate** command can be freely mixed with other shape commands and a total of up to 100 **interpolate** and **table** commands can be entered.<sup>2</sup> Note that **table** and **interpolate** are actually two forms of the same command so that they store information in the same arrays. The total number of **table** and **interpolate** commands entered together cannot exceed 100.

As an example, the following approximates a metal-poor 4.5e4 K stellar atmosphere. The energies are entered in Rydbergs:

```
// following is 45000 K atmosphere from Shields and Searle
interpolate (0.00001 -11.106) (.58 -1.5792) (.99 -1.44) (1.01 -1.7018)
continue 1.8 -1.905) (1.81 -1.939) (2.57 -2.208) (2.59 -2.247) (3 -2.3994)
continue (3.02 -2.8193) (3.49 -2.9342) (3.51 -4.143) (3.99 -5.582)
```

<sup>2</sup>Limits to the use of the **interpolate** command existed in versions 73 and before, but have been lifted.

```
continue (4.01 -6.3213) (6 -9.9) (10 -17.3) (20 -30) (1e7 -30)
q(h) = 52.778151
```

Note that the continuum should be specified between  $1.001 \times 10^{-8}$  Ryd and  $7.354 \times 10^6$  Ryd even if the intensity is small. If it is not fully specified then a warning will be issued and a model computed with the unspecified continuum set to zero. As a further note, it is important that the continuum be physically correct. For instance, stellar model atmospheres predict almost no X-ray emission while real OB stars *are* X-ray sources (although neglecting X-rays for these stars is generally a safe approximation). See page 50 below for a more detailed discussion.

## 6.9 Laser, frequency = 3.5 Ryd [rel width 0.02]

The intensity of the radiation field will be very small except within  $\pm 5\%$  of the specified energy where it will be very large. The energy is specified in Rydbergs and it is interpreted as a log if it is negative. This is provided as a way to check on the computation of the photoionization rate integrals.

The optional second number changes the relative width of the laser. The relative width is the ratio  $dE/E$  where  $dE$  is the half width of the laser. The laser will only be active within  $\pm dE$  of  $E$ . The code would return an error condition if  $dE$  is so small that the laser does not happen to be within  $\pm dE$  of  $E$  as evaluated by the code's energy mesh. The fractional width probably should not be made smaller than roughly 0.01 but the code does not protect against too small a value of  $dE$ .

Another way to make a laser is to save out a transmitted radiation field using the **save transmitted continuum** command, edit this file, and, by hand, increase the intensity of the continuum at particular cells. This is described where the **table read** command is defined.

## 6.10 Power law, slope = -1.4 [hi cut = 6 Ryd low cut = .1, Kelvin]

*N.B. IT IS VERY DANGEROUS TO USE THIS COMMAND.* The radiation field will be a power law with slope given by the first parameter. It has optional low-energy and high-energy exponential cutoffs  $\nu_{high\ cut}$  and  $\nu_{low\ cut}$  in Rydbergs. The form of the continuum is

$$f_\nu = \nu^{+\alpha} \exp(-\nu/\nu_{high\ cut}) \exp(-\nu_{low\ cut}/\nu) [\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}]. \quad (6.10)$$

The first number on the command line is the slope  $\alpha$ . Note that there is no implicit negative sign in this exponent; typical AGN have  $\alpha_{ox} \sim -1.4$ , (Zamorani et al., 1981). The second (optional) number is the high-energy cutoff  $\nu_{high\ cut}$ . The third optional number is the low-energy cutoff  $\nu_{low\ cut}$ . Both are expressed in Rydbergs and they can be omitted from right to left. The default values are  $10^4$  and  $10^{-4}$  Ryd.

If the keyword **Kelvin** appears then both cutoff energies are interpreted as temperatures in Kelvin rather than energies in Rydbergs. The temperature is a log if it is less than or equal to 10 or the keyword **log** appears, and the linear temperature itself otherwise. If you do not use the keyword **Kelvin**, the cutoffs will always be interpreted as linear quantities.

It is generally a *very bad* idea to use this command. CLOUDY treats the entire radiation field between *very* low and *very* high energies. Extrapolating reasonable radiation fields past the optical-ultraviolet region into radio or  $\gamma$ -ray energies will have unexpected effects. Power-law continua with slopes smaller than  $-1$  will have unphysically large photon occupation numbers and brightness temperatures at very long wavelengths. This will probably produce catastrophic Compton cooling and/or free-free heating. Continua with slopes greater than  $-1$  will be dominated by the radiation field at energies of many MeV resulting in large Compton heating and pair-production rates. The exponential cutoffs can prevent this but they also

Table 6.1: AGN Continuum		
$\nu(\text{Ryd})$	$\log(F_\nu)$	slope
1.00(−5)	−3.388	+2.50
9.12(−3)	4.0115	−1.00
0.206	2.6576	−0.50
1.743	2.194	−1.00
4.130	1.819	−3.00
26.84	−0.6192	−0.70
7.35(+3)	−2.326	−1.67
7.40(+6)	−7.34	−1.12

drive the radiation field to zero intensity when either argument in the exponential becomes large. This is unphysical and can cause numerical problems.

It is *much* better to use the **interpolate** command and enter physically reasonable low-energy and high-energy radiation fields. There is a special version of the command, **table power law** for entering a well-behaved power-law continuum.

## 6.11 Table command

### 6.11.1 Overview

Any of several radiation field shapes that are stored as a permanent part of the code can be entered with this command. This is a special version of the **interpolate** command. The same interpolation on a table of input frequencies and fluxes described there is done. The **table** command can be freely mixed with other shape commands and a total of up to 100 **table** and **interpolate** commands can be entered.

### 6.11.2 Table AGN

If the keyword **AGN** appears (note the presence of a leading space) then a continuum similar to that deduced by Mathews and Ferland (1987) will be used. The continuum is meant to be similar to typical radio quiet active galaxies. The points used to describe this continuum are given in Table 6.1.

This radiation field differs from the Mathews and Ferland (1987) SED only in that the continuum is assumed to have a sub-millimeter break at 10 microns. For wavelengths longer than 10 microns the continuum is assumed to have a slope  $f_\nu \propto \nu^{+2.5}$ , appropriate for a self-absorbed synchrotron continuum (Rybicki and Lightman, 1979). Note that this represents a typical observed continuum, and may not be directly related to the continuum actually striking BLR gas (Korista et al., 1997b).

The energy of the sub-millimeter break is not well determined observationally but has a major impact on high density, high ionization parameter models, as discussed by Ferland and Persson (1989), Ferland et al. (1992), and Ferland (1999a). The energy of the infrared break can be adjusted with the **break** keyword. The break can be adjusted between the limits of 0.2 Rydberg and  $1.001 \times 10^{-8}$  Ryd by entering the keyword **break** followed by a number specifying the energy of the break. The number is interpreted as the log of the energy in Rydbergs if it is negative and as linear Rydbergs if positive. It is interpreted as the linear wavelength of the break in microns if the keyword **microns** also appears. If no number appears, but the keywords **no break** does, then a break at the low-energy limit of the code ( $1.001 \times 10^{-8}$  Ryd) is assumed. The following shows equivalent ways of generating a continuum with a break at 10 microns;

Table 6.2: Akn 120 Continuum

$\nu(\text{Ryd})$	$f_\nu$
1.0(−5)	1.5(−26)
1.9(−5)	1.6(−26)
3.0(−4)	1.4(−23)
2.4(−2)	8.0(−25)
0.15	1.6(−25)
0.30	1.8(−25)
0.76	7.1(−26)
2.0	7.9(−27)
76.	1.1(−28)
7.6(+2)	7.1(−30)
7.4(+6)	1.3(−34)

```

table AGN break .00912 // energy in Ryd
table AGN break -2.04 // log of energy in Ryd
table AGN break 10 microns // wavelength in microns
table AGN no break // no sub-millimeter break

```

Note that the nature of the SED in AGN is still an open question. The shape given here is very simplistic and quite uncertain in the ionizing ultraviolet. Moreover, it would not be surprising if the BLR sees a far different continuum than we do. This shape may not be correct for low redshift Seyfert galaxies (Binette et al., 1989; Clavel and Santos-Lleo, 1990) and direct observations of high-redshift quasars suggest a far softer continuum than this (Zheng et al., 1997; Korista et al., 1997b). It is probably best to only use this shape in exploratory situations and generate a specific AGN radiation field using either the **ratio** or **AGN** commands.

### 6.11.3 Table akn120

If the keyword **akn120** appears then the continuum summarized by Peterson (private communication) is used. The continuum is described by the observed flux at Earth [ $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$ ] and is given in Table 6.2.

The monochromatic luminosity at 1320 Å is  $\nu L_\nu = 1.84 \times 10^{44} \text{ h}^{-2} \text{ erg s}^{-1}$ , where  $h \equiv H_0/100 \text{ km s}^{-1} \text{ mpc}^{-1}$ , so, setting  $h = 0.75$ , the **akn120** SED could be generated by the commands

```

nul(nu) = 44.514 at 0.6906 Ryd
table akn120

```

### 6.11.4 Table cooling flow

This generates the continuum shape described by Johnstone et al. (1992) and used in Ferland et al. (1994, 2002). It is a co-added series of Raymond-Smith collisional-equilibrium continua and was chosen to represent the spectrum at a point within a typical cooling flow.

### 6.11.5 Table Crab

This generates the SED of the synchrotron-emitting regions of the Crab Nebula. This is the net observed continuum, originating in both the pulsar and nebula, and not the pulsar continuum alone.

By default the SED derived by [Atoyan and Aharonian \(1996\)](#) and shown in [Hester \(2008\)](#) is used. If the option **Davidson** appears then the continuum summarized by [Davidson and Fesen \(1985\)](#) is used. These two SEDs, shown in Figure 6.2, have substantial differences in the UV/FUV.

This is an intensity command.

According to [Davidson and Fesen \(1985\)](#), the total luminosity of the Crab is  $L_{tot} = 10^{38.14} \text{ erg s}^{-1}$ . The Crab SED could be generated by combining the commands

```
luminosity (total) 38.14
table Crab
```

### 6.11.6 Table Draine [factor=1.7]

This enters the galactic background radiation field given by equation 23 of [Draine and Bertoldi \(1996\)](#). The radiation field is only defined over a very narrow wavelength range so it is only appropriate for certain very simple PDR calculations. It is shown in Figure 6.3 along with the radiation field produced by the **table ism** command. This command specifies both the shape and intensity of the continuum.

The optional scale factor changes the intensity of the continuum. By default it is a linear scale factor but the keyword **log** changes this.

This radiation field is defined up to an energy very close to 1 Rydberg. It may spill over into the hydrogen-ionizing continuum for certain choices of the continuum-bin resolution. Add the **extinguish** command to insure that H-ionizing radiation is extinguished if this is needed. The code will print a comment if this is not done.

This continuum should only be used for restricted tests since the vast majority of the electromagnetic spectrum is undefined. It was created to compute the Leiden PDR test cases (the `pdr_leiden*` simulations in the test suite) and the paper by [Röllig et al. \(2007\)](#).

This radiation field is isotropic. This is an intensity command.

### 6.11.7 Table HM96 [factor=-1]

This enters the [Haardt and Madau \(1996\)](#) background continuum for a redshift of  $z = 2.16$ . This is the original form of the command and is maintained for reference. The cosmic microwave background is not included - use the **CMB** command to add this component. Note that this table specifies both the shape and intensity of the radiation field. There is an optional multiplicative scale factor to change the intensity. If the scale factor is less than or equal to zero then it is interpreted as the log of the scale factor.

This radiation field is isotropic. This is an intensity command.

### 6.11.8 Table HM05 redshift 2.21 [quasar; factor=-1]

This enters the Haardt & Madau (2005 private communication) radiation field at any redshift  $0 \leq z \leq 8.9$ . It interpolates on tables kindly provided by Francesco Haardt. There are two forms of the radiation field - the default includes both quasars and galaxies. If the keyword **quasar** occurs then a radiation field considering only quasars is used. The cosmic microwave background is not included - use the **CMB** command to add this component. Note that this table specifies both the shape and intensity of the radiation field. There is an optional multiplicative scale factor to change the intensity. If the scale factor is less than or equal to zero then it is interpreted as the log of the scale factor.

The radiation field is isotropic. This is an intensity command.

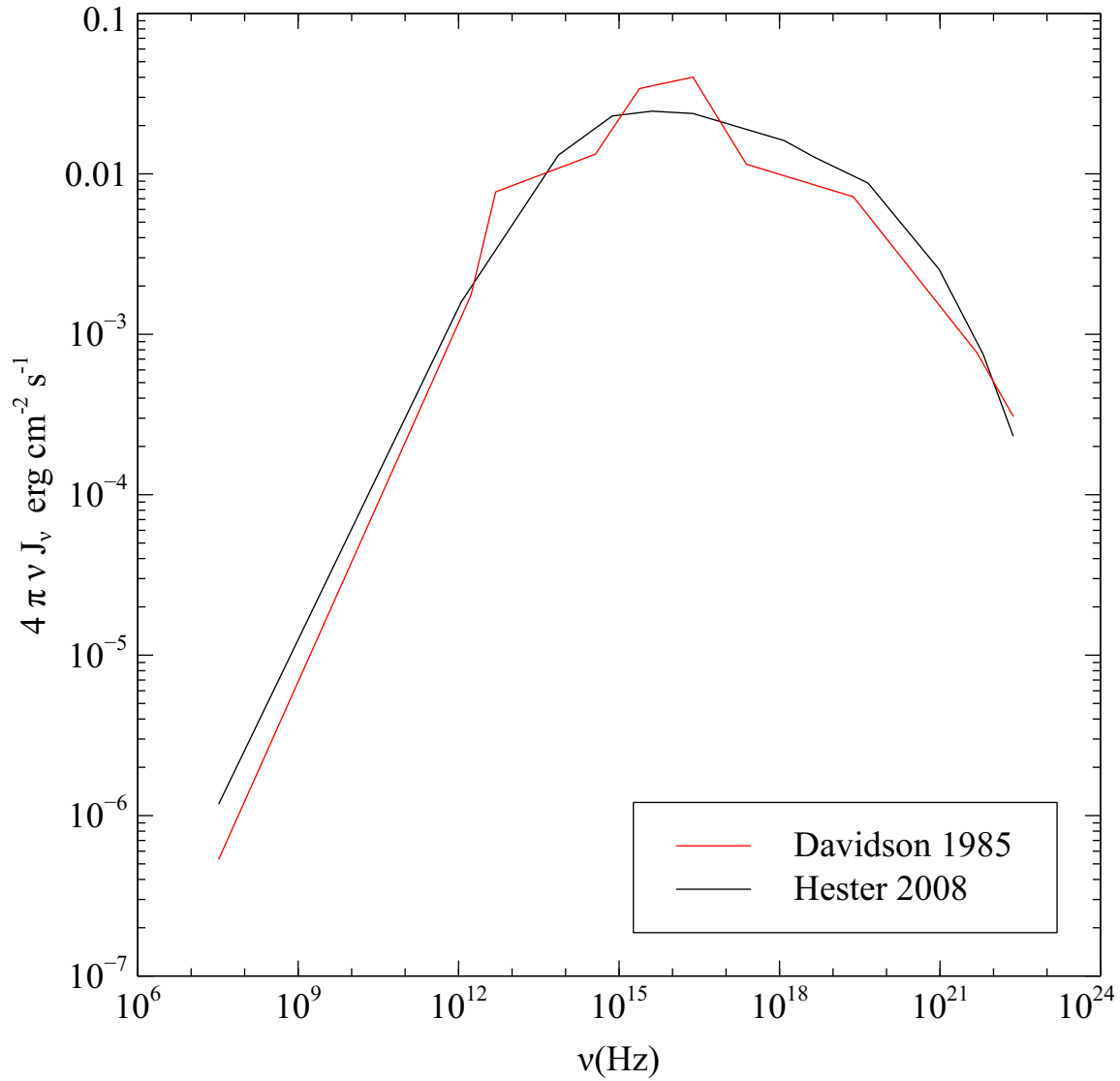


Figure 6.2: The SEDs produced by the **table Crab** commands are compared. The red line is the SED from [Davidson and Fesen \(1985\)](#) and was the default used by CLOUDY through versions C10. The black line is the current default, derived by [Atoyan and Aharonian \(1996\)](#) and shown in [Hester \(2008\)](#)

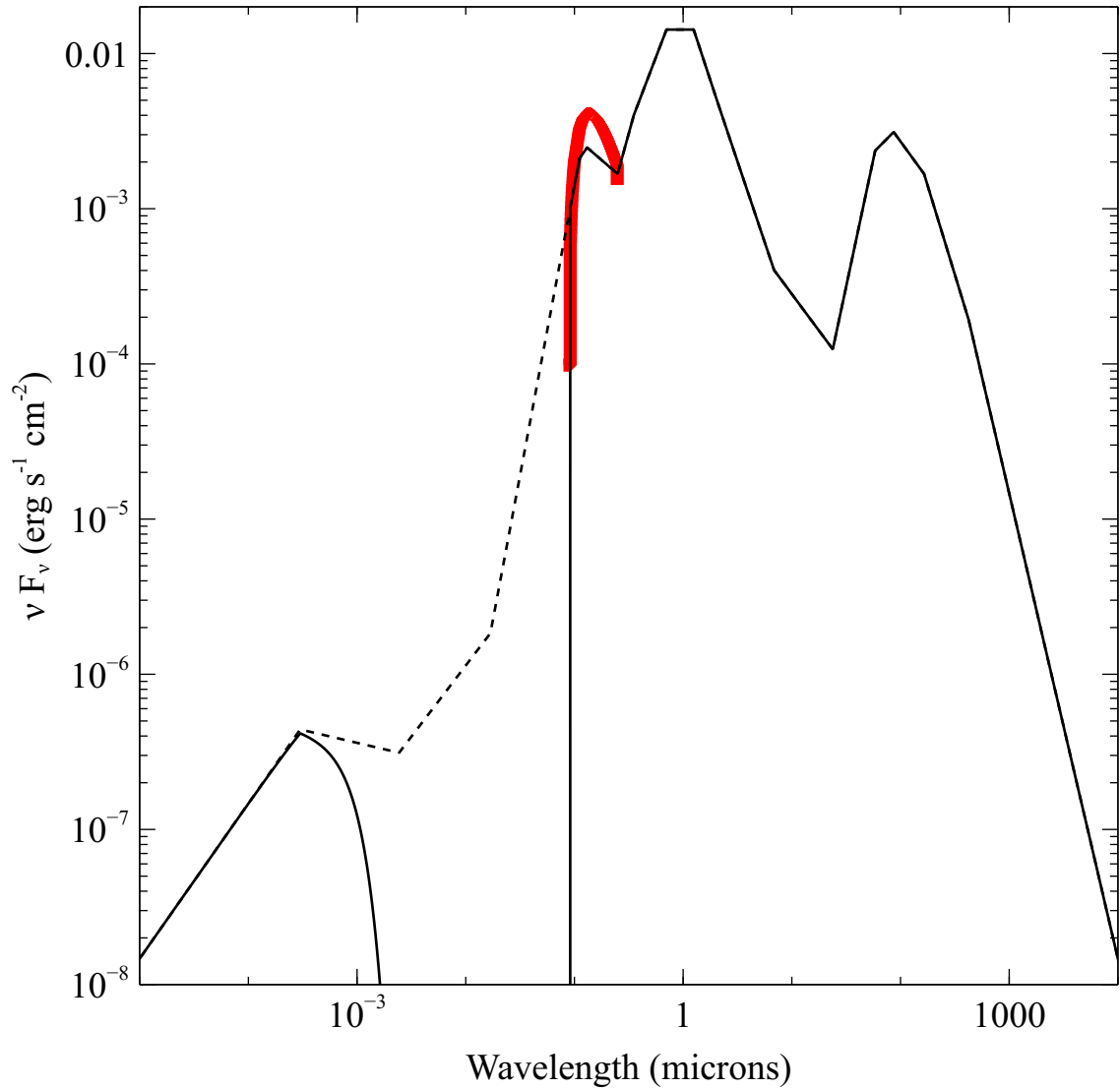


Figure 6.3: The SED produced by the **table ISM** command is the lighter line. The infrared cirrus is the peak at  $\lambda \sim 100 \mu\text{m}$  and starlight dominates at shorter wavelengths. The points just shortward of the Lyman limit ( $0.0912 \mu\text{m}$ ) are interpolated—actually it is thought that interstellar extinction removes most of this continuum. The dashed line shows the interpolated SED and the solid line shows the effects of absorption introduced by adding the **extinguish** command. The heavy red line is the **table Draine** continuum.

Table 6.3: ISM Radiation Field

$\log(\nu)$	$\log \nu f_\nu$	$\log \nu$	$\log \nu f_\nu$
9.00	-7.93	14.14	-2.30
10.72	-2.96	14.38	-1.79
11.00	-2.47	14.63	-1.79
11.23	-2.09	14.93	-2.34
11.47	-2.11	15.08	-2.72
11.55	-2.34	15.36	-2.55
11.85	-3.66	15.54	-2.62
12.26	-2.72	16.25	-5.68
12.54	-2.45	17.09	-6.45
12.71	-2.57	18.00	-6.30
13.10	-3.85	23.00	-11.30
13.64	-3.34		

### 6.11.9 Table ism [factor = 0.7]

The local interstellar radiation field is generated with the keyword **ism**. This uses Figure 2 of [Black \(1987\)](#) to represent the *unextinguished* local interstellar radiation field (see Figure 6.3). This command specifies *both* the shape and luminosity of the radiation field. The continuum generated by CLOUDY is exactly that given by Black except that the radiation field between 1 and 4 Ryd is interpolated from the observed or inferred values. Actually it is thought that this part of the radiation field is heavily absorbed by gas in the ISM so that little 1 to 4 Ryd radiation exists, at least in the galactic plane. Such absorption can be introduced with the **extinguish** command.

The **table ism** command also specifies the intensity of the incident radiation field since this is directly observed. There is an optional scale factor to change the intensity of the entire radiation field. It is the log of the scale factor if less than or equal to zero and the scale factor itself if positive. The actual numbers used by CLOUDY to interpolate on Black's table are given in Table 6.3. The frequencies are in Hz, and the product  $\nu f_\nu$  in  $\text{erg cm}^{-2} \text{s}^{-1}$ .

This does not include the cosmic microwave background. Use the **CMB** command to add this component.

The actual ISM radiation field incident on a typical region in the galactic plane could be generated by:

```
table ISM
CMB
extinguish column = 22 leak=0
```

This radiation field is isotropic. This is an intensity command.

### 6.11.10 Table power law [spectral index -1.4, low =.01, hi =20]

This produces a power-law continuum that is well behaved at both the high and low energy ends. The default shape, assumed when no numbers occur on the command line, is the form  $f_\nu \propto \nu^\alpha$ . Here  $\alpha = -1$  for the spectral midrange between 10 microns and 50 keV, and the continuum has slopes  $f_\nu \propto \nu^{5/2}$  at lower energies (appropriate for self-absorbed synchrotron, eq 6.54, p.190, [Rybicki and Lightman, 1979](#)) and  $f_\nu \propto \nu^{-2}$  at higher energies. Note that much of the X-ray literature will use an implicit negative sign in defining the energy index, as in equation 13.2 of AGN3. CLOUDY never uses implicit negative signs so a

Table 6.4: Power Law Continuum

$\nu$ (Ryd)	slope
1.00(−8)	+2.50
9.115(−3)	−1.00
3676.	−2.
7.40(+6)	−

typical AGN will have an energy index of roughly  $-1.5$ . Table 6.4 summarizes the continuum that is produced by this command if no other parameters are specified.

Three optional numbers may appear on the command line. The first number sets the slope of the mid-range spectral component (infrared to X-ray) and has a default of  $-1$  ( $f_\nu \propto \nu^{-1}$ ). The next two numbers adjust the energy limits of the mid-range spectral component. Their default units are Rydbergs but the keyword **microns** will change the units to microns *for the first energy only*. The second number is the energy (in Rydbergs) of the infrared break. The default is 0.009115 Ryd (10 microns). If this second number is zero then the low energy limit to the continuum ( $1.001 \times 10^{-8}$  Ryd) will be used. The number is interpreted as the log of the energy in Rydbergs if it is negative and linear otherwise. Note that, with no infrared break, free-free heating will probably be significant for denser clouds. A power-law continuum with a low energy break at 1 micron would minimize this heating and could be generated with the command

```
// a power-law with index -1 and 1 micron break
table power law slope -1, 1 micron break
```

The following uses the default power law

```
// another example, a power-law with index -1
// and 10 micron break, (the default)
table power law slope -1
```

The third optional number is the energy (in Rydbergs) of the break in the X-ray continuum. The default is 50 keV and if it is zero then the high-energy limit of the continuum ( $7.354 \times 10^6$  Ryd) is used. The number is interpreted as a log if the energy of the infrared break is entered as a log and linear otherwise. The numbers may be omitted from right to left.

### 6.11.11 Table read "contin.txt"

This reads in the radiation field predicted from a previous CLOUDY calculation. The name of the file containing the spectrum predicted from the first calculation continuum must be enclosed in a pair of double quotes. The first calculation saves the radiation transmitted through a cloud with the **save transmitted continuum** command. Subsequent calculations use the **table read** command to include this field.

The transmitted spectrum of the first model will include all transmitted radiation, including line emission, and will write that out as a single spectral energy distribution. When the second model reads that in, it will have no knowledge of what was what in the first model. It will treat it as an incident SED without further specifics. So the [O III] 5007 flux reported by the second model will be that produced by the second model only, but the 5007 photons from the first model will included "anonymously" in the incident SED.

The **save transmitted continuum** command produces a file containing the frequency in Rydbergs and the transmitted continuum  $\nu f_\nu$  [ $\text{erg cm}^{-2} \text{s}^{-1}$ ]. This continuum is the sum of the attenuated incident continuum and the fraction of the cloud's diffuse emission that is transmitted in the outward direction. The first line of the input file contains header information and must not be deleted.

The keyword **last** must appear on the **save transmitted continuum** command if more than one iteration is done. If it does not then the radiation field predicted in each iteration will be saved and the code will become confused when it tries to read the file.

The **table read** command can be freely mixed with all of the other radiation field shape commands. Any number of **table read** commands can be entered.<sup>3</sup> The **save continuum** file must have been produced by the same version of CLOUDY.

This command does not set the intensity of the radiation field. This must be done with any of the intensity or luminosity commands.

The following gives an example of first creating a file containing the transmitted radiation field then using this file as the incident radiation field in a second calculation.

```
title this finds transmitted continuum due to warm absorber
hden 9
ionization parameter 1
stop effective column density 21
table AGN
iterate
save transmitted continuum file = "absorber.txt" last
```

Now use this continuum in a second calculation:

```
table read file = "absorber.txt"
luminosity 45
radius 18
hden 9
```

### 6.11.12 Table Rubin

Nearly all attempts at modeling the Orion Nebula have found that theoretical stellar atmospheres do not produce enough flux near 4 Ryd (see, for example, [Mathis, 1982, 1985](#); [Rubin et al., 1991](#); [Sellmaier et al., 1996](#)).

Bob Rubin has modified the emergent radiation field from one of the [Kurucz \(1979\)](#) models to better account for the presence of high-ionization lines in the Orion Nebula. This modified SED can be accessed with the **table Rubin** command. The continuum started life as a  $\log g = 4$ ,  $T_{eff} = 37,000$  K Kurucz model, but the flux between 41 eV and 54 eV was raised by a factor of 11 to reproduce the [Ne III] optical and IR lines.

### 6.11.13 Table XDR

This generates the X-ray SED described in [Maloney et al. \(1996\)](#),

$$f_\nu = f_0 \times \left( \frac{E}{100 \text{ keV}} \right)^{-0.7} [\text{erg cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1}], \quad (6.11)$$

over the energy range 1 – 100 keV. The radiation field has negligible intensity outside this range.

---

<sup>3</sup>Only one table read command could be entered in versions 90 and before.

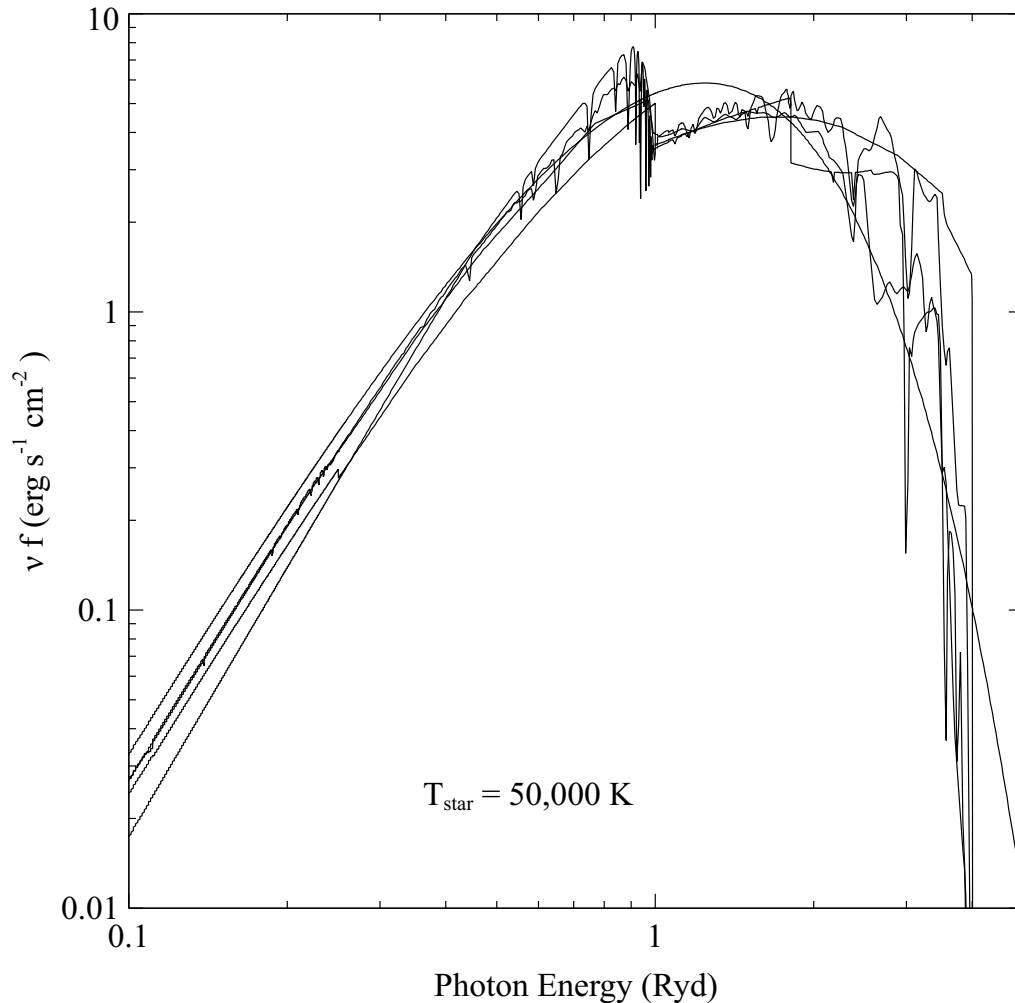


Figure 6.4: This figure shows the emergent radiation field predicted by five 5e4 K stars included with the code. The smoothest is the blackbody, and the Kurucz (1991) and Rauch (1997) atmospheres show the most structure. stars

## 6.12 Table stars command

Several sets of emergent SEDs from stellar atmosphere calculations are accessible. The command has several sub-keywords that indicate which set of atmospheres to use.

Figure 6.4 compares predictions for five of the 5e4 K SEDs that are available. These include a blackbody and atmospheres computed by Mihalas (1972), Kurucz (1979), Kurucz (1991) and Rauch (2003). All were normalized to have the same total luminosity ( $10^{38} \text{ erg s}^{-1}$ ) observed from a distance of  $10^{18} \text{ cm}$ . Note the order of magnitude dispersion among the continua for energies around 4 Ryd.

These commands specify only the continuum shape. It is still necessary to specify a luminosity. Tout et al. (1996) provide convenient fitting formulae giving zero age main sequence luminosities as functions of stellar mass and metallicity.

**Danger!** Many forms of the **table stars** commands accept the **log** keyword to indicate that the log of the stellar temperature is entered. Many also accept the surface gravity, normally referred to as “log g”, as a second parameter. The “log” in “log g” would cause the temperature to be interpreted as the log of the

temperature. Either do not enter the string “log g”, or write it as “logg” or “log(g)”.

### 6.12.1 Overview of available stellar SEDs

In versions C06.02 and before the stellar continua were entered into the code on a case by case basis. New continua could only be introduced by writing new code. Beginning in C07.02 Peter van Hoof developed a unified treatment so that any continuum could be used by putting it into a standard format. This is far more flexible and allows more continua to be entered.

All grids have a range of surface temperature (or age in the case of stellar population synthesis models) and many also include a range of surface gravity or metallicity. The **table star** command will interpolate on these tables to calculate an SED with the specified parameters. More information on the various grids that are supported can be found on our web site <http://wiki.nublado.org/wiki/StellarAtmospheres>.

To list all the grids that have already been compiled on your system, you can use the **table star available** command. This will list all the standard grids that were installed from the webpage above (including their parameters), but not the custom grids that you created yourself. Note that this command will only list valid binary files that can be used in the current setup of the code. This implies that if the binary files were compiled with a **set continuum resolution** command, then this command needs to be repeated in front of the **table star available** command in order to see the binary files.

To list all the SEDs that are contained in a single compiled stellar atmosphere grid, you can use the **table star <grid> list** command. For more details see our webpage listed above.

### 6.12.2 High-energy component

Theoretical stellar atmospheres emit little energy above 4 Ryd while real OB stars *are* X-ray sources. [Sciortino et al. \(1990\)](#) find a correlation between the X-ray and bolometric luminosities which can be fitted by

$$\log(L_x) = 1.08(+0.06/-0.22) \log(L_{bol}) - 9.38(+2.32/-0.83). \quad (6.12)$$

The X-ray luminosity is typically  $\sim 6.4$  dex fainter than the bolometric luminosity. A source temperature of 0.5 keV is quoted by Sciortino et al. This X-ray component must be explicitly added as an independent part of the incident radiation field. Tests show that the high-energy light has little effect on conditions in the H II region but *does* affect the ionization in the surrounding PDR.

### 6.12.3 Starburst99 files

It is possible to read in predictions from Starburst99 ([Leitherer et al., 1999](#)).<sup>4</sup> The Starburst99 SEDs are unified with the stellar atmosphere treatment. See our web site <http://wiki.nublado.org/wiki/StellarAtmospheres> and Appendix B.2 below for more details.

The procedure is to create your Starburst99 calculation on their web site (we tested the version at STScI). Store the Starburst99 output file “\*.spectrum1” as a file with a “.stb99” or “.stb” extension. Compile it as in the following example

```
compile star "some_file.stb99"
```

You can optionally include the keyword **stellar** or **nebular** if you want to use only the stellar or the nebular component of the interstellar radiation field (these are the fourth and fifth column of the Starburst99

<sup>4</sup>The **table starburst** command, which existed for this purpose in versions through C07, has been replaced with this **table stars** command.

calculation, respectively). The default is to use the total spectrum, which is the sum of the stellar and nebular component. This would be the equivalent of including the emission from nearby star forming regions in your calculation. If you don't want that, you can use the stellar component only, as in the following example

```
compile star "some_file.stb99" stellar
```

The above commands will produce files `some_file.ascii` and `some_file.mod`, which can then be used in the **table stars** command:

```
table star "some_file.mod" age=6e7 years
```

The number on the **table star** command is age of the starburst. It has the same units as the ages given in the Starburst99 data file and is normally given in years. It is interpreted as a log if  $\leq 10$  or if the keyword **log** appears, and as the linear age if  $> 10$  or if the keyword **linear** appears.

It is critical that the original Starburst99 file not be changed in any way at all. Doing so will trick the code into generating bogus results. In any case, it is a good idea to make a plot of the generated radiation field, using column 1 and 2 of the output from the **save continuum** command, to confirm that it is correct.

Starting with the C10 release it is possible to combine several Starburst99 runs with different metallicities into a single 2-dimensional grid. This allows interpolation in both age and log Z. This has to be done by compiling each of the Starburst99 runs as described above and then manually merging the “.ascii” files into a single “.ascii” file. Appendix B.2 gives details how the merged file should be formatted. An example of a merged file is available on the StellarAtmospheres page of the Cloudy wiki linked at the start of this subsection. The resulting file should then be compiled using

```
compile star "merged_file.ascii"
```

and used as follows

```
table star "merged_file.mod" age=6.7 log(Z)=-1.2
```

### 6.12.4 PopStar grids

You can convert PopStar grids into “.ascii” files so that they can be compiled and used in CLOUDY. You can either use a single PopStar grid, allowing interpolation in age, or combine several PopStar grids for the same initial mass function but different metallicities allowing interpolation in age as well as log Z. Detailed instructions can be found on [wiki.nublado.org/wiki/StellarAtmospheres](http://wiki.nublado.org/wiki/StellarAtmospheres).



# Chapter 7

## CHEMICAL COMPOSITION

### 7.1 Overview

The default solar composition is summarized in Table 7.1. C and O abundances come from photospheric abundances of [Allende Prieto et al. \(2002, 2001\)](#), while N, Ne, Mg, Si, and Fe are from [Holweger \(2001\)](#). The helium abundance is a typical value for nebulae with near-solar compositions. The remainder of the first thirty elements comes from [Grevesse and Sauval \(1998\)](#). Meteoritic and photospheric abundances agree for most elements. They differ by significant amounts for P, S, Cl, and Mn. These are fairly volatile elements so may be deficient in meteorites. For these four the means of the meteoritic and photospheric abundances were used.

These default abundances are maintained for backwards compatibility. The **abundances GASS10** command described in section 7.4.3 will use values from [Grevesse et al. \(2010\)](#).

Abundances are always specified by *number* relative to *hydrogen*, not by mass or relative to silicon. Abundances are relative to the total hydrogen density, the sum of H in atomic, ionic, and molecular form. These are gas-phase abundances and do not include material locked into grains. The composition will be printed in the header information that starts the printout. You should check this to confirm that the right composition is used.

The following sections describe how to modify the chemical composition.

### 7.2 Absolute abundances and scale factors

Abundances can be specified as either *absolute abundances* or as *scale factors*. An absolute abundance gives the abundance of an element relative to hydrogen. An example might be  $n(\text{O})/n(\text{H}) = 4 \times 10^{-4}$ . A relative abundance is given relative to another value. An example might be the abundance relative to the solar value,  $n(\text{O})/n(\text{H}) = 4 \times [n(\text{O})/n(\text{H})]_{\odot}$ .

### 7.3 Precedence

There are many ways to specify an abundance. It is even possible to specify different abundances for the same element in the same input script. If the absolute abundance is specified with more than one command then the last abundance is used. If the abundance is specified by both its absolute abundance and by a scale factor then both are used. Either of the following will multiply the default H II region nitrogen abundance by a factor of two:

Table 7.1: Solar Composition

A			12+log	log	$n/n(\text{H})$	ref
1	H	Hydrogen	12.00	0.00	1.00E+00	GS98
2	He	Helium	11.00	-1.00	1.00E-01	text
3	Li	Lithium	3.31	-8.69	2.04E-09	GS98
4	Be	Beryllium	1.42	-10.58	2.63E-11	GS98
5	B	Boron	2.79	-9.21	6.17E-10	GS98
6	C	Carbon	8.39	-3.61	2.45E-04	AP02
7	N	Nitrogen	7.93	-4.07	8.51E-05	H01
8	O	Oxygen	8.69	-3.31	4.90E-04	AP01
9	F	Fluorine	4.48	-7.52	3.02E-08	GS09
10	Ne	Neon	8.00	-4.00	1.00E-04	H01
11	Na	Sodium	6.33	-5.67	2.14E-06	GS98
12	Mg	Magnesium	7.54	-4.46	3.47E-05	H01
13	Al	Aluminium	6.47	-5.53	2.95E-06	GS98
14	Si	Silicon	7.54	-4.46	3.47E-05	H01
15	P	Phosphorus	5.51	-6.50	3.20E-07	GS98*
16	S	Sulphur	7.27	-4.74	1.84E-05	GS98*
17	Cl	Chlorine	5.28	-6.72	1.91E-07	GS98
18	Ar	Argon	6.40	-5.60	2.51E-06	GS98
19	K	Potassium	5.12	-6.88	1.32E-07	GS98
20	Ca	Calcium	6.36	-5.64	2.29E-06	GS98
21	Sc	Scandium	3.17	-8.83	1.48E-09	GS98
22	Ti	Titanium	5.02	-6.98	1.05E-07	GS98
23	V	Vanadium	4.00	-8.00	1.00E-08	GS98
24	Cr	Chromium	5.67	-6.33	4.68E-07	GS98
25	Mn	Manganese	5.46	-6.54	2.88E-07	GS98*
26	Fe	Iron	7.45	-4.55	2.82E-05	H01
27	Co	Cobalt	4.92	-7.08	8.32E-08	GS98
28	Ni	Nickel	6.25	-5.75	1.78E-06	GS98
29	Cu	Copper	4.21	-7.79	1.62E-08	GS98
30	Zn	Zinc	4.60	-7.40	3.98E-08	GS98

References: GS98: [Grevesse and Sauval \(1998\)](#), GS98\* - mean of photospheric and meteoritic, H01: [Holweger \(2001\)](#), AP01, AP02 [Allende Prieto et al. \(2001, 2002\)](#).

```
abundances H II region
element scale factor nitrogen 2
```

or

```
element scale factor nitrogen 2
abundances H II region
```

The **element scale factor** option applies a scale factor while the **element abundance** option sets an absolute abundance. The **abundances H II region** command uses one of the absolute abundance mixtures that are stored by the code. This command enters the gas-phase abundances of all 30 elements and also includes interstellar grains. The **element** command changes some details about a particular element.

In the following example both commands set absolute abundances so the first nitrogen **abundance** will have no effect and the final nitrogen abundance will be the default H II region abundance

```
element abundance nitrogen -4.7
abundances H II region
```

In the following only the second nitrogen scale factor has any effect since the second scale factor overwrites the first:

```
element scale factor nitrogen 3
element scale factor nitrogen 2
abundances H II region
```

The result will be H II region abundances with nitrogen having twice its normal value. Similarly, the combination

```
element abundance nitrogen -4
element scale factor nitrogen 2
```

in either order would result in  $n(\text{N})/n(\text{H}) = 2 \times 10^{-4}$  since the first command sets an absolute abundance of  $10^{-4}$  and the second command doubles this.

The chemical composition is printed at the start of the calculation. Be sure to confirm that the composition has been entered correctly.

## 7.4 Abundances he c...

The abundances of all elements can be entered with the command **abundances** followed by: a) a complete set of abundances, b) the keyword **all** and a single number to set all of the abundances, or c) a second keyword to select one of the stored abundance sets.

### 7.4.1 Arbitrary abundances

The **abundances** command can be used to specify the abundances of all elements as a series of numbers. The elements must be in exactly the same order as indicated in Table 7.1 unless the order is altered with the **elements read** command. Abundances for all active elements must be specified. Elements can be turned off with the **elements off** command. The composition can be specified on several lines with **continue** lines following the initial **abundances** line. Abundances of zero are not allowed; CLOUDY will stop if they are entered.

*N.B.* In the following examples the name of an element is written before its abundance. This is only for readability. The code makes no attempt to read the symbols. The numeric abundances *must* appear in the same order expected by the code.

The best way to enter abundances is as *absolute abundances*, as in the following example

```

abundances he =-1 li =-9 be =-11 b =-9 c =-4.3 n =-5 o =-2.3
continue f =-7 ne =-1.2 na =-3 mg =-8
continue al =-8 si =-8 p =-6 s =-8 cl =-9 ar =-8 k =-6
continue ca =-8 sc =-9 ti =-7 v =-8 cr =-6.3 mn =-6 fe =-8
continue co =-9 ni =-8 cu =-7 zn =-7

```

The abundances can also be entered as a set of scale factors indicating the desired abundances relative to the current set absolute abundance. These will be solar by default. The following example doubles the oxygen abundance and lowers the iron abundance

```

abundances he =1 li =1 be =1 b =1 c =1 n =1 o =2
continue f =1 ne =1 na =1 mg =1
continue al =1 si =1 p =1 s =1 cl =1 ar =1 k =1
continue ca =1 sc =1 ti =1 v =1 cr =1 mn =1 fe =0.0000001
//deplete iron
continue co =1 ni =1 cu =1 zn =1;

```

It is better to specify absolute abundances since the default solar composition changes from time to time.

The code checks the sign of all of the entered abundances to decide which style was entered. The numbers are interpreted as linear scale factors if *all* are positive, and as logs of the abundance relative to hydrogen if *any* are negative.

### 7.4.2 Setting all at once

If the keyword **all** appears and exactly one number is entered then all of the elements heavier than hydrogen are given this absolute abundance. The number is the log of the abundance if it is less than or equal to zero and the abundance itself if it is positive. Either of the following commands will give all elements between and including helium and zinc an absolute abundance of  $10^{-10}$  by number relative to hydrogen:

```

abundances all -10
abundances all 1e-10

```

The **metals** command will set abundances of all elements heavier than helium.

### 7.4.3 Stored abundance sets

Table 7.2 lists the abundance sets that are stored as a permanent part of the code. These sets are entered if there are no numbers on the **abundances** command but a keyword occurs as in the following examples. The four-character part of the keyword that must be matched for the key to be recognized is capitalized in the second line of the table. The following gives some examples:

```

abundances Cameron
abundances H II region no grains
abundances h ii region
abundances nova
abundances planetary nebula
abundances primordial

```

The assumed abundances are from a variety of sources. Table 7.2 gives their present values.

**Cameron** These are from [Cameron \(1982\)](#). Note that the helium abundance is very low, either it or the Big Bang is wrong.

Table 7.2: Stored Abundance Sets

	Atom	H II Region	Planetary	Nova	Cameron	Primordial	ISM	Crab
	key	H II, H II	PLANetary	NOVA	CAMERon	PRIMordial	ISM	CRAB
2	He	0.095	0.10	0.098	0.0677	0.072	0.098	0.70
3	Li	5.4(-11)	1.0(-20)	2.05(-9)	2.20(-9)	1(-10)	5.4(-11)	-
4	Be	1.0(-20)	1.0(-20)	2.62(-11)	4.50(-11)	1(-16)	1.0(-20)	-
5	B	8.9(-11)	1.0(-20)	7.60(-10)	3.40e-10	-	8.9(-11)	-
6	C	3.0(-4)	7.8(-4)	9.40(-3)	4.22(-4)	-	2.51(-4)	70(-4)
7	N	7.0(-5)	1.8(-4)	9.80(-3)	8.72(-5)	-	7.94(-5)	1.23(-4)
8	O	4.0(-4)	4.4(-4)	1.70(-2)	6.93(-4)	-	3.19(-4)	17.0(-4)
9	F	1.0(-20)	3.0(-7)	3.02(-8)	2.90(-8)	-	2.0(-8)	-
10	Ne	6.0(-5)	1.1(-4)	2.03(-3)	9.77(-5)	-	1.23(-4)	5.33(-4)
11	Na	3.0(-7)	1.9(-6)	2.06(-6)	2.25(-6)	-	3.16(-7)	-
12	Mg	3.0(-6)	1.6(-6)	3.80(-5)	3.98(-5)	-	1.26(-5)	0.8(-4)
13	Al	2.0(-7)	2.7(-7)	2.95(-6)	3.20(-6)	-	7.94(-8)	-
14	Si	4.0(-6)	1.0(-5)	3.55(-5)	3.76(-5)	-	3.16(-6)	-
15	P	1.6(-7)	2.0(-7)	3.73(-7)	3.72(-7)	-	1.6(-7)	-
16	S	1.0(-5)	1.0(-5)	1.62(-5)	1.88(-5)	-	3.24(-5)	0.35(-4)
17	Cl	11.0(-7)	1.7(-7)	1.88(-7)	1.78(-7)	-	1.0(-7)	-
18	Ar	3.0(-6)	2.7(-6)	3.63(-6)	3.99(-6)	-	2.82(-6)	-
19	K	1.1(-8)	1.2(-7)	1.35(-7)	1.35(-7)	-	1.1(-8)	-
20	Ca	2.0(-8)	1.2(-8)	2.29(-6)	2.35(-6)	-	4.1(-10)	-
21	Sc	1.0(-20)	1.0(-20)	1.22(-9)	1.16(-9)	-	1(-20)	-
22	Ti	5.8(-10)	1.0(-20)	8.60(-8)	9.00(-8)	-	5.8(-10)	-
23	V	1.0(-10)	1.0(-20)	1.05(-8)	9.50(-9)	-	1.0(-10)	-
24	Cr	1.0(-8)	1.0(-20)	4.84(-7)	4.80(-7)	-	1.0(-8)	-
25	Mn	2.3(-8)	1.0(-20)	3.42(-7)	3.50(-7)	-	2.3(-8)	-
26	Fe	3.0(-6)	5.0(-7)	4.68(-5)	3.38(-5)	-	6.31(-7)	3.24(-5)
27	Co	1.0(-20)	1.0(-20)	2.24(-9)	8.27(-8)	-	1.0(-9)	-
28	Ni	1.0(-7)	1.8(-8)	1.76(-6)	1.80(-6)	-	1.82(-8)	-
29	Cu	1.5(-9)	1.0(-20)	1.87(-8)	2.00(-8)	-	1.5(-9)	-
30	Zn	2.0(-8)	1.0(-20)	4.52(-8)	4.70(-8)	-	2.0(-8)	-
	grains	Orion	AGB	no	no	no	ISM	no

**Crab Nebula** These are from model M1, Table 3, of [Pequignot and Dennefeld \(1983\)](#). Elements they did not include are from work in progress. Grains are not included by default. They must be added separately.

**nova** These are roughly those derived by [Ferland and Shields \(1978\)](#) for the classical nova V1500 Cygni. Abundances close to solar are assumed for those they did not measure.

**H II region** The H II region abundances are a subjective mean of the Orion Nebula abundances determined by [Baldwin et al. \(1991\)](#), [Rubin et al. \(1991\)](#), [Osterbrock et al. \(1992\)](#), and [Rubin et al. \(1993\)](#). The grains are the large-R size distribution grains described by [Baldwin et al. \(1991\)](#) but with the physics updated as described by [van Hoof et al. \(2004\)](#). The keywords **H II region**, **H II region**, or **Orion** can be used to obtain this abundance set. Abundances of some rare species were taken from the ISM mix of [Savage and Sembach \(1996\)](#). Abundances entered in the table as “1E-20” are not real values, simply values chosen to be small enough to be of no consequence. I would appreciate learning about better numbers.

**planetary nebula** These abundances are from [Aller and Czyzak \(1983\)](#) and [Khromov \(1989\)](#), with high depletions assumed for elements they do not list. The grains are from unpublished work of Kevin Volk on post-AGB stars. The derived dust to gas ratios of different PNe have a large spread. Evidence summarized by [Clegg and Harrington \(1989\)](#) suggests that some PNe have dust to gas ratios roughly ten times smaller than ISM. However, [Mallik and Peimbert \(1988\)](#) find dust to gas ratios similar to ISM and [Borkowski and Harrington \(1991\)](#) find one object with a dust-to-gas ratio an order of magnitude above ISM. The grain composition of planetary nebulae should be treated on a case by case rather than statistical basis. Abundances entered as “1E-20” are not real values, simply values chosen to be small enough to be of no consequence. I would appreciate learning about better numbers.

**ISM** The gas-phase abundances are an average from the work of [Cowie and Songaila \(1986\)](#) for the warm and cold phases of the interstellar medium together with numbers from the warm and cool phases towards  $\xi$  Oph ([Savage and Sembach, 1996](#)). The oxygen abundance<sup>1</sup> is from [Meyer et al. \(1998\)](#), F is from [Snow et al. \(2007\)](#), and Co is from [Mullman et al. \(1998\)](#). The grains are the interstellar medium grains defined by [Mathis et al. \(1977\)](#). The ISM, H II region, and Orion abundances are not the same, although one can make the case that they should be.

**old solar 84** The composition will be the solar used in versions 84 - 94 of the code. These are defined in Table 7.3 and were taken from the meteoritic abundances of [Grevesse and Anders \(1989\)](#) with extensions by [Grevesse and Noels \(1993\)](#). All three of the keywords **old solar 84** must appear.

**GASS10** will use solar abundances from [Grevesse et al. \(2010\)](#). The abundances are listed in Table 7.4. The command must appear as **abundances GASS10**.

## 7.4.4 Grains, gas-phase depletions, and quantum heating

Certain elements, especially Si, Ca, Al, Mg, and Fe, are heavily depleted onto grains in the ISM. The abundance sets specified by the **h ii region**, **ISM**, or **planetary nebula** keywords will include grains and the gas-phase mixtures given in Table 7.2. The bottom line of the table lists the type of grains that are included by default. These types are defined in the section on grains starting on page 67.

<sup>1</sup>The ISM O abundance was changed from 5.01 to  $3.19 \times 10^{-4}$  in version 95.

Table 7.3: Old Solar Composition

				Solar	
1	H	Hydrogen	1	0.00	12.00
2	He	Helium	0.1	−1.00	11.00
3	Li	Lithium	2.04E-09	−8.69	3.31
4	Be	Beryllium	2.63E-11	−10.58	1.42
5	B	Boron	7.59E-10	−9.12	2.88
6	C	Carbon	3.55E-04	−3.45	8.55
7	N	Nitrogen	9.33E-05	−4.03	7.97
8	O	Oxygen	7.41E-04	−3.13	8.87
9	F	Fluorine	3.02E-08	−7.52	4.48
10	Ne	Neon	1.17E-04	−3.93	8.07
11	Na	Sodium	2.06E-06	−5.69	6.31
12	Mg	Magnesium	3.80E-05	−4.42	7.58
13	Al	Aluminium	2.95E-06	−5.53	6.47
14	Si	Silicon	3.55E-05	−4.44	7.55
15	P	Phosphorus	3.73E-07	−6.43	5.57
16	S	Sulphur	1.62E-05	−4.79	7.21
17	Cl	Chlorine	1.88E-07	−6.73	5.27
18	Ar	Argon	3.98E-06	−5.40	6.60
19	K	Potassium	1.35E-07	−6.87	5.13
20	Ca	Calcium	2.29E-06	−5.64	6.36
21	Sc	Scandium	1.58E-09	−8.80	3.20
22	Ti	Titanium	1.10E-07	−6.96	5.04
23	V	Vanadium	1.05E-08	−7.98	4.02
24	Cr	Chromium	4.84E-07	−6.32	5.68
25	Mn	Manganese	3.42E-07	−6.47	5.53
26	Fe	Iron	3.24E-05	−4.49	7.51
27	Co	Cobalt	8.32E-08	−7.08	4.92
28	Ni	Nickel	1.76E-06	−5.75	6.25
29	Cu	Copper	1.87E-08	−7.73	4.27
30	Zn	Zinc	4.52E-08	−7.34	4.66

Table 7.4: 2010 Solar Composition

Solar				
1	H	1	0	12
2	He	8.51E-02	-1.07	10.93
3	Li	1.12E-11	-10.95	1.05
4	Be	2.40E-11	-10.62	1.38
5	B	5.01E-10	-9.3	2.7
6	C	2.69E-04	-3.57	8.43
7	N	6.76E-05	-4.17	7.83
8	O	4.90E-04	-3.31	8.69
9	F	3.63E-08	-7.44	4.56
10	Ne	8.51E-05	-4.07	7.93
11	Na	1.74E-06	-5.76	6.24
12	Mg	3.98E-05	-4.4	7.6
13	Al	2.82E-06	-5.55	6.45
14	Si	3.24E-05	-4.49	7.51
15	P	2.57E-07	-6.59	5.41
16	S	1.32E-05	-4.88	7.12
17	Cl	3.16E-07	-6.5	5.5
18	Ar	2.51E-06	-5.6	6.4
19	K	1.07E-07	-6.97	5.03
20	Ca	2.19E-06	-5.66	6.34
21	Sc	1.41E-09	-8.85	3.15
22	Ti	8.91E-08	-7.05	4.95
23	V	8.51E-09	-8.07	3.93
24	Cr	4.37E-07	-6.36	5.64
25	Mn	2.69E-07	-6.57	5.43
26	Fe	3.16E-05	-4.5	7.5
27	Co	9.77E-08	-7.01	4.99
28	Ni	1.66E-06	-5.78	6.22
29	Cu	1.55E-08	-7.81	4.19
30	Zn	3.63E-08	-7.44	4.56

Grains can also be specified separately with the **grains** command. If you use the **grains** command to specify another type of grains then you should include the keyword **no grains** on the abundances line to prevent the default grains from also being used.

If you set the keyword **no grains** to not include the default grains and do not specify another set of grains with the **grains** command then grains will not be included in the calculation but the depleted gas-phase abundances will still be used.<sup>2</sup> This is, of course, not self-consistent.

Quantum or single-photon heating will be considered for all grain species where it will be important. Quantum heating only affects the Wien tail of the grain thermal-emission spectrum. The **no qheat** option on the **abundances** command will disable quantum heating.

Figure 7.1 compares the continuum predicted in the test case `grains_qheat`, a part of the code's test suite. Quantum heating is normally included and the **no qheat** option was used to disable it to make this comparison.

### 7.4.5 Interactions between the abundances and grains commands

It is possible to include grain species with both the **abundances** command, described here, and with the **grains** command. For simplicity you should only set the grain abundances only once. If you specify the same grains more than one time you are asking for trouble. The rules for how these commands interact are described elsewhere.

You should check that you have the expected grain abundances by looking at the list of grain abundances given at the start of the calculation and at the value of  $A_V/N_H$  given at the end.

## 7.5 Abundances starburst, $Z=10$

This form of the **abundances** command interpolates on Fred Hamann's grid of abundances for an evolving starburst in a massive galactic core. The chemical evolution model is more fully described by [Hamann and Ferland \(1993\)](#). This grid is model M5a of that paper. It uses a star formation rate and infall timescales very close to, but slightly faster than, the "standard" elliptical model (see also [Arimoto and Yoshii, 1987](#); [Matteucci and Greggio, 1986](#); [Matteucci and Tornambe, 1987](#); [Bica, 1988](#)). Its IMF also has a slope very similar to, but slightly steeper than ( $x = 1.0$  instead of  $1.1$ ), that of the standard elliptical model. The main difference is that the IMF has a lower mass cutoff at  $M = 2.5M_\odot$  instead of  $\sim 0.1M_\odot$  in the standard models. This allows the gas to reach much higher metallicities before the gas is locked up in low-mass stellar remnants.

The metallicity of the gas relative to solar appears on the line. It is interpreted as the log of the metallicity if it is less than or equal to zero, and the linear metallicity if positive. The keywords **log** or **linear** will force the number to be interpreted appropriately. The limits to the range of possible metallicities are  $10^{-3}Z_{sun}$  and  $36Z_{sun}$ .

This command works by generating scale factors that multiply the current standard abundance. This is solar by default. The command does not derive absolute abundances. If you change the abundances with a second **abundance** command then the scale factors will multiply those new abundances.

The keyword **trace** will print the abundances of all elements as a function of metallicity between the full  $10^{-3}Z_{sun}$  and  $36Z_{sun}$  limits. The code will then stop.

<sup>2</sup>In versions 77 and before, the abundances of depleted elements were set to solar values when **no grains** was set.

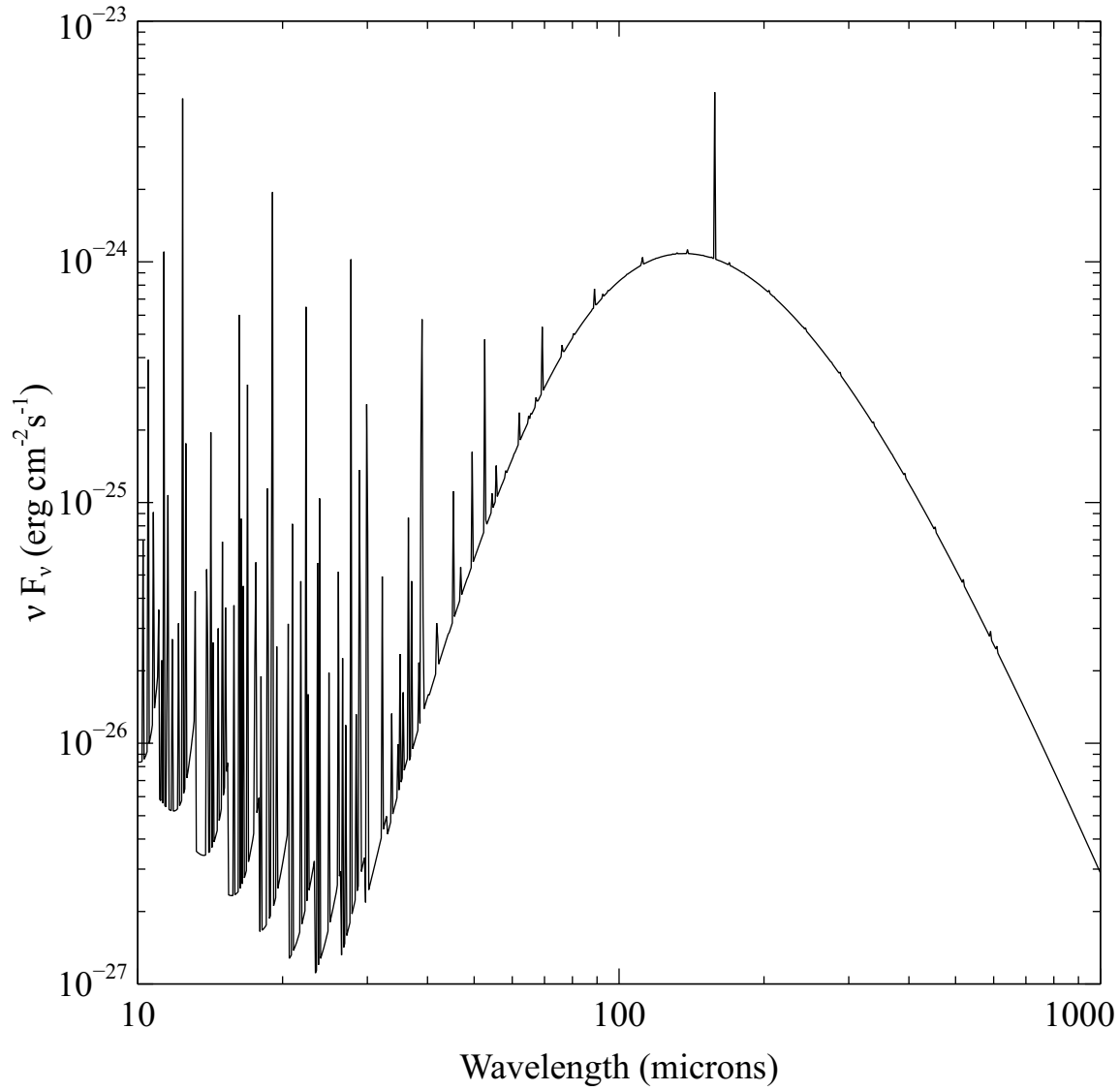


Figure 7.1: This figure shows the net emission computed by the test case `grains_qheaat`. The solid line includes quantum heating while the dashed line has disabled it.

## 7.6 Element name [scale, abundance, off, log, table]

This sets the abundance of a particular element. The command has several keywords that change the behavior of the command.

### 7.6.1 Element name scale

If the keyword **scale** appears then the number on the line is a scale factor multiplying the current abundance of the element. The number is a linear scale factor if it is positive or if the **linear** keyword appears and it is the log of the scale factor if the number is negative. If the key **log** appears (note the leading space) then the scale factor is interpreted as a log irregardless of its sign.

### 7.6.2 Element name abundance

If **abundance** appears then the number is the absolute abundance of the element by number relative to hydrogen. The number is the log of the abundance unless the **linear** keyword appears.

### 7.6.3 Element name ionization

This allows the ionization distribution of an element to be set. Each number is the ionization fraction,  $n(A^{+i})/n(A)$ , for successive stages of ionization. The code will scan off up to A+1 numbers, where A is the atomic number of the element. If any numbers are negative then all are interpreted as logs of the ionization fraction. If there are fewer than A+1 numbers then the missing stages of ionization are assumed to have zero abundance.

The total density of all ions must add up to the total density of the element. The code imposes several particle conservation rules to insure that mass is conserved. The density of the ions will be renormalized so that the total abundance of the element is equal to the value specified by other commands.<sup>3</sup>

This command does not specify the chemical state. The H<sub>2</sub> fraction can be set with the **set H2** command. Chemistry is disabled if you set the ionization distribution of an element that is part of the chemical network. It will not be possible to obtain a chemical solution if the abundances of the atom and ions cannot respond to changes in the chemistry.

All of this is unphysical and is only intended as a way to test the code.

### 7.6.4 Element name off

If the keyword **off** appears (note the leading space) then the element is not included in the calculation. The ionization equilibrium, opacity, and cooling due to the element will not be computed. The abundance must still be specified when the **abundances** command is used unless the element is excluded with the **elements read** command.

The keyword **on** will include an element that was previously turned off in the same input stream.

You can save computer time if you turn an element off. This is especially true for third- and fourth-row elements. These take longer to compute because of the large number of inner-shell electrons. They often have negligible effects on the thermal and ionization structure because of their low abundances.

<sup>3</sup>In versions C08 and before this command did not confirm that the sum of the ionization fractions was unity. The abundance of each stage of ionization was set to the product of the ionization fraction times the abundance set by other commands. If the fractions did not add up to unity the effect was to change the total abundance of the element.

Memory for the species that are present is dynamically allocated when the code starts. When the code is used to compute a large grid of models it is not possible to turn on an element that was turned off for the first model since the needed memory does not exist. You can turn off an element in later models since the element is simply not computed. In later calculations in a grid the code will ignore any attempt to turn on an element that was initially turned off.

The chemical solution may become destabilized if an element that forms molecules is turned off. Do not turn off elements that are part of the chemistry if the calculation extends into a PDR or molecular cloud. The code will generate a warning if this is done.

Turning off an element with this command has other side effects. For instance, the following input stream would produce unexpected results:

```
element zinc ionization -3 0 -4
init "ism.ini"
element zinc on
```

because the `ism.ini` file turns off zinc. This destroys the memory of the **element zinc ionization** command, which sets the ionization of the element. So, when the element is turned back on with the **element zinc on** command the ionization will be determined self consistently rather than set to the constant values.

### 7.6.5 Element limit off -12

Elements with abundances that are smaller than the number on the line will be ignored. The number is the log of the limiting abundance by number relative to hydrogen. This is an easy way to turn off elements that have trivial abundances. Table 7.5 lists the elements in terms of decreasing abundance. The command

```
elements limit off -7
```

would cause all elements at Cobalt and above in Table 7.5 to be turned off.

### 7.6.6 Elements read

Normally CLOUDY expects the abundances entered with the **abundances** command to occur in exactly the same order as the atomic numbers of the elements. These begin with helium and include all elements through zinc. The **elements read** command makes it possible to change this order or to leave certain elements out entirely. The command begins with the line **elements read**, follows with a list of elements, and ends with a line beginning with the keyword **end**.

This order will be used for all **abundances** commands that follow this command. If an element does not occur in the list then its value cannot be set by an **abundances** command. This does not turn an element off - this is done with the **element name off** command.

The following example shows an input stream that changes the **abundances** command so that it behaves more like version 84 of the code. Only the elements in the list were present in that version. The **elements read** command sets the elements that will be entered then the missing elements are turned off with the **element off** command.

```
elements read
helium
carbon
nitrogen
oxygen
```

Table 7.5: Solar composition sorted by abundance

A	Symbol	Name	$\log n(x)/n(\text{H})$
4	Be	Beryllium	-10.58
5	B	Boron	-9.21
21	Sc	Scandium	-8.83
3	Li	Lithium	-8.69
23	V	Vanadium	-8.00
29	Cu	Copper	-7.79
9	F	Fluorine	-7.52
30	Zn	Zinc	-7.40
27	Co	Cobalt	-7.08
22	Ti	Titanium	-6.98
19	K	Potassium	-6.88
17	Cl	Chlorine	-6.72
25	Mn	Manganese	-6.54
15	P	Phosphorus	-6.50
24	Cr	Chromium	-6.33
28	Ni	Nickel	-5.75
11	Na	Sodium	-5.67
20	Ca	Calcium	-5.64
18	Ar	Argon	-5.60
13	Al	Aluminium	-5.53
16	S	Sulphur	-4.74
26	Fe	Iron	-4.55
12	Mg	Magnesium	-4.46
14	Si	Silicon	-4.46
7	N	Nitrogen	-4.07
10	Ne	Neon	-4.00
6	C	Carbon	-3.61
8	O	Oxygen	-3.31
2	He	Helium	-1.00
1	H	Hydrogen	0.00

```

neon
sodium
magnesium
aluminum
silicon
sulphur
argon
calcium
iron
nickel
end of elements
c
element Lithium off
element Beryllium off
element Boron off
element Fluorine off
element Phosphor off
element Chlorine off
element Potassium off
element Scandium off
element Titanium off
element Vanadium off
element Chromium off
element Manganese off
element Cobalt off
element Copper off
element Zinc off

```

In summary: Turning an element off with the **element off** command does not remove that element from the list of abundances entered with the **abundances** command. Leaving an element out of this list with the **elements read** command does not turn off that element.

### 7.6.7 Element name table

If the keyword **table** appears on the **elements** command then the code will read in a list of position-dependent abundances for a particular element. This might, for instance, be used to model variable depletions. The following is an example.

```

element carbon table depth
-30 -4
3 -4
5 -3
7 -2
9 -1
end of table

```

The first number on each line is the log of the radius (the default) or depth (if the keyword **depth** also appears on the **element** line). The second number is the log of the abundance of the element at that point, by number relative to hydrogen. The table ends with a line starting with the keyword **end**. Up to 500 pairs may be entered. This command always specifies the absolute abundance and not the scale factor.

The chemical composition printed at the start of the calculation is always the composition at the illuminated face of the cloud. If the table gives composition as a function of radius then the composition will be evaluated at the inner radius of the cloud. If the table gives the composition as a function of depth

then the composition will be evaluated as a depth of  $10^{-30}$  cm. The table must extend to this depth as in the example above.

## 7.7 Fluctuations abundances, period, max, min, phase

This makes the metallicity vary with radius as a sine wave. This is designed to investigate the effects of chemical inhomogeneities upon the emission-line spectrum and was implemented to search for solutions to the  $t^2$  problem (Kingdon and Ferland, 1995).

The first number is the log of the period  $P$  of the sine wave in centimeters. The second two numbers are the logs of the largest and smallest metallicities over the sine wave and have the same effect as the metals scaling factor entered with the **metals** command.

The **fluctuations** command is more fully described in the description of the density version.

## 7.8 Grains

This command controls how grains are included in the calculation. They are not included by default. Grains are included in the compositions set by some **abundances** commands (see Table 7.2 above). Grain physics was originally developed in collaboration with Peter van Hoof, Peter G. Martin, and Joe Weingartner, Peter van Hoof did the majority of the coding, and he is the maintainer of the code. Reviews are given by Spitzer (1948, 1978), and Martin (1978). Baldwin et al. (1991), Weingartner and Draine (2001b), van Hoof et al. (2004) and Weingartner et al. (2006) describe the theory incorporated in the code.

The **save grain** commands produce output giving details about the grains. Some details of the grain physics can be adjusted with the **no grain ...** family of commands. The **compile grains** command (page 218 below) is used to create new grain opacity files, or to recompile them if the code's energy mesh is changed.

### 7.8.1 Using the built-in grain types

The grain types summarized in Table 7.6 are included in the code's data files. The table gives the grain material, its size distribution, and the name of the grain opacity file that it uses. In most cases these will be sufficient - nothing more needs to be done to set up the grains.

Grains are composed of elements that are condensed from the gas phase. It would be inconsistent to assume solar abundances for all elements and also include grains. In reality certain elements, especially Ca, Al, Ti, and Fe, are strongly depleted from the gas phase in the ISM and are believed to be present as grains. The **metals deplete** command can be used to deplete elements that are included in grains.

Several of the standard abundance sets that are specified with the **abundances** command include grains. The elements which make up the grains are depleted from the gas phase in these abundance sets. Elements are not depleted in sets that do not include grains by default.

- **grains ISM** specifies grains with a size distribution and abundance appropriate for the ISM of our galaxy. This includes both a graphitic and silicate component and generally reproduces the observed overall extinction properties for a ratio of extinction per reddening of  $R_V \equiv A_V/E(B-V) = 3.1$ . This is the default and will be used if no keywords occur on the **grains** command. If either keyword **graphite** or **silicate** also appears then only that grain type is included. Both species are included if neither keyword appears.

Table 7.6: Standard Grain Types

Keyword	Filename	Type	Size distribution
	graphite_0m010.opc	Graphite	Single 0.01 $\mu\text{m}$
	graphite_0m100.opc	Graphite	Single 0.1 $\mu\text{m}$
	graphite_1m000.opc	Graphite	Single 1 $\mu\text{m}$
ISM single graphite	graphite_ism_01.opc	Graphite	Unresolved ISM
ISM graphite	graphite_ism_10.opc	Graphite	ISM, 10 bins
Orion single graphite	graphite_orion_01.opc	Graphite	Unresolved Orion
Orion graphite	graphite_orion_10.opc	Graphite	Orion, 10 bins
grey single	grey_ism_01.opc	Grey	Unresolved ISM
grey	grey_ism_10.opc	Grey	ISM, 10 bins
PAH single	pah1_ab08_01.opc	PAH	Unresolved AB08
PAH	pah1_ab08_10.opc	PAH	AB08, 10 bins
	pah1_c120.opc	PAH	120 C atoms
	pah1_c15.opc	PAH	15 C atoms
	silicate_0m010.opc	Silicate	Single 0.01 $\mu\text{m}$
	silicate_0m100.opc	Silicate	Single 0.1 $\mu\text{m}$
	silicate_1m000.opc	Silicate	Single 1 $\mu\text{m}$
ISM single silicate	silicate_ism_01.opc	Silicate	Unresolved ISM
ISM silicate	silicate_ism_10.opc	Silicate	ISM, 10 bins
Orion single silicate	silicate_orion_01.opc	Silicate	Unresolved Orion
Orion silicate	silicate_orion_10.opc	Silicate	Orion, 10 bins

- **grains Orion** specifies graphitic and silicate grains with a size distribution and abundance appropriate for those along the line of sight to the Trapezium stars in Orion. The Orion size distribution is deficient in small particles and so produces the relatively grey extinction observed in Orion (Baldwin et al., 1991). If either keyword **graphite** or **silicate** appears then only that grain type is included. Both species are included if neither keyword appears.
- **grains PAH** turns on PAHs. See page 71 below for more details.

**Grain abundances** An optional scale factor on the command line changes the grain abundance relative to its default value. If the keyword **log** appears or if the number is less than or equal to zero then the number is the log of the scale factor. It is the linear factor if the keyword **linear** appears or if no keyword appears and the number is positive.

It is also possible to change the abundances of the grains with the **metals grains** command. The **metals** command scales the abundances of all elements more massive than helium by a scale factor. If the keyword **grains** occurs then the grain abundance will also be scaled up or down. This would keep the grains to metals abundance ratio constant.

The following example uses ISM gas-phase abundances, Orion silicates with dust to gas ratio twice the default value, and ISM graphite with default ISM abundances.

```
// use ISM abundances but DO NOT include ISM default grains
abundances ISM no grains
// Orion silicate with twice the Orion abundance
grains Orion silicate 2
// ism graphite with ISM dust to gas ratio
grains ISM graphite
```

The default H II region grain abundances are close to the ISM value. Planetary nebula grain abundances are quite uncertain. Clegg and Harrington (1989) find dust-to-gas ratios below the ISM value, while Borkowski and Harrington (1991) find a dust-to-gas ratio an order of magnitude above ISM in a hydrogen-deficient planetary nebula. Mallik and Peimbert (1988) find dust-to-gas ratios roughly equal to the ISM in a sample of PN's. Stasińska and Szczerba (1999) discuss properties of a sample of PNe. In view of this scatter the grain abundance of PNe should probably be treated as a free parameter.

**Size resolved or averaged grains** Grains in the ISM have a broad range of sizes, often described by a power-law distribution (Mathis et al., 1977). By default the grains will be resolved into ten size bins. If the keyword **single** appears then the grains will have properties determined by averaging over the entire size range. If the keyword **distribution** appears then the code will resolve the size distribution. This is the default and will be used if no keyword appears. The **single** option may save some machine time but will give a less realistic representation of the grain physics. This is because many grain properties such as temperature and charge depend strongly on the size. In particular, the photoelectric heating of the gas can be underestimated if the single mean grain is used.

## 7.8.2 Interactions between abundances and grains commands

Be careful when specifying grains with more than one **grains** command or with both the **abundances** and **grains** commands. The order in which the commands appear in the input stream does make a difference. These commands have the following precedence:

- An **abundance** command will override all grains set with a previous **abundances** command. So with the following pair

```
abundances ism
abundances old solar 84
```

ISM grains stay in place since grains are not included in the old solar mixture.

```
abundances ism
abundances orion
```

only Orion grains will be included

- An **abundances** command will NOT override any grains set with a previous **grains** command. It will not add any grains either. Instead it will implicitly behave as if the option **no grains** was given on the **abundances** command.

```
grains orion
abundances ism
```

only Orion grains are included

- A **grains** command given after an **abundances** command or another **grains** command will add to those already included, even if it would cause the same set of grains to be included twice. A warning will be printed if the latter occurs. For instance, the following would add the ISM grains twice and generate a warning;

```
abundances ism
grains ism
```

- An **abundance** command that does not set any grains will not override any grains set with a previous **abundances** command.

The following would result in the Orion gas-phase composition but ISM grains

```
abundances Orion no grains
grains ism
```

The following will use ISM grains and Orion abundances, but will not include Orion grains since the **abundances** command comes after the **grains** command;

```
grains ism
abundances Orion
```

The order is swapped in the following. This results in Orion gas-phase abundances and both ISM and Orion grains

```
abundances Orion
grains ism
```

To avoid confusion it is best to only specify grains with only the **abundances** command or by including the **no grains** option on the **abundances** command and then including explicit **grains** commands. In any case, be sure to check the resulting output to verify that things are set properly.

### 7.8.3 Creating your own grain types

New types of grains may be introduced by first generating data files that specify the size distribution and refractive indices for the full energy range considered by the code. These are then converted to opacities with the **compile grains** command. The process is described further where the **compile grains** command is discussed. The result is a new “.opc” file.

The code will read an opacity file whenever a double quote (") occurs anywhere on the command line. If a double quote is found then the code will look for the name between a pair of quotes, as in “special.opc”, and will stop if the file cannot be found or if the second quote is missing. If the file exists then this grain species will be included. So don't place a quote on the **grains** command unless there is a pair of quotes surrounding a filename since the code will stop. The contents of that file will determine whether the calculations are size-resolved or not, irrespective of the keywords **distribution** or **single**.

### 7.8.4 PAHs

PAH's are not included by default but are added with the **PAH** option on the **grains** command. A detailed treatment of the physics of PAH's is implemented, including photoelectric heating and collisional processes as discussed by [Weingartner and Draine \(2001a\)](#), and stochastic heating effects following [Guhathakurta and Draine \(1989\)](#). A power-law distribution of PAH sizes with 10 size bins ([Abel et al., 2008](#), hereafter AB08), and two single-sized PAH's, are included in the downloaded data files. AB08 is the default and will be used if no further options occur on the command line. If the keyword **single** also appears then an unresolved size distribution with their mean properties is used.

The PAH opacity functions were derived by Kevin Volk from a variety of sources. The original opacity function is from [Desert et al. \(1990\)](#) and [Schutte et al. \(1993\)](#). Kevin adapted the opacities from these papers to agree with the infrared plateaus seen in the Orion Bar ([Bregman et al., 1989](#)). The optical/far-UV opacity values have a gradual change to atomic cross sections so that you get the correct X-ray cross sections.

The command **grains PAH C15** will include a single small PAH with 15 carbon atoms per molecule, with an abundance relative to hydrogen of  $n(\text{PAH})/n(\text{H}_{\text{tot}}) = 1.986 \times 10^{-7}$ , corresponding to  $n(\text{C})/n(\text{H}_{\text{tot}}) = 2.979 \times 10^{-6}$ . The command **grains PAH C120** will include a large PAH with 120 carbon atoms per molecule and an abundance relative to hydrogen of  $n(\text{PAH})/n(\text{H}_{\text{tot}}) = 2.483 \times 10^{-8}$ , also corresponding to  $n(\text{C})/n(\text{H}_{\text{tot}}) = 2.979 \times 10^{-6}$ .

PAHs appear to exist mainly at the interface between the  $\text{H}^+$  region and the molecular clouds. Apparently PAHs are destroyed in ionized gas ([Sellgren et al., 1990](#), AGN3 section 8.5) by ionizing photons and by collisions with ions (mainly  $\text{H}^+$ ) and may be depleted into larger grains in molecular regions. By default the code assumes that the PAH abundance scales with the ratio  $n(\text{H}^0)/n(\text{H})$  although this can be changed. This produces very few grains in ionized and fully molecular gas, but the PAHs will have their default abundance when the gas is atomic. This is consistent with Sellgren's observations of the Orion Bar.

The **set PAH** command makes it possible to specify several other laws describing how PAH abundances depend on physical conditions. Note that if PAHs are present in predominantly molecular gas then they will soak up nearly all of the free electrons. This has major effects on the predictions of the chemistry network.

### 7.8.5 Variable grain abundances

The **function** option on the **grains** command makes it possible to vary the abundance of any grain species across a cloud. (The **abundances** command does not have the **function** option.) This option works by setting the local abundance of a grain species to the product of the intrinsic abundance and the value returned by the function *GrnVryDpth*. That routine can be modified by the user to specify a scale factor that might depend on other physical conditions or location. Alternatively, you can supply the keywords

**function sublimation** which will turn on a predefined grain abundance function that mimics the effects of grain sublimation. It will steeply lower the grain abundance when the grain temperature is above the sublimation temperature for a given grain bin. The function that is used is as follows:

$$A_g = \exp \left[ - \left( \frac{T_g}{T_{\text{subl}}} \right)^3 \right].$$

All the other multipliers for the grain abundance are still in effect when the keyword **function** is used. This means that the abundance multiplier supplied with the **grains** command is also included, as well as the factor supplied in the **metals grains** command. So the abundance of the grain is given by the default abundance multiplied with the two numbers mentioned here times whatever the grain abundance function returns.

If the **grains** command sets the abundance of a single grain species then the **function** option will only apply to that particular species. If the option occurs on a **grains** command that specifies more than one species of grains (as in the **ISM** keyword) then all species enabled by that command are affected. This is probably unphysical since small grains are easier to destroy than large grains. However, it is possible to define a different behavior of the grain abundance in routine *GrnVryDpth* for each individual grain size bin.

The code does not attempt to conserve the mass of the grain constituents. The gas-phase abundances are not automatically changed where the grain abundances are changed. This can be done by entering abundances with a depth-dependent table of abundances using the **elements read** command.

### 7.8.6 Line intensities with grains

Two sets of line intensities, the intrinsic and emergent spectra, are included in the main output. These differ in how the effects of extinction by continuous opacity source, especially, are treated. In general, the observed spectrum of an emission-line region containing dust depends on the geometry and the viewing angle.

*The intrinsic spectrum:* This is the spectrum produced within the cloud and does not include effects of dust that lies outside the line-forming region. Photon destruction by all background opacity sources (including grains) are always fully treated (i.e., [Hummer, 1968](#), [Kalkofen, W., 1987](#)), and the predicted intrinsic intensities always includes this destruction. These intensities *do not* include the reddening effects of any grains or other opacity sources that lie outside the line-forming region. For instance, this would not include the effects of grains in the PDR that lies outside the  $\text{H}^+$  region.

*The emergent spectrum:* In an open geometry this would be the spectrum if the geometry were observed from the illuminated face of the cloud. In this case it assumes that the ionized gas has a large molecular cloud behind the shielded face of the ionized gas and the effects of reflection from the molecular cloud are included. The emergent line intensities include contributions from absorption by grains, and reflection off the molecular cloud. In a closed geometry this would be the spectrum observed from outside the emission-line regions, looking through the cloud from its outermost layers.

It can be shown that the reddening or extinction across a photoionized  $\text{H}^+$  layer will always be small in the optical or IR (AGN3). Any reddening that does occur must happen in clouds outside the  $\text{H}^+$  region. The effects of grains external to the emission-line region are very geometry dependent. One approach is to correct the observed spectrum for reddening to obtain an intrinsic spectrum, and to then compare this intrinsic spectrum with that computed by the code.

These issues are discussed further in the section *Line intensities in a dusty open geometry*, in the chapter *Observed Quantities*, in Part 2 of HAZY.

### 7.8.7 Extinction for point and extended sources

Grain extinction is given by the cross section [ $\text{cm}^2$ ] per H nucleon:  $\sigma = \kappa/n(\text{H})$ , where  $\kappa [\text{cm}^{-1}]$  is the opacity due to grains and  $n(\text{H})[\text{cm}^{-3}]$  is the local density of H in all forms. The opacity includes both absorption and scattering. The scattering opacity depends on the geometry of the absorbing cloud, as described next and in AGN3 section 7.3.

Light scattering off grains is not isotropic. The angular dependence is often approximated by the Henyey-Greenstein function. The scattering theory predicts the fraction of scatterings, given by the grain asymmetry factor  $g$ , that are “forward scattering”, that is, change the direction of the scattered photon by less than 90 degrees (i.e. into the forward  $2\pi$  sr). The asymmetry parameter  $g$  is defined as the average value of  $\cos(\theta)$ , where  $\theta$  is the angle between incident and scattered photon. So for isotropic scattering  $g = 0$ , while for strongly forward scattering,  $g$  will be close to 1.

Rather than the total scattering cross section  $\sigma_s$ , an effective scattering cross section  $\sigma_{scat} = (\sigma_s(1 - g))$  contributes to extinction for extended sources. This discounts light scattered into the forward  $2\pi$  sr. The asymmetry parameter  $g$  approaches unity at high energies, so that  $\sigma_{scat}$  becomes much less than  $\sigma_{abs}$ . For an extended source such as a diffuse cloud the loss of photons by small-angle scattering will be compensated by a similar gain of photons from rays that are nearly parallel, so that total opacity is  $\sigma_{abs} + \sigma_s(1 - g)$ . This is referred to as **extended source extinction** and would apply to a resolved H II region like the Orion Nebula.

For a point source such as a star even a small deflection of starlight by forward scattering removes light from the ray and so counts as extinction. In this case the total grain opacity is simply  $\sigma_{abs} + \sigma_s$ . This is referred to as the **point source extinction** and is the quantity measured in extinction studies of stars.

The code keeps track of both measures of extinction since a beam of light passing through an H II region is attenuated by the extended extinction while the observational stellar literature will quote a point source extinction.

### 7.8.8 Grains-related commands

A group of **no grain** commands turn off various physical processes.

There are several **save** commands that will output predicted properties of the grains.

**save grains** This command will give some additional information about the grain properties.

**save continuum** This produces files that include the infrared continuum emitted by the gas and grains.

**grain no heating or no cooling** The keyword **no heating** on the **grains** command will turn off heating of the gas by grain photoelectric emissions. The keyword **no cooling** will turn off all forms of cooling of the gas by collisions with the grains. Either violates energy conservation, of course.

**grains no reevaluate** The **no reevaluate** option on the **grains** command will speed up a calculation by not continuously reevaluating grain quantities. Roughly a 30% speedup can be achieved. This is potentially dangerous and can destabilize a solution and/or lead to wrong results. It should be used under certain experimental circumstances and not in a true simulation of a cloud.

**set nchrg** The grain charge distribution is resolved into the number of discrete integral charge states set by the **set nchrg** command. The default is two charge states. The population of each of charge state is determined self-consistently by solving the grain ionization-recombination balance equations as described in [van Hoof et al. \(2004\)](#).

**Forcing quantum heating on or off** By default, quantum (also called “stochastic” or “single-photon”) heating is included for size-resolved species when it is significant. [Guhathakurta and Draine \(1989\)](#) describe the formalism used here. The method was originally implemented by Kevin Volk and subsequently revised and generalized by Peter van Hoof. This is considered for all species except for the unresolved size distributions. To save time quantum heating is only treated when the grain cooling time is sufficiently short compared with the time between heating events. Quantum heating is considered for a given size bin if the ratio of the volume of the largest and the smallest grain in that particular bin is less than 100. This means that quantum heating is considered for all of our resolved distributions, as well as all single-sized grains, but not for unresolved distributions (except the unresolved AB08 distribution, where it *is* used by default).

In the zone printout an asterisk will appear next to the name of a grain if quantum heating is important.

The keyword **qheat** will force quantum heating to always be considered for species where it is important. This is the default for all resolved size distributions so this keyword is not needed. The keyword **no qheat** will disable quantum heating for an individual **grains** command. Grain species with quantum heating enabled and disabled can be mixed.

Quantum heating can be turned off for all species with the **no grain qheat** command described below.

## 7.8.9 Effects of grains

Grains have several effects on interstellar gas (see AGN3, Chapter 7). Refractory elements are depleted from the gas phase, thus removing coolants from the gas ([Kingdon et al., 1995](#)). Grains absorb the incident continuum and reradiate an infrared continuum ([Bottorff et al., 1998](#)). Higher-energy photons ionize the grains, establishing a net charge, and so affect the charge balance of the gas ([Baldwin et al., 1991](#)). Photoejection of electrons following absorption of a UV photon heats the gas. Grains surfaces are sites of important chemical reactions, atomic/ion charge transfer, and molecular freeze-out when temperatures become low. Grains are a net sink of free electrons in fully molecular regions—this greatly influences PDR models. Several processes partially couple the temperatures of the gas and dust ([van Hoof et al., 2004](#)).

The heating and cooling of the grains and gas are done self-consistently. Grains are heated by direct absorption of the incident continuum, by the line and continuum emission within the cloud, and by gas collisions. Grains cool by collisions with the gas, the thermionic effect, and by radiation. The balance between heating and cooling establishes the temperature for each grain size and type. Grains affect the gas temperature by heating, mainly by the grain photoelectric effect and the thermionic effect, and by cooling, mainly by free-particle capture onto the grain surface.

## 7.8.10 Grain-related quantities that are printed

Several quantities related to the grain properties are reported.

The chemical composition is reported as the calculation starts. This includes a block giving the abundances of the elements that are incorporated in grains. If the grain abundance varies with depth then this is for the conditions at the illuminated face. A typical printout appears as follows:

```

Grain Chemical Composition
C : -4.1243  O : -4.2374  Mg: -4.8394  Si: -4.8394  Fe: -4.8394

Number of grains per hydrogen
Carbonaceous: -7.144  Silicate: -7.418

```

After the calculation is complete there is a summary of some properties of the grains:

```
Average Grain Properties (over radius):
sil-a0slm01* sil-a0slm02* sil-a0slm03* sil-a0slm04* sil-a0slm05* sil-a0slm06* sil-a0slm07* sil-a0slm08* sil-a0slm09* sil-a0slm10
nd:          0          1          2          3          4          5          6          7          8          9
<Tgr>: 1.031e+02    9.156e+01    8.352e+01    7.854e+01    7.647e+01    7.556e+01    7.017e+01    6.218e+01    5.472e+01    4.989e+01
<Vel>: 1.620e+01    2.530e+02    5.102e+02    1.008e+03    1.908e+03    3.188e+03    4.218e+03    4.802e+03    5.183e+03    5.381e+03
<Pot>: 9.085e-01   -3.674e-01   -9.865e-01   -1.049e+00   -8.803e-01   -6.611e-01   -7.209e-01   -9.144e-01   -1.055e+00   -1.116e+00
<D/G>: 2.014e-05    2.969e-05    4.379e-05    6.464e-05    9.554e-05    1.416e-04    2.112e-04    3.186e-04    4.913e-04    3.264e-04

gra-a0glm01* gra-a0glm02* gra-a0glm03* gra-a0glm04* gra-a0glm05* gra-a0glm06* gra-a0glm07* gra-a0glm08* gra-a0glm09* gra-a0glm10
nd:          10         11         12         13         14         15         16         17         18         19
<Tgr>: 1.207e+02    9.886e+01    8.591e+01    8.088e+01    8.047e+01    7.164e+01    5.921e+01    4.733e+01    3.644e+01    3.030e+01
<Vel>: 2.500e+01    3.807e+02    9.346e+02    2.205e+03    4.155e+03    5.682e+03    6.422e+03    5.650e+03    5.099e+03    4.990e+03
<Pot>: 8.393e-01   -7.959e-01   -1.138e+00   -1.019e+00   -7.800e-01   -9.040e-01   -1.116e+00   -1.224e+00   -1.263e+00   -1.273e+00
<D/G>: 3.396e-05    3.691e-05    4.021e-05    4.401e-05    4.874e-05    5.554e-05    6.739e-05    9.234e-05    1.458e-04    6.589e-05
Dust to gas ratio (by mass): 2.374e-03, A(V)/N(H) (pnt):1.296e-022, (ext):8.245e-023, R:3.247e+000 AV(ext):7.158e-003 (pnt):1.125e-002
```

Finally, the **save grain abundances** command give the abundances as a function of depth.

## 7.9 Metals 0.05 [log, linear, grains; deplete]

This command multiplies the abundances of the entire mixture of metals (elements heavier than helium) by the scale factor entered on the line. This is useful when the effects of global enrichments or depletions of the elements are to be investigated. If the number is less than or equal to zero it is assumed to be the log of the scale factor and the linear scale factor if it is positive. The **linear** and **log** keywords force that interpretation of the number.

Combinations such as

```
abundances planetary nebula
metals 3
```

or

```
metals 3
abundances planetary nebula
```

would multiply the planetary nebula gas-phase abundances by three,<sup>4</sup> while

```
metals -10
```

would multiply the default solar mixture by  $10^{-10}$ .

### 7.9.1 Scaling grains and metals together

It seems likely that the grain to hydrogen ratio scales with the total gas-phase metallicity. The optional keyword **grains** on the **metals** command causes the grain abundance to also be scaled by the factor on the line. The basic assumption is that the grain to metals ratio does not depend on metallicity while the grain to gas (hydrogen) ratio depends linearly on the metallicity. It is still necessary to include grains with either the **grains** command or by specifying a chemical composition that contains grains (with the **abundances** command). The scale factor that appears on the **metals** command will further multiply the grain abundance specified on the **grains** command. That is, the combination

```
grains 0.5
metals and grains 0.5
```

<sup>4</sup>Limits to the ordering of the **abundances** and **metals** commands existed before version 72 but have been lifted.

(in any order) will result in a grain abundance that is a quarter of the default and a metallicity that is half of solar.

In the following example the ISM gas phase *and* grain abundances are each increased by a factor of two over their default values;

```
abundances ISM
metals and grains 2
```

### 7.9.2 Metals deplete—gas-phase depletion factors

It is possible to alter an existing set of abundances by depletion onto grains. In the ISM the observed depletion is a function of the gas density (Spitzer, 1985 models this), so there is not really a universal depletion pattern. A set of scale factors that are roughly those appropriate for relatively dense ISM gas ( $\sim 1 \text{ cm}^{-3}$ ) is built into the code. Table 7.7 lists the depletions that will be assumed if the keyword **deplete** occurs on the **metals** command but no numbers are on the line. These are loosely based on the depletions listed by Jenkins (1987) and Cowie and Songaila (1986). This table is obviously incomplete and I would appreciate learning of better references.

This command can be combined with commands that specify abundances and the **grains** command to specify an arbitrary set of grain and gas-phase abundances. Specifying grains by themselves (with the **grains** command) does not change the gas-phase abundances, which is not self-consistent. The code will complain if you do this, but still perform the simulation.

The following is an example of using the nova abundance mixture, depleting it with this command, and then setting ISM grains.

```
abundances nova
metals deplete
grains
```

These commands do not attempt to conserve mass. In particular, the grain mass will be less than the mass of depleted heavy elements because the nova mixture has enhanced CNO, while the ISM grains have only a corresponding solar depletion of missing material (see, however, Snow and Witt, 1996, who show that even this is not true).

Table 7.7: Depletions

	Depl	Reference
He	1.00	noble gas
Li	0.16	<a href="#">White, 1986</a>
Be	0.6	<a href="#">York et al., 1982</a>
B	0.13	<a href="#">Federman et al., 1993</a>
C	0.4	
N	1.	
O	0.6	
F	0.3	<a href="#">Snow and York, 1981</a>
Ne	1.0	noble gas
Na	0.2	
Mg	0.2	
Al	0.01	
Si	0.03	
P	0.25	<a href="#">Cardelli et al., 1991</a>
S	1.0	
Cl	0.4	
Ar	1.0	noble gas
K	0.3	<a href="#">Chaffee and White, 1982</a>
Ca	1(-4)	
Sc	5(-3)	<a href="#">Snow and Dodgen, 1980</a>
Ti	8(-3)	<a href="#">Crinklaw et al., 1994</a>
V	6(-3)	<a href="#">Cardelli, 1994</a>
Cr	6(-3)	<a href="#">Cardelli et al., 1991</a>
Mn	5(-2)	<a href="#">Cardelli et al., 1991</a>
Fe	1(-2)	
Co	1(-2)	
Ni	1(-2)	
Cu	0.1	<a href="#">Cardelli et al., 1991</a>
Zn	0.25	<a href="#">Cardelli et al., 1991</a>



# Chapter 8

## DENSITY LAWS

### 8.1 Overview

Hydrogen plays a fundamental role in any astrophysical plasma because of its large abundance. As a result the hydrogen density [ $\text{cm}^{-3}$ ] is a fundamental parameter. Commands that specify how the hydrogen density is set, and how it changes with radius or depth, are described in this section. Constant density is the default. In this case the total hydrogen density (the sum of the protons in atomic, ionic, and molecular form, given by the command **hden**) is kept constant. Many other density or pressure distributions can also be computed.

A cloud can be isobaric, maintain constant pressure, if the timescale for changes, for instance in the continuum source or the cooling time, is short compared with the dynamical or sound-crossing time  $t_d$

$$t_d = \frac{\Delta r}{c_s} [\text{s}] \quad (8.1)$$

where  $\Delta r$  is the cloud thickness and  $c_s$  is the sound speed (AGN3 eq 6.25)

$$c_s = \left( \frac{\gamma k T_0}{\mu_0 m_H} \right)^{\frac{1}{2}} [\text{cm s}^{-1}]. \quad (8.2)$$

### 8.2 Constant density, pressure, gas pressure

This command specifies how the density changes across the cloud. The **hden** command usually specifies the initial hydrogen density. Several commands determine how the density changes with radius. These are described next.

#### 8.2.1 Constant density

This is the default. The hydrogen density, the sum

$$n(\text{H}) = n(\text{H}^0) + n(\text{H}^+) + 2n(\text{H}_2) + \sum_{\text{other}} n(\text{H}_{\text{other}}) [\text{cm}^{-3}] \quad (8.3)$$

is kept constant. This is not quite an isochoric density law because the total particle density is not constant—the electron and molecular fractions can vary with depth. I prefer this type of model because the homology relations with the ionization parameter (Davidson, 1977) are preserved. The hydrogen nucleon density is set with the **hden** command.

### 8.2.2 Constant gas pressure [index = -1.1]

An isobaric density law is specified with this command. The gas pressure

$$P_{gas} = n_{tot} k T_e [\text{dyne cm}^{-2}] \quad (8.4)$$

where  $n_{tot}$  is the total particle density [ $\text{cm}^{-3}$ ], is kept constant. The optional index  $\alpha$  can be any value, positive or negative, and will force the pressure to change as a power-law of the radius;

$$P_{gas}(r) = P_0 \left( \frac{r}{r_0} \right)^\alpha [\text{dyne cm}^{-2}] \quad (8.5)$$

where  $P_0$  is the pressure at the illuminated face of the cloud.

### 8.2.3 Constant pressure [no continuum, no abort]

This holds the total pressure constant. This includes ram, magnetic, turbulent, particle, and radiation pressure. The equation of state, the relation between gas density, pressure, and temperature, is given by

$$\begin{aligned} P_{tot}(r) &= P_{tot}(r_0) + \int a_{rad} \rho dr + \int g \rho dr \\ &= P_{gas} + P_{ram} + P_{turb} + P_{mag} + P_{lines} + \Delta P_{rad} + \Delta P_{grav} \end{aligned} [\text{dyne cm}^{-2}] \quad (8.6)$$

where  $a_{rad}$  is the radiative acceleration [ $\text{cm s}^{-2}$ ] due to the attenuated incident continuum,  $g$  is the (negative) gravitational acceleration [ $\text{cm s}^{-2}$ ], and  $\rho$  is the gas density [ $\text{gm cm}^{-3}$ ].

$P_{gas} = n_{tot} k T_e$  is the thermal gas pressure. The ram pressure is  $P_{ram} = \rho u_{wind}^2$ , where  $u_{wind}$  is the flow velocity. This is only present for a wind geometry. The turbulent pressure is  $P_{turb} = \rho u_{turb}^2 / 2$ , where  $u_{turb}$  is the turbulent velocity set with the **turbulence** command. The magnetic pressure is  $P_{mag} = B^2 / 8\pi$ , where the magnetic field  $B$  is set with the **magnetic field** command. Both magnetic and turbulent pressures are zero by default. If either dominates the total pressure then the density will be nearly constant.

$P_{lines}$  is the nearly isotropic radiation pressure due to trapped emission lines (Ferland and Elitzur, 1984, and Elitzur and Ferland, 1986). CLOUDY will stop if the internal line radiation pressure builds up to more than half of the total pressure since such clouds would be unstable unless they are self-gravitating (Elitzur and Ferland, 1986). It is necessary to do at least a second iteration when radiation pressure is important since the total line optical depths must be known to compute line widths and level populations reliably. If more than one iteration is done then the radiation pressure will not be allowed to exceed the gas pressure on any except the last iteration. If the option **no abort** appears on the command line the code will never stop because of excessive radiation pressure. The radiation pressure is still computed and the simulation will probably become unstable when  $P_{lines} > P_{gas}$ .

When the outward force due to the attenuation of the incident radiation field and the inward force of gravity are balanced by the pressure gradient, the cloud will be in hydrostatic equilibrium (Ascasibar and Díaz, 2010). The required change to the total pressure is given by the integrals and referred to as  $\Delta P_{rad}$  and  $\Delta P_{grav}$ , respectively. The **no continuum** option will turn off the  $\Delta P_{rad}$  term. Gravity must be turned on separately using the **gravity** command described below.

### 8.2.4 Constant pressure set 6.5

The **set** option specifies the initial pressure. A number, the log of the pressure in ISM  $nT$  units ( $\text{K cm}^{-3}$ ), must appear.

An initial gas density must still be specified with one of the commands in this Chapter. This command works by first solving for the equilibrium temperature at the density that was specified. The density is then

changed, using a Newton-method solver, to have the pressure match that specified. The solver will raise or lower the density assuming that pressure and density are directly related to one another.

There are possible ambiguities in this solution since the same pressure can sometimes be achieved with more than one density. This is the well-known three-phase stability phenomenon ([Field et al., 1969](#)).

### 8.2.5 Constant pressure timescale = 2.3e9 s, alpha=-1

The pressure changes as a function of time. It is given by

$$P_o(t) = P_o(t_o) \left(1 + \frac{t}{t_{\text{scale}}}\right)^\alpha \text{ [dyne cm}^{-2}\text{]} \quad (8.7)$$

The timescale  $t_{\text{scale}}$  is the first number on the line and the power-law index  $\alpha$  is the second. Here  $P_o(t_o)$  is the static pressure evaluated at the illuminated face of the cloud.

### 8.2.6 The reset option

This changes the behavior of the **constant pressure** command. By default the gas pressure in the first zone is derived from the specified hydrogen density and the resulting kinetic temperature. The hydrogen density is the fundamental quantity. In later iterations the initial hydrogen density is kept constant but the kinetic temperature may change as details of the line radiative transfer change. The resulting gas pressure,  $\propto nT$ , may not have exactly the same value on successive iterations. The total pressure in constant pressure clouds will change slightly as a result. The change in the pressure is small, typically only a few percent.

The **reset** option tells the code to keep the total pressure at the illuminated face constant, from iteration to iteration, rather than the hydrogen density. The **reset** option works by allowing the gas density to change to try to match the total pressure found in previous iterations.

This changes the behavior of the **constant pressure** command. By default the gas pressure in the first zone is derived from the specified hydrogen density and the resulting kinetic temperature. The hydrogen density is the fundamental quantity. In later iterations the initial hydrogen density is kept constant but the kinetic temperature may change as details of the line radiative transfer change. The resulting gas pressure,  $\propto nT$ , may not have exactly the same value on successive iterations. The total pressure in constant pressure clouds will change slightly as a result. The change in the pressure is small, typically only a few percent.

The **reset** option tells the code to keep the total pressure at the illuminated face constant, from iteration to iteration, rather than the hydrogen density. The **reset** option works by allowing the gas density to change to try to match the total pressure found in previous iterations.

## 8.3 Gravity [options]

The **gravity** command tells the code to balance the gravitational acceleration by varying the total pressure as described in [Ascasibar and Díaz, 2010](#).

### 8.3.1 Gravity [spherical, plane-parallel]

One of the keywords **spherical** or **plane-parallel** must appear. Each of these commands specifies the symmetry of the mass distributions and activates self-gravitational pressure.

### 8.3.2 Gravity external [Mass = 10 $M_{\odot}$ , extent = 3 parsecs, powerlaw = -2]

Additional mass components can be specified by any number of these commands. The first number of represents the mass. The units depend upon the symmetry (which must be specified separately – see above). In the spherical case, this number represents the mass (in solar masses) of a pointlike star located at  $r = 0$ ; in the plane-parallel case, it corresponds to the surface density (in  $M_{\odot} \text{ pc}^{-2}$ ) of a uniform mass sheet at  $z = 0$ . The number is interpreted as linear unless the keyword **log** is specified. Two optional parameters are the physical extent of the mass component (in parsecs, linear unless **log** appears) and a power-law index. Together these specify the mass accumulation function

$$M_{\text{enclosed}} = M(r/r_0)^{\alpha}. \quad (8.8)$$

The last two parameters can be omitted from right to left. Point sources or infinitesimally thin sheets are the default. The default index is zero.

## 8.4 Dark [options]

This command provides a gravitational pressure term due to a dark-matter distribution. At present, there is only one option, a standard [Navarro et al. \(1996\)](#) (NFW) profile.

### 8.4.1 Dark NFW virial radius = 18 [characteristic radius = 17]

This command specifies an NFW profile uniquely specified by their virial and characteristic radii  $r_{200}$  and  $r_s$ , respectively. The second parameter can be omitted and has the default value  $r_s = r_{200}/10$ . Both parameters are interpreted as logarithms of distances in cm.

## 8.5 Dlaw [options]

An arbitrary density law, specified by the user, will be used. There are two forms of this command. It is possible to either edit the source to create a new routine that calculates the density at an arbitrary depth or to interpolate on a table of points.

If the density or density law is specified with both this command and others, such as **hden**, **constant pressure**, etc, only the last command will be honored.

It is possible to specify a change in densities so extreme that the code will have convergence problems. CLOUDY works by linearizing all equations. It is possible to specify a change in the density that is so extreme that conditions change too much for the solvers to converge. The code uses adaptive logic to adjust the zoning and should prevent this from happening but the heuristics may be fooled by drastic density laws. The code will generate a warning if the density does change by too much—if this happens the cure is to not use such large density contrasts.

### 8.5.1 dlaw p1, p2, p3...

This is the default form of the command. It passes the parameters on the command line to a user-provided function. There are up to ten parameters. A new function *fabden* must be written by the user and the version of *fabden* already in CLOUDY must be deleted. (The code will stop if the initial version of *fabden*

is not replaced.) CLOUDY will call *fabden* as needed to determine the density as a function of depth. The arguments of the function are the radius and the depth. Both are in centimeters and are double precision variables. The function must return the hydrogen density ( $\text{cm}^{-3}$ ) as a double precision variable. The code provided in the function must use the ten or fewer parameters in the structure *dlaw* to compute the density at the current position

The following is an example of a function in which the density is the product of the first number on the command line and the depth.

```
/*fabden called by dlaw command, returns density for any density law */
#include "cddefines.h"
#include "dlaw.h"
#include "fabden.h"

double fabden(double radius, double depth)
{
    return( depth*dlaw.DensityLaw[0] );
}
```

### 8.5.2 Dlaw wind

This sets up a density profile consistent with a steady-state wind and the continuity equation. The steady-state velocity profile is parametrized as in [Springmann \(1994\)](#):

$$v(r) = v_* + (v_\infty - v_0) \sqrt{\beta_1 x + (1 - \beta_1) x^{\beta_2}}. \quad (8.9)$$

where  $x \equiv 1 - r_*/r$  and we set  $r_*$  to the inner radius of the cloud (except that  $x$  has a minimum value 0.01 for computational stability). The mass loss rate into  $4\pi$  steradians ( $\dot{M}$ ) then allows the density via continuity:

$$n(r) = \dot{M} / (4\pi m_H \mu r^2 v(r)), \quad (8.10)$$

where  $\mu$  is the mean molecular weight of the gas. The parameters must be specified in this order:  $\dot{M}$ ,  $v_\infty$ ,  $\beta_2$ ,  $\beta_1$ ,  $v_0$ ,  $v_*$ . Only the first three are required.  $\dot{M}$  should be given as  $M_\odot \text{ yr}^{-1}$ . All velocities should be given as  $\text{km s}^{-1}$ . The final three may be omitted right to left and take default values  $\beta_1 = v_0 = v_* = 0$ . All values are interpreted as linear values.

This command sets the hydrogen density. This command is experimental.

### 8.5.3 Dlaw table [depth, radius]

If the keyword **table** appears on the **dlaw** command then the code will read in a set of ordered pairs of radii and densities. The original form of this option was added by Kevin Volk. There must be two numbers per line as in the example below. The first number is the log of the radius or depth [cm] and is followed by the log of the hydrogen density [ $\text{cm}^{-3}$ ]. If the keyword **depth** also appears on the command line then the first number is interpreted as the log of the depth from the illuminated face and the table must begin with a depth smaller than  $10^{-30}$  cm, the first point where the depth is evaluated. The first number is interpreted as the log of the radius if **depth** does not appear. The ordered pairs end with a line with the keyword **end** in columns 1 through 3. Up to 500 pairs may be entered.

Linear interpolation in log-log space is done. The following is an example.

```

dlaw table depth
continue -35 4
continue 12 4
continue 13 5
continue 14 6
continue 15 7
end of dlaw

```

Be sure that the first and last radii or depths extend beyond the computed geometry—this law is only be used for interpolation and the code will stop if extrapolation is necessary. Note that the first depth must be smaller than  $10^{-30}$  cm, and also that there must not be a space in the first column of any lines with numbers—the code will think that an end of file has been reached. Alphabetic characters can be placed anywhere on the line and will be ignored—I placed the word **continue** in the first four columns for this reason (it is actually totally ignored).

## 8.6 Fluctuations density period ...

This specifies a density that varies as a sine wave. It was introduced to investigate the effects of inhomogeneities upon the emission-line spectrum (see [Mihalzki and Ferland, 1983](#); [Kingdon and Ferland, 1995](#)). The first number is the log of the period  $P$  of the sine wave in centimeters. The second two numbers are the logs of the largest and smallest hydrogen densities over the sine wave. Order is important here. The last optional number is a phase shift  $\phi$  (in radians) which allows the initial zone to occur at any part of the sine wave. If it is omitted the calculation will begin at the maximum density. If the phase is set to  $\pi$  the calculation will start at the minimum density.

The density is scaled according to the relation

$$n(r) = \left( \frac{n_{\max} - n_{\min}}{2} \right) \times \cos \left( \Delta r \frac{2\pi}{P} + \phi \right) + \left( \frac{n_{\max} + n_{\min}}{2} \right) [\text{cm}^{-3}] \quad (8.11)$$

where  $n_{\max}$  and  $n_{\min}$  are the maximum and minimum densities and  $\Delta r$  is the depth into the cloud, measured from the illuminated face.

The simulation may result in a large number of zones since the code must spatially resolve the density fluctuations. The zone thickness is not allowed to exceed  $\sim 0.05$  of the period so that each cycle is divided into at least 20 zones. This may result in very long execution times. The total number of zones (this sets the code's execution time) will be at least 20 times the number of cycles over the nebula.

The keyword **column** will replace the depth variable in equation 8.11 with the total hydrogen column density. The period should then be the column density of one cycle. This will more evenly weight the final column density over low- and high-density gas.

The **fluctuations abundances** command proves a mechanism for varying the gas-phase abundances of the elements.

## 8.7 Globule [density =2, depth =16, power =2]

This produces a density law that would be appropriate for a power-law density gradient irradiated from the outside (see, for example, [Williams, 1992](#)). The total hydrogen density  $n(r)$  is given by

$$n(r) = n_o \left( \frac{R_{\text{scale depth}}}{R_{\text{scale depth}} - \Delta r} \right)^\alpha = n_o \left( 1 - \frac{\Delta r}{R_{\text{scale depth}}} \right)^{-\alpha} [\text{cm}^{-3}] \quad (8.12)$$

where  $n_o$  is the background density outside the cloud, with default value  $1 \text{ cm}^{-3}$ , and  $\Delta r$  is the depth into the cloud, measured from the illuminated face. The log of  $n_o$  is the optional first number on the command line. The variable  $R_{scale}$  depth is the scale depth for the cloud and has a default of one parsec,  $R_{scaledepth} = 3.086 \times 10^{18} \text{ cm}$ . Other scale depths are specified by the optional second parameter, which must be entered as a log of the scale depth in cm. The optional third argument is the index  $\alpha$ , which has the default<sup>1</sup>  $\alpha = 1$ . The arguments can be omitted from right to left.

## 8.8 hden 5.6, [proportional to R -2,...]

The first number is the log of the total (ionic, atomic, and molecular) hydrogen density at the illuminated face of the cloud. This is the sum

$$n(\text{H}) = n(\text{H}^0) + n(\text{H}^+) + 2n(\text{H}_2) + \sum_{\text{other}} n(\text{H}_{\text{other}}) [\text{cm}^{-3}]. \quad (8.13)$$

If the optional keyword **linear** appears then the number is the density itself and not its log.

For situations where the hydrogen atom is close to LTE and the gas is hot, there is a problem in defining the neutral hydrogen density because of the well-known divergence of the partition function, as discussed, for instance, by [Mihalas \(1978\)](#). The atomic hydrogen density is defined as the total population in all computed levels. In most circumstances, i.e.,  $n(\text{H}) \leq 10^{15} \text{ cm}^{-3}$  and  $T \leq 10^4 \text{ K}$ , the ambiguity is much less than 1%.

Several options are available to specify optional power-law dependencies on depth variables. These are described in the next sub-sections.

### 8.8.1 Power-law dependence on radius

The second (optional) number is the exponent for a power-law radial density dependence, as in the following example:

```
hden 9, power =-2
```

i.e.,

$$n(r) = n_o(r_o) \left( \frac{r}{r_o} \right)^\alpha [\text{cm}^{-3}]. \quad (8.14)$$

In this example  $n_o$ , the density at the illuminated face of the cloud, will be  $10^9 \text{ cm}^{-3}$ . The optional power law is relative to radius, the distance to the central object, not the depth into the cloud. If  $\alpha = -2$  then the density will be proportional to the inverse square of the radius. Both density and photon flux will fall off as an inverse square and the cloud will tend to have the same ionization parameter (and hence physical conditions) across the ionized zone.

### 8.8.2 Clouds extending to infinity

For an inverse-square density law there is a critical value of the number of ionizing photons emitted by the central object, corresponding to an ionization front at infinite radius;

$$Q_{\text{crit}}(\text{H}) = \alpha_B(T_e) n_o^2 4\pi r_o^3 [\text{s}^{-1}]. \quad (8.15)$$

<sup>1</sup>The default index was 2 for versions 89 and before.

A hydrogen ionization front will not be present and the model will extend to infinite radius when  $Q(\text{H}) \geq Q_{\text{crit}}(\text{H})$ . In this expression  $\alpha_B(\text{Te})$  is the hydrogen Case B recombination coefficient and  $n_o$  and  $r_o$  are the inner density and radius respectively. Generally, a hydrogen ionization front will not be present if the density falls off faster than an inverse square law, but rather the level of ionization will tend to *increase* with increasing radius. In either case, if a reasonable outer radius is not set, the calculation will extend to very large radii, an unphysically small density will result, and usually the code will crash due to floating point underflow, followed by division by zero. It is usually necessary to set an outer radius when the density falls off with an index  $\alpha \leq -2$ , since, for most circumstances, the cloud will remain hot and ionized to infinite radius and zero density.

### 8.8.3 Power-law dependence on depth

The density will depend on the depth into the cloud rather than the radius if both the optional exponent *and* the keyword **depth** appear:

```
hden 9, power ==-2, scale depth = 13
```

The density is given by

$$n(r) = n_o(r_o) \left( 1 + \frac{\Delta r}{R_{\text{scale}}} \right)^\alpha [\text{cm}^{-3}] \quad (8.16)$$

where  $R_{\text{scale}}$  is the scale depth and  $\Delta r$  is the depth. The log of  $R_{\text{scale}}$  [cm] is the third number on the line and must be set.

### 8.8.4 Power-law dependence on column density

The local hydrogen density will depend on the total hydrogen column density if both the optional exponent and the keyword **column** appear;

```
hden 9, power ==-2, scale column density = 21
```

Here the density is given by

$$n(r) = n_o(r_o) \left( 1 + \frac{N(\text{H})}{N(\text{H})_{\text{scale}}} \right)^\alpha [\text{cm}^{-3}] \quad (8.17)$$

where  $N(\text{H})$  is the total hydrogen column density [ $\text{cm}^{-2}$ ] from the illuminated face to the point in question, and  $N(\text{H})_{\text{scale}}$  [ $\text{cm}^{-2}$ ] is the scale column density. The log of  $N(\text{H})_{\text{scale}}$  is the third number.

# Chapter 9

## GEOMETRY

### 9.1 Overview

This section describes commands that determine the geometry of the emission-line region. Many of the quantities used below are defined in the section on geometry in the Chapter *DEFINITIONS*.

The geometry is always spherical but can be made effectively plane parallel by making the radius much greater than the thickness of the nebula. It is also possible to compute a model in which the emission-line region is almost a disk. A covering or filling factor can be specified and the cloud can be either static or expanding.

### 9.2 Age 44 years [off]

For an equilibrium geometry the code assumes that the cloud is old enough for atomic processes to have become time steady. The **age** command allows the code to confirm that the microphysics is indeed time steady. The age of the cloud is given on the command line. The default units are linear seconds. The keyword **log** will force the code to interpret the number as a log. The keywords **minutes**, **days**, **weeks**, **fortnights**, **months**, **years**, **centuries**, and **millennia** change the units.

The code keeps track of many timescales during a calculation. After the calculation is complete it will check that none of the equilibrium timescales for significant physical processes were longer than the age of the cloud. The code will complain if the age of the cloud is not set but still compute the model. If a physical process is not significant, for instance, the H<sub>2</sub> formation timescale in a highly-ionized gas, the age is set to a negative number. This retains the value while not including the process as a significant part of the physical simulation.

If the keyword **off** appears then the age will not be checked.

### 9.3 Aperture commands

#### 9.3.1 Aperture [slit, beam]

The **aperture** command simulates observing a part of the computed structure with a spectrometer. It was first incorporated into the code by Peter van Hoof who wrote the original version of this section.

One of the keywords **slit** or **beam** must appear. The keyword **beam** tells the code to simulate observing a resolved nebula with a small pencil beam centered very close to the central source. If the keyword **slit**

appears then the computed structure is simulated to be observed with a long slit that extends over the *entire* width of the nebula, also positioned very close to the center. In the long slit case, it is assumed that the observer has added up all the flux from the source over the full length of the slit. It is not now possible to simulate an off-axis long slit or pencil beam.

The **aperture** command only affects how volume emissivities are added together to form the final line spectrum printed in the main CLOUDY output and saved with the **save lines** command. When optimizing line fluxes, or line flux ratios, the quantities observed through the aperture will be used. This command has no effect on any aspect of the calculation of conditions in the gas. It also does *not* affect the spectral energy distribution predicted with the **save continuum** commands. This will always be integrated over the entire nebula.

This command only affects the line luminosities in the luminosity case. When the intensity case is used and the inner radius is not specified all integrations are for a pencil beam through a plane-parallel slab.

In the following a quantity  $\alpha$  is defined with the following meaning:  $\alpha = 0$  in the pencil beam case (we are observing along a single line of sight passing through the center of the nebula),  $\alpha = 1$  in the long-slit case (we are observing through a narrow slit placed over the center of the nebula; the slit is longer than the nebula and the flux is integrated over the entire slit), and  $\alpha = 2$  in the general case (we are observing the flux integrated over the entire nebula). The default index is  $\alpha = 2$ .

In all cases an observed quantity  $Q_\alpha$  can be defined for a line  $\lambda$  as

$$Q_\alpha(\lambda) = C_\alpha D_\alpha \int \left( \frac{r}{r_0} \right)^\alpha \varepsilon(\lambda) dr, \quad (9.1)$$

where  $\varepsilon(\lambda)$  is the line's volume emissivity [ $\text{erg cm}^{-3}\text{s}^{-1}$ ] and

$$\begin{aligned} C_0 &= 2 \\ C_1 &= 2\pi r_0, \\ C_2 &= 4\pi r_0^2 \end{aligned} \quad (9.2)$$

where  $r_0$  is the inner radius of the nebula. The covering factor  $D_\alpha$  depends on the geometry and is

$$\begin{aligned} D_0 &= 1/2, \quad 1 \\ D_1 &= \Theta/2\pi \quad . \\ D_2 &= \Omega/4\pi \end{aligned} \quad (9.3)$$

For the entire nebula ( $\alpha = 2$ ) this is the familiar definition (see also Sect. 9.5). In the long slit case ( $\alpha = 1$ ),  $D_1$  is the fraction of a large circle in the plane that is being observed that actually passes through nebular material. In the pencil beam case ( $\alpha = 0$ ),  $D_0$  indicates whether only the front or back side of the line of sight is covered with nebular material ( $D_0 = 1/2$ ) or if both sides are covered ( $D_0 = 1$ ). The covering factor for the entire nebula is set with the **covering factor** command. This is the quantity  $D_2$ . You can set the quantities  $D_0$  or  $D_1$  using the **aperture covering factor** command described below.

In the luminosity case  $Q_\alpha$  will have units  $\text{erg s}^{-1}$  for the entire nebula,  $\text{erg cm}^{-1} \text{s}^{-1}$  for the long slit case, and  $\text{erg cm}^{-2} \text{s}^{-1}$  for the pencil beam. In the intensity case the units are  $\text{erg cm}^{-2} \text{s}^{-1}$ . The luminosity and intensity cases are defined on page 11.

$Q_\alpha$  is the quantity printed in the main CLOUDY output and by the **save lines** command in the default setup. However, if the distance to the object is set with the **distance** command, we can convert this quantity into an observed flux at Earth. In the luminosity case we can construct the following relations between observed quantities and the quantities predicted by the code. These neglect interstellar extinction of course. The flux measured at the Earth will be

$$F_\alpha(\lambda) = \frac{A_\alpha}{4\pi D^2} Q_\alpha(\lambda) [\text{erg cm}^{-2}\text{s}^{-1}], \quad (9.4)$$

with

$$\begin{aligned} A_0 &= \Omega_b D^2 \\ A_1 &= \Theta_s D \\ A_2 &= 1 \end{aligned} \quad (9.5)$$

Here  $F_\alpha$  is the observed flux [ $\text{erg cm}^{-2} \text{s}^{-1}$ ]  $D$  is the distance of the object [cm], as specified with the **distance** command,  $\Theta_s$  is the slit width [radian], and  $\Omega_b$  is the surface area of the pencil beam [sr].

If the **print line flux at Earth** command is used, then CLOUDY will do this conversion for you and  $F_\alpha$  will be reported in the main CLOUDY output as well as the **save lines** output.  $F_\alpha$  will then also be used when optimizing line fluxes. You can set the value of  $\Theta_s$  or  $\Omega_b$  with the **aperture size** command described below.

In the intensity case (the intensity case implies  $\alpha = 0$ ) the relation between the observed surface brightness  $S(\lambda)$  and  $Q_o(\lambda)$  is simply:

$$S(\lambda) = \frac{\Omega (1 \text{ arcsec}^2)}{4\pi} Q_0(\lambda) \approx 1.87043 \times 10^{-12} Q_0(\lambda) [\text{erg cm}^{-2} \text{s}^{-1} \text{arcsec}^{-2}]. \quad (9.6)$$

### 9.3.2 Aperture size 2.5

This command should be used in conjunction with the **aperture [slit, beam]** and **print line flux at Earth** commands. It will have no effect otherwise. It allows you to set the slit width [arcsec] or the surface area of the pencil beam [ $\text{arcsec}^2$ ]. These are the quantities  $\Theta_s$  and  $\Omega_b$  used in Eq. 9.5. The quantity entered will always be treated as a linear quantity. If this command is not used, the code will assume a default slit width of 1 arcsec, or a beam area of 1  $\text{arcsec}^2$ .

### 9.3.3 Aperture covering factor 0.6

This command should be used in conjunction with the **aperture [slit, beam]** command. It allows you to set the quantity  $D_\alpha$  defined in Eq. 9.3. A single number should appear on the command line which should be between 0 and 1. The default value is 1.

## 9.4 Clumping factor = 0.05 [index = -1]

This is another name for the **filling factor** command described on page 91. It takes the same options, and includes the same physics, as described there.

## 9.5 Covering factor 0.3

This sets a covering factor  $\Omega/4\pi$  for the emission-line region (see AGN3 section 5.9). The argument is the log of the covering factor if less than or equal to zero and the linear covering factor if positive. It is impossible to specify a covering factor of zero.

The covering factor affects both the luminosity of the emitted spectrum and the radiative transfer of lines and continua. If a covering factor is set and the luminosity case used then the luminosities will be for a shell covering  $\Omega$  sr of the central object. Line luminosities will scale nearly linearly with the covering factor. The covering factor does not strongly affect the line intensities in the intensity case, where the emission per unit area of cloud is considered. The covering factor does have second-order effects on the spectrum because of changes in the transport of the diffuse radiation fields.

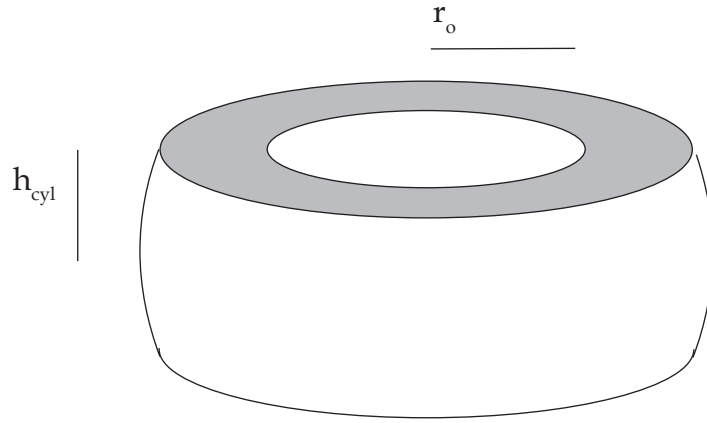


Figure 9.1: This figure shows the geometry assumed when the **cylinder** command is used.

This covering factor is referred to as the geometric covering factor, and is stored as the variable *covgeo*. A second covering factor, *covrt*, affects the transfer of lines and continua. This command sets both covering factors.

If no covering factor is entered and **sphere** is not set then the default is for a geometric covering factor of unity (the shell fully covers the continuum source) but a radiative covering factor of zero (i.e., an open geometry).

## 9.6 Cylinder log semi height =9.12

The model will be spherical, but truncated so as to simulate a cylinder (see [Ferland et al., 1982](#)). Figure 9.1 gives an example of the assumed geometry.

The inner and outer radii of the cylinder are set by the **radius** command. The **cylinder** command sets the full height of the cylinder to twice the number entered on the command. The argument is the log of the semi-height in cm.

The effective volume element used to compute the emissivity of the gas is given by

$$dV = 4\pi r_o^2 \left( \frac{r}{r_o} \right) \left( \frac{\min(r, h_{cyl})}{r_o} \right) f(r) dr [\text{cm}^3] \quad (9.7)$$

where  $r_o$  is the inner radius,  $h_{cyl}$  is the cylinder half-height, and  $f(r)$  is the filling factor. The default value is  $h_{cyl} = 10^{35}$  cm.

Changing the emissivity as described by equation 9.7 is the only effect of this command. It does not alter the radiative transfer methods and is only formally correct when the continua and lines are optically thin.

When combined with the **aperture slit** command, it will be assumed that the slit is oriented along the rotational axis of the cylinder. If the slit is oriented at an angle, you can model this geometry by dividing the height of the cylinder by the cosine of the angle. If the slit is perpendicular to the rotational axis you can simply omit the cylinder command since it will have no effect on the predicted spectrum.

## 9.7 Distance 3.2 linear parsecs

This sets the distance to the object from the Earth. The number is the log of the distance in centimeters. The **linear** keyword forces the number to be interpreted as the linear distance and the **parsecs** keyword changes the units to parsecs.

If the distance is set then it is possible to predict the emission-line fluxes observed at Earth if the luminosity case is computed. If the distance is set with this command then the observed emission-line fluxes at the Earth will be printed if the **print line flux** command is also entered.

This command can be combined with the **aperture** command to simulate observing parts of a nebula from the Earth.

## 9.8 Filling factor = 0.05 [index =-1]

The first number is the filling factor  $f(r)$  for a clumpy model (AGN3 Section 5.9). It can be either the filling factor itself (which is greater than zero and less than or equal to one) or the log of the filling factor (if it is less than or equal to zero). The second optional number is the index for a power-law variation of the filling factor  $f(r)$ , i.e.,

$$f(r) = f(r_0) \left( \frac{r}{r_0} \right)^\alpha \quad (9.8)$$

where  $r_0$  is the inner radius of the cloud.

The filling factor is used in two ways. The first is to modify the volume emissivity of the gas,

$$dE = \epsilon f(r) dV \frac{\Omega}{4\pi} [\text{erg s}^{-1}] \quad (9.9)$$

where  $\Omega/4\pi$  is the covering factor. The second is to modify the optical depth scale

$$d\tau = \alpha_{l,u} \left( n_l - n_u \frac{g_l}{g_u} \right) f(r) dr \quad (9.10)$$

(see [Osterbrock and Flather, 1959](#)).

A filling factor greater than unity is not allowed. CLOUDY will set a filling factor of unity if a value greater than one is entered. The code will complain (but compute the model) if a filling factor is set in a constant pressure model since this makes no physical sense.

## 9.9 Illumination angle 45 deg [radians]

The plane-parallel slab is illuminated by a beam  $\theta$  away from the normal. The default is  $\theta = 0$  (normal illumination). The angle is in degrees unless the keyword **radian** appears.

The only effect of this command is to cause the beam of incident radiation to be attenuated by  $\tau n / \cos(\theta)$  where  $\tau n$  is the normal optical depth of the zone. The line and diffuse continua optical depth scale, which is defined normal to the plane, are not directly affected by this command.

*N.B.* If this is used with the **grid** or **vary** options the angle must be given in radians. See the discussion of the commands with a **vary** option.

## 9.10 Radius **r(inner)** [**r(outer)**, **thickness**; **parsec**; **linear**]

The first number is the log of the inner radius. The second optional number sets a stopping radius and is either the log of the outer radius (if it is larger than the first number) or the log of the thickness of the cloud (if it is less than or equal to the first number).

The numbers are normally interpreted as the log of the radii in cm. If the optional keyword **linear** appears then the numbers are interpreted as linear numbers. The default units are centimeters. The arguments will be interpreted as the log of the radii in parsecs if the keyword **parsec** appears. Arguments will be interpreted as linear parsecs if both keywords appear. The following gives examples of its use.

```
radius 19.5          // log of inner radius in cm
radius 19.5 18.5     // as above, but a thickness of 3x10^18 cm
radius 19.5 20       // inner radius as above, outer radius 10^20 cm
radius 100 linear    // inner radius of 100 cm
radius 0 parsecs     // log of radius in parsecs, so inner radius 1 pc
radius 1 to 3 linear parsecs // inner radius 1 pc, outer 3 pc
```

The default outer radius is effectively infinite (actually  $10^{31}$  cm). If the intensity case is used then a starting radius of  $10^{30}$  cm will be set by default. Under most circumstances this will result in a plane-parallel geometry.

Page 209 describes a problem that can occur if the second parameter is used with the **vary** option. Please read it if you will vary the radius with the outer radius set. The **stop thickness** command provides a way to set a stopping thickness without specifying a starting radius.

## 9.11 Sphere [options]

CLOUDY normally assumes an open geometry, i.e., that the gas covering factor is small. The **sphere** command<sup>1 2</sup> should be included to change this assumption for a closed geometry, one where the covering factor of the gas is large and the model spherical. This command tells CLOUDY to take into account ionization by the diffuse continua and lines produced in the far side of the nebula (i.e., from beyond the central object), and not to attenuate the ionizing continuum by pure scattering opacities, such as electron scattering, back scattering by grains, or Rayleigh scattering.

This option should be set when the geometry is spherical and gas nearly fully covers the continuum source. It should not be set when the covering factor is small so that emission from a cloud is unlikely to encounter another cloud. This latter case is the default. In the language of Van Blerkom and Hummer (1967), **sphere** causes CLOUDY to assume the symmetric case (their equation 2.14), rather than the default zero case (their equation 2.13) for diffuse continua. Here these are referred to as closed and open geometries, respectively.

Situations can occur where it is not obvious whether or not **sphere** should be used. In this case it would be best to compute models with and without **sphere** and compare results. In most cases this will only make a 10–15% difference in predicted quantities.

<sup>1</sup>The **slit** and **beam** options were recognized by the **sphere** command before version 96. These options were moved to the **aperture** command which was introduced in version 96.

<sup>2</sup>Before version 96 the **sphere** command included an option to change the covering factor. The covering factor was removed from the **sphere** command. Only the **covering factor** command changes the covering factor.

### 9.11.1 Sphere expanding or static

Two optional keywords, **expanding** and **static**, determine how line transfer is handled. If **expanding** (the default when **sphere** is entered) is set then CLOUDY assumes that line photons escaping from the illuminated face of the cloud are Doppler shifted away from lines of absorbing material on the far side of the shell. This will be the case if the expansion velocity exceeds the Doppler width by large amounts. If **static** is set then line photons do interact on both sides so that even line photons produced at the illuminated face of the cloud will be strongly trapped by material on the far side.  $L\alpha$  radiation pressure in the  $H^+$  region will probably be significant if **sphere static** is set and grains are not present.

It is necessary to iterate at least one time when the **static** option is used since the total line optical depths are not known on the first iteration. All optical depths are determined self-consistently on second and further iterations.

The specific effects of **sphere** are the following: The total continuous optical depths are assumed to be twice the computed optical depths, and the initial optical depth is half the total. All diffuse reemission (bremsstrahlung, free-bound, etc.) is counted in the outward beam rather than only half. Scattering opacities are not considered in the attenuation of the incident radiation field. When **static** is set, the optical depth in  $L\alpha$  in the inner direction is set to  $10^5$  on the first iteration. Otherwise it is  $10^{-20}$ . The total optical depths of lines are twice their computed depth for the static case. Finally, ionization by lines and continua produced in the far side of the nebula is included. At the end of the iteration all inward optical depths are set to half of the total value computed from the previous iteration.

## 9.12 Stop depth...

## 9.13 Stop thickness...

The **stop depth** and **stop thickness** commands provide methods to set the thickness of a cloud without specifying its radius. They are described in other sections.



# Chapter 10

## OPTICAL DEPTHS AND RADIATIVE TRANSFER

### 10.1 Overview

Line transfer is relatively unimportant in low-density clouds such as H II regions and planetary nebulae. Radiative transfer can be important in other environments, such as nova shells and the broad-line region of active nuclei, where excited states of hydrogen have significant populations and subordinate lines become optically thick. In other cases grains are present and all lines can be absorbed by background opacity. All radiative transfer effects are included in the treatment of line formation, including line thermalization, destruction by background opacities, pumping by the incident continuum, and escape from the cloud.

It is necessary to iterate upon the solution if emission lines are optically thick since total optical depths are not known on the first iteration. The default is for a single iteration. This is often adequate for low-density nebulae such as planetary nebulae or H II regions. A second iteration is sometimes enough to establish a fairly accurate line optical depth scale for many resonance transitions. Further iterations are usually needed when subordinate lines are also optically thick. The **iterate to convergence** command will iterate until the optical-depth scale is well defined.

Line-radiation pressure cannot be computed accurately until the total line optical depths are known, so this quantity is only meaningful after the first iteration. CLOUDY will stop if the internal radiation pressure exceeds half of the surface gas pressure in a constant-pressure model since such a geometry is unstable unless it is self-gravitating. The radiation pressure is not allowed to exceed half the gas pressure on the initial iterations of a multi-iteration constant-pressure model. This is to prevent the calculation from stopping when the optical depth scale is not yet well converged.

The following sections outline various commands that affect the radiative transfer.

### 10.2 Case A [options]

This has the same options as the Case B command but sets the  $L\alpha$  optical depth to a very small value by default. This does not turn off induced processes, which are normally ignored when Case A is assumed. You would use the **no induced processes** command to do that.

### 10.3 Case B [ $\tau_{\text{Ly}\alpha} = 9$ ; options]

This command is used to check the line emission from the hydrogen and helium atoms in the Case B limit (AGN3 section 4.2). This command *should not* be used in any model that is supposed to represent a real physical environment. It is intended only to provide an easy way to check predictions of the code against simple, more limited, calculations. In particular, when this is used the Lyman-line optical depths will be made artificially large. This may affect the ionization and temperature of the gas.

With no options this command sets the inner optical depth of  $\text{Ly}\alpha$  for all atoms and ions of the H- and He-like iso-electronic sequences to  $10^5$  so that even a one-zone model will be close to Case B.<sup>1</sup> The optional number is the log of the  $\text{Ly}\alpha$  optical depth. One-sided escape probabilities are used so the total escape probability is simply that for the inward direction. In keeping with the Case B approximation the **Case B** command suppresses excited-state line optical depths.

The atoms include all collisional processes. Case B does not define the population of the ground or first excited state so a true comparison with Case B results should have collisions from these levels turned off. This is done with the Hummer and Storey option (with the key **hum**), to allow comparison with their 1987 and 1995 papers. Collisions from the ground and first excited states *are* included if this second option is not specified. Collisions between levels with  $n \geq 3$  *are* included unless the **atom H-like collision off** or **atom He-like collision off** commands are given. Collisions between the 2s and 2p levels are always included unless the **atom H-like collisions 2s2p off** command is given.

In the case of the He-like isoelectronic sequence the **Case B** command sets the optical depths in the singlet Lyman lines to a large value. The Hummer & Storey option has no effect on the He-like sequence.

The **no Pdest** option turns off destruction of Lyman lines by background opacity.

There are several side effects of this command that may alter the spectrum or physical conditions in unexpected ways. The large  $\text{Ly}\alpha$  optical depth will often result in an especially strong radiation field within this line. This affects the gas through photoionization of excited metastable states of H and He and of those elements with a small enough ionization potential. The **no photoionization** option on the **Case B** command tells the code not to include photoionization from excited metastable states like the 2s level of  $\text{H}^0$ . But these strong diffuse fields will also strongly affect the level of ionization of the gas, making the resulting ionization equilibrium a fiction. Optically thin gas is actually described by Case C (Ferland, 1999b, Luridiana et al., 2009 and AGN3 Section 11.4) where continuum pumping enhances Balmer lines. The large Lyman-line optical depths that result from the **Case B** command will prevent continuum resonant pumping of the atom. Beware.

This command is used in the test suite to perform classical PDR simulations which ignore the  $\text{H}^+$  region and assume that the PDR is illuminated by a radiation field with no hydrogen-ionizing radiation. Classical PDR calculations do not include a full treatment of H or He so their ions are only produced by cosmic rays. CLOUDY does a full treatment of the physics of  $\text{H}^0$  and  $\text{He}^0$  and will find a thin layer of highly ionized gas. This is produced by Lyman-line pumping into excited states, especially metastable 2s, which are then photoionized by relatively low-energy light. The process stops when the Lyman line optical depths become large enough for the atom to become self-shielding. The **Case B** command will stop this process from ever becoming important by starting with large Lyman line optical depths. (The process would not happen in a realistic calculation which included the  $\text{H}^+$  region since Lyman line optical depths through the  $\text{H}^+$  region are large.)

This command is included in the “homework problem” PDR simulations in the test suite to stop Lyman line pumping from occurring. A better solution would be to include the PDR as an additional layer outside the  $\text{H}^+$  region. The Lyman line optical depths across the ionized gas will be large and prevent continuum

<sup>1</sup>Before version 96 the default optical depth was  $10^9$ . This caused extreme  $\text{Ly}\alpha$  behavior in a grain-free H II region. The lower value is a better estimate of the physics that occurs in an actual H II region.

pumping from occurring in the PDR. Combining the H II region and PDR also results in a self-consistent calculation ([Abel et al., 2005](#) and [Abel et al., 2008](#)).

## 10.4 Case C [options]

This has the same options as the Case B command but sets the  $L\alpha$  optical depth to a very small value by default. Case C is described by [Ferland \(1999b\)](#) and [Luridiana et al. \(2009\)](#).

## 10.5 Diffuse fields [outward, OTS]

This specifies which method is to be used to transfer the diffuse fields, the emission from gas within the computed structure. The options are **outward only** and **OTS**.

The **OTS** option takes into account optical depths in both the inward and outward directions. The **OTS** option has a **SIMPLE** option which will do a very simple OTS approximation without taking optical depths into account. All diffuse fields with energies capable of ionizing hydrogen are assumed to do so, and those with smaller energies freely escape. This is intended as a debugging tool.

If **outward** is chosen then the code will check for a number. This determines which of the many forms of the outward-only approximation ([Tarter, 1967](#)) is used. The default<sup>2</sup> is 2. This is intended for testing the code.

This choice does not strongly affect the predicted emission-line spectrum but it does change the temperature at the illuminated face of the cloud.

## 10.6 Double optical depths

On second and later iterations the code uses the total optical depths of the computed structure to find the outwardly-directed radiation field. This command doubles the total optical depth so that the shielded face of the cloud becomes the mid-plane of a structure that is twice as thick as the computed cloud.

This original purpose of this command was to simulate a geometry in which ionizing radiation strikes the plane-parallel cloud from both sides. Examples are a  $L\alpha$  forest cloud or the diffuse ISM. The total line and continuum optical depths are set to twice the computed optical depth at the end of the iteration. The computed model is then one half of the cloud and the other half of the cloud is assumed to be a mirror image of the first half. Doubling the total line and continuum optical depths at the end of the iteration is the *only* effect of this command. Physical quantities such as the physical thickness, column densities, or line emission *are not* affected.

This approximation makes sense if the cloud is optically thick in lines but optically thin (or nearly so) in continua. Lines such as the  $L\alpha$  transitions of He I and He II can be important sources of ionizing radiation. Their transport will be handled correctly in this limit when this command is used. Continuum transport out of the cloud will also be treated correctly, but attenuation of the incident continuum will *not* be if the cloud is optically thick in the continuum.

The second use of this command is when the outer edge of a computed structure is not the other edge of the cloud. A typical PDR calculation is an example. The calculation starts at the illuminated face and continues until the gas becomes cool and molecular. The stopping point often does not correspond to the outer boundary of the molecular cloud, but rather is a point that is “deep enough” for a given study. The optical depths are always computed self-consistently. On second and later iterations the total optical depths

<sup>2</sup>OTS was the default in version 86 and before.

are normally those of the computed structure. Near the shielded face the outward optical depths will be small and radiation will freely escape in the outward direction. The gas temperature may fall dramatically due to the enhanced cooling resulting from the free escape of line photons. In real PDRs considerable neutral or molecular material probably extends beyond the stopping point so that line photons do not freely escape. The shielding effects of this unmodeled extra material can be included with this command. Then, the shielded face of the cloud will correspond to the mid-plane of the overall structure and lines will not artificially radiate freely into the outer (unmodeled) hemisphere.

## 10.7 Iterate [2 times]

This specifies the number of iterations to be performed. The default is a single iteration, a single pass through the model. At least a second iteration should be performed in order to establish the correct total optical depth scale when line transfer or radiation pressure is important. Two iterations are sometimes sufficient and will be done if no numbers are entered on the command line. A comment will be printed after the last iteration if the total optical depth scale has not converged and further iterations are needed.

### 10.7.1 Number of iterations

There is a slight inconsistency in how the code counts the number of iterations. The way it functions in practice is what makes the most sense to me.

The word *iterate* is from Latin for “again.” So the true number of “agains” should be one less than the total number of calculations of the cloud structure. When the **iterate** command is not entered there is one calculation of the structure and so formally no iterations. If any one of the following commands is entered:

```
iterate
iterate 0
iterate 1
iterate 2
```

then exactly two calculations of the structure will be done. If the number on the line is two or greater, then the number will be the total number of calculations of the structure.

### 10.7.2 Iterate to convergence [max =7, error =.05]

This is a special form of the **iterate** command in which the code will continue to iterate until the optical depths have converged or a limit to the number of iterations has been reached. The optional first number on the line is the maximum number of iterations to perform with a default of 10. The second optional number is the convergence criterion. The default is for relative optical depths to have changed by less than 0.20 between the last two iterations. The optional numbers may be omitted from right to left. If all transitions are optically thin then only a second iteration is performed.

### 10.7.3 Convergence problems

The code generally will not converge if it has not done so within ten or so iterations. The most common reason for convergence problems is that the specified column density or thickness causes the simulation to end very near a prominent ionization front. In this case very small changes in the physical conditions result in large changes in the optical depths. This is a physical, not numerical, problem. The code will not have convergence problems if an optical depth is used as a stopping criterion instead.

## 10.8 No scattering opacity

This turns off several pure scattering opacities. These include scattering by grains, electron scattering, and the extreme damping wings of Lyman lines (Rayleigh scattering). When scattering opacity is included and an open geometry is computed the scattering opacity is assumed to attenuate the incident radiation field as  $(1 + 0.5 \tau_{scat})^{-1}$  rather than  $\exp(-\tau)$  (Schuster, 1905).

Scattering can be neglected in a spherical geometry with gas fully covering the source of ionizing radiation. Scattered photons are not really lost but continue to diffuse out with (perhaps) a slight shift in energy. Electron scattering is generally the most important scattering opacity in a grain-free mixture. If  $\tau_{scat} \leq 1$  then it is reasonable to consider electron scattering as a heating and cooling process but not as an absorption mechanism if the energy shifts are not large (i.e.,  $h\nu \ll mc^2$ ) and the geometry is spherical (this is not correct for  $\gamma$ -ray energies, of course). CLOUDY is not now designed to work in environments that are quite Compton thick, but should work well for clouds where the electron scattering optical depths are less than or of order unity.

When this command is entered scattering processes such as Compton energy exchange and grain scattering are still included as heating, cooling, and ionization processes, but not as extinction sources. (Thermal and ionization effects of Compton scattering are turned off with the **no Compton** command). The **no scattering opacity** command is automatically generated when **sphere** is specified.

## 10.9 Turbulence = 100 km/s [log, dissipate]

This enters a microturbulent velocity  $u_{turb}$ . The velocity is given in  $\text{km s}^{-1}$  on the command line although the code works with  $\text{cm s}^{-1}$  internally. The turbulent line width  $u_{turb}$  is zero by default, but the value that is entered must be  $u_{turb} \geq 0$ . If the optional keyword **log** appears then the number is interpreted as the log of the turbulence. Alternatively, you can also enter the keyword **equipartition** which is discussed further below.

Turbulent pressure is included in the equation of state when the total pressure is computed.<sup>3</sup> The **no pressure** option on this command says not to include turbulent pressure in the total pressure.

Turbulence affects the shielding and pumping of lines. Fluorescent excitation of lines becomes increasingly important for larger turbulent line widths since a larger part of the continuum can be absorbed by a line. Line pumping is included as a general excitation mechanism for all lines using the formalism outlined by Ferland (1992) and described further in a section of Part 3. The line-center optical depth varies inversely with the line width velocity  $u$  so the effects of line optical depths and trapping become smaller with increasing line width. Larger  $u$  inhibits self-shielding.

### 10.9.1 Definitions

The Doppler width of any line that is broadened by both thermal motions and turbulence that is given by a Gaussian is given by the quadratic sums of the thermal and turbulent parts,

$$u = \sqrt{u_{th}^2 + u_{turb}^2} = b = \sqrt{2}\sigma \text{ [cm s}^{-1}\text{]}. \quad (10.1)$$

Here  $b$  is the Doppler parameter used in much of the UV absorption-line literature,  $\sigma$  is the standard deviation (often called the dispersion) for a normal distribution, and  $\sigma^2$  is the variance. For a thermal

<sup>3</sup>Turbulence was not included as a pressure term in versions 06.02 and before.

distribution of motions the average velocity along the line of sight (Mihalas, 1978, equation 9-35, page 250) and the most probable speed (Novotny, 1973, p 122) of a particle with mass  $m$  are both given by

$$u_{th} = \sqrt{2kT/m} \text{ [cm s}^{-1}\text{]}. \quad (10.2)$$

This command sets  $u_{turb}$ . Note that with these definitions the full-width half-maximum (FWHM) of a line is equal to

$$u(FWHM) = u\sqrt{4\ln 2} \text{ [cm s}^{-1}\text{]}. \quad (10.3)$$

### 10.9.2 Turbulent pressure

For an ideal gas the thermal pressure is  $P = nkT$  while the energy density is  $1/2nkT$  per degree of freedom, so for a monatomic gas is  $U = 3/2nkT$ . Turbulent motions add pressure and energy terms that are analogous to thermal motions if the turbulence has a Gaussian distribution. Note that the turbulent velocities may be organized, or lined up in certain directions, if the gas is magnetically controlled. This presents a complication that is ignored.

Heiles and Troland (2005) discuss both turbulence and magnetic fields. Their equation 34 gives the turbulent energy density in terms of the one-dimensional turbulent velocity dispersion  $\Delta V_{turb,1D}^2$  (or standard deviation). Note that we write velocities in terms of  $u$  with the relationship  $u^2 = 2\Delta V_{turb,1D}^2$ . Their energy density can be rewritten as a pressure:

$$\begin{aligned} P_{turb} = \frac{F}{6}\rho u_{turb}^2 &= 3.9 \times 10^{-10} F \left( \frac{n_{tot}}{10^5 \text{ cm}^{-3}} \right) \left( \frac{u_{turb}}{1 \text{ km s}^{-1}} \right)^2 \text{ [erg cm}^{-3}\text{; dyne cm}^{-2}\text{]} \\ &= 2.8 \times 10^6 F \left( \frac{n_{tot}}{10^5 \text{ cm}^{-3}} \right) \left( \frac{u_{turb}}{1 \text{ km s}^{-1}} \right)^2 \text{ [cm}^{-3} \text{ K}] \end{aligned} \quad (10.4)$$

where  $n_{tot}$  is the total hydrogen density,  $u_{turb}$  is the turbulent velocity, and He/H= 0.1 was assumed. The term  $F$  accounts for how the turbulent velocity field is ordered (Heiles and Troland, 2005, their equation 34).  $F$  is 2 for turbulent velocities that are perpendicular to the magnetic field as in Alfven waves and  $F$  is 3 for isotropic turbulent motions. The default value of  $F = 3$  is changed by entering a new value as a second number on this command line.

### 10.9.3 Energy dissipation

The **dissipate** option on the **turbulence** command provides a way in include conversion of wave energy into heat (see Bottorff and Ferland, 2002). When the option is used a third number, the log of the scale length for the dissipation in cm, must appear. Then the turbulent velocity will have the form

$$u_{turb}(r) = u_{turb}(r_0) \exp(-\Delta r/r_{scale}) \text{ [cm s}^{-1}\text{]} \quad (10.5)$$

where  $u_{turb}(r_0)$  is the turbulence at the illuminated face and  $\Delta r$  is the depth into the cloud. The wave mechanical energy is assumed to have been converted into heat with a local heating rate given by (Bottorff and Ferland, 2002)

$$G(r) = 3.45 \times 10^{-28} 2^{-3/2} u_{turb}^3(r) \text{ [erg cm}^{-3} \text{ s}^{-1}\text{]} \quad (10.6)$$

### 10.9.4 Equipartition turbulent - magnetic pressures

The **equipartition** option on the **turbulence** command sets the turbulent velocity to an equipartition between magnetic and turbulent energy densities. That is,

$$P_{turb} = \frac{F}{6}\rho u_{turb}^2 = P_{mag} = \frac{B^2}{8\pi} \text{ [erg cm}^{-3}\text{]}. \quad (10.7)$$

The **magnetic field** command sets  $B$ . The turbulent velocity is determined from the magnetic field assuming equation 10.7. Heiles and Crutcher (2005) argue that the correlation between turbulent and magnetic pressures, while true on average, does not hold in detail for specific regions of the ISM. When this option is used, you can optionally add the parameter  $F$  on the command line (the default is  $F = 3$ ). The keyword **no pressure** is supported, but not **dissipate**.

### 10.9.5 Turbulence command heads up!

*N.B.!* In the default (non-equipartition) form of the command, the turbulent velocity is the first number on the command line. The  $F$  parameter is the second number. The energy-dissipation scale length is the third number and must appear after  $u_{turb}$  and  $F$ . These numbers can only be omitted from right to left. In the equipartition case you can only specify  $F$ , which then is the first number on the command line. The energy-dissipation scale length is not supported in the equipartition case. The keyword **vary** is only supported in the non-equipartition case, in which case the turbulent velocity is varied.

The turbulent velocity must be less than the speed of light. The code will stop if  $u_{turb} \geq c$  is specified.

## 10.10 vlaw alpha=-1

This specifies a turbulent velocity that is a power law in radius. The number is the power law  $\alpha$  on radius. It must be negative. The turbulence will be given by

$$u = u_0 \left( r/r_0 \right)^\alpha \quad (10.8)$$

where  $r_0$  is the inner radius and  $u_0$  is the initial turbulence specified with the **turbulence** command.



# Chapter 11

## THERMAL SOLUTIONS

### 11.1 Overview

This Chapter describes options that affect the thermal solution and the gas kinetic temperature.

The accuracy of the thermal solution is set by the error tolerance in the heating—cooling balance. This is set with the **set temperature tolerance** command. Other commands can change some details of the thermal solution.

### 11.2 **cextra -14.231 [temp to the 1.5 power]**

This adds an extra cooling term due to some unspecified physical process. The first number is the log of the cooling rate [ $\text{erg cm}^{-3} \text{ s}^{-1}$ ]. The second number is an optional exponent that specifies a temperature dependence. The cooling will be given by

$$\Lambda = 10^{c_1} \times \left( \frac{T_e}{10^4 \text{ K}} \right)^{c_2} [\text{erg cm}^{-3} \text{ s}^{-1}] \quad (11.1)$$

where  $c_1$  and  $c_2$  are the two numbers entered with this command. If the second optional argument  $c_2$  is not specified then zero (i.e., constant cooling) is assumed.

The function evaluating **cextra** sets the variable *cextxx*. The expression can be easily changed to other forms by changing how this variable is set.

### 11.3 **Constant temperature, t=1e4 K [linear]**

A constant gas kinetic temperature calculation will be performed. The number is the electron temperature and is interpreted as the log of the value if it is  $\leq 10$  or if the keyword **log** is present. The optional keyword **linear** forces interpretation as a linear quantity. The temperature must be within the temperature limits of the code, currently  $2.8 \text{ K} \leq T \leq 1.001 \times 10^{10} \text{ K}$ .

By default the temperature is specified in Kelvin. The keywords **eV** and **keV** are also accepted.

Collisional ionization of all atoms and ions is included so this option can be used to produce clouds in coronal or collisional equilibrium.

**WARNING!** It is also necessary to specify a stopping criterion of some kind when this command is used. Most thermal-equilibrium calculations stop when the electron temperature falls below some lowest value, set with the **stop temperature** command and with the default value 4000 K. This cannot happen with a

constant-temperature model. For instance, a constant temperature model of a planetary nebula will continue until the default limit to the number of zones (now 1400) is reached. The *vast* majority of the cloud will consist of predominantly neutral gas well outside the hydrogen Strömgren sphere. This gas will have a small ambient level of ionization and emission due to collisional ionization. The resulting emission-line spectrum might be surprising since the neutral gas contributes significant emission.

Any of the stopping criteria described in the Chapter *Stopping Criteria* can be used. A more physical constant temperature model of a ionized cloud could be done by using the **stop efrac** command to stop the calculation when the hydrogen ionization front is reached.

## 11.4 Constant grain temperature 20K [linear]

Normally the temperature of each grain material and size is determined by balancing heating and cooling. This command sets the grain temperature to the indicated quantity.

If the **linear** keyword appears then the number is interpreted as the linear temperature. Otherwise numbers  $\leq 10$  are interpreted as a log of the temperature.

Other aspects of the grain physics are controlled with the **grain** command.

## 11.5 Coronal equilibrium, T=1e7 K [linear]

Coronal equilibrium, in which the gas is collisionally ionized, is assumed. The number is interpreted as the log of the gas kinetic temperature if the argument is  $\leq 10$  or the keyword **log** is present, and the linear temperature otherwise. The optional keyword **linear** will force the interpretation as a linear temperature. This holds the electron temperature at the specified value.

It is necessary<sup>1</sup> to also specify some sort of stopping criteria. The calculation will probably continue until the default limit to the number of zones is reached if a stopping criterion is not specified. As an example, the following would compute the properties of  $1 \text{ cm}^{-3}$  of a low density gas at a million degrees Kelvin:

```
coronal, T=1e6K
hden 0      // H density 1 cm^-3
set dr 0    // set zone thickness of 1 cm
stop zone 1 // do only one zone
```

The code does require that at least one radiation field source be specified. This command works by including a very faint laser near the high-energy limit of the radiation field so no other radiation need be specified. This spectral component should have no effect on the computed physical conditions due to both its faintness and the small cross section for interactions between  $\gamma$ -rays and matter.

If this is the only energy source specified then it is considered an intensity command. Emission-line intensities will be predicted, as described on page 11, unless a radius is also specified.

Figure 11.1 shows the soft X-ray line and continuum emission predicted from the input stream in the test case `ism_hot_brems.in`.

The **time init** option provides a way to set initial conditions for a time-dependent cloud. This is described beginning on page 129 where the **time** command is discussed.

<sup>1</sup>In versions 87 and before the **coronal** command set the zone thickness to 1 cm and stopped after computing one zone.

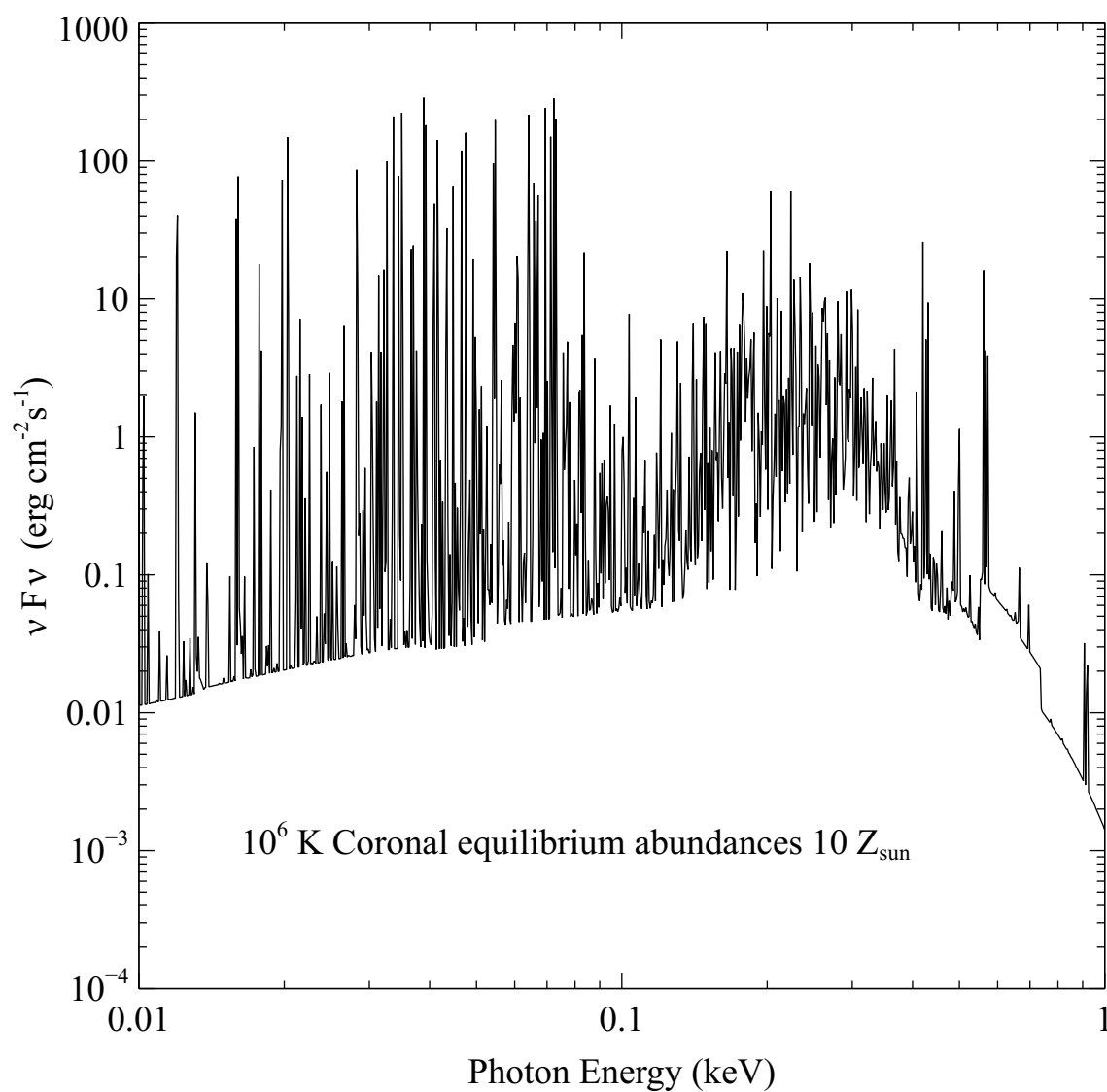


Figure 11.1: This shows the soft X-ray emission from the hot phase of a metal-rich ISM in coronal equilibrium. The input script `ism_hot_brems.in` was used to create the predicted spectrum.

## 11.6 Cosmic rays [options...]

This adds cosmic rays and their heating and ionization. The command must be specified with at least the first give letters to avoid ambiguity with the **cosmology** command.

This physics is described by [Ferland and Mushotzky \(1984\)](#), the subsection *Cosmic Ray Interactions* in the section *Other Physical Processes* in Part 3 of this document, and section 11.3 of AGN3. Cosmic rays mainly heat ionized gas and both heat and create secondary ionizations in neutral gas. All of this is done self-consistently ([Dalgarno et al., 1999](#)).

The **set csupra** command provides a way to specify an  $H^0$  secondary ionization rate. This has many of the same effects as introducing cosmic rays and uses the same code variables. The rate introduced by the **set csupra** command is not self-consistent with the rest of the calculation but does provide a way to test the code in certain simple limits.

Cosmic rays must be included if the calculation extends into molecular regions. The ion-molecule chemistry that occurs in the cold ISM requires a source of ionization ([Dyson and Williams, 1997](#)). In fact, most estimates of the galactic cosmic ray background are based on the abundances of chemical ions such as  $H_3^+$  ([McCall et al., 2003](#); [Shaw et al., 2008](#)). The chemistry network will probably collapse if the gas becomes molecular but cosmic rays are not present. The code will complain but try to compute the model if a simulation without cosmic rays extends into cold gas. If cosmic rays are not included in the calculation and the neutral hydrogen ionization rate falls below  $10^{-17} s^{-1}$  the code will print a comment stating that the ionization rate fell below the galactic background rate.

### 11.6.1 Cosmic rays background [1.2]

This includes galactic background cosmic rays. We adopt the [Indriolo et al. \(2007\)](#) mean  $H^0$  cosmic ray ionization rate of  $2 \times 10^{-16} s^{-1}$ . The  $H_2$  secondary ionization rate is then  $4.6 \times 10^{-16} s^{-1}$ ,<sup>2</sup>. ([Glassgold and Langer \(1974\)](#) give the relationship between  $H^0$  and  $H_2$  ionization rates.) CLOUDY determines the heating and ionization rates of cosmic rays self consistently, as appropriate for the local molecular, atomic, and electron densities (see AGN3 Section 11.3).

An optional scale factor specifies the cosmic ray ionization rate relative to this background value. The scale factor is assumed to be a log unless the keyword **linear** also appears.

The background rate is an active research area. [McCall et al. \(2003\)](#) find a background rate  $1.2 \times 10^{-15} s^{-1}$  for a galactic sight line. [Shaw et al. \(2008\)](#) find a rate about five times larger from detailed modeling of the sight line to Zeta Per. [Pellegrini et al. \(2007\)](#) find a significantly enhanced ionization rate in M17. [Suchkov et al. \(1993\)](#) find cosmic ray ionization rates that are several dex larger than the galactic background in the starburst galaxy M82.

### 11.6.2 Cosmic ray rate -17.3

If the keyword **rate** appears then the command specifies the log of the  $H^0$  ionization rate [ $s^{-1}$ ] in predominantly neutral gas. The default is  $2.5 \times 10^{-17} s^{-1}$  taken from [Williams et al. \(1998\)](#).

### 11.6.3 Cosmic rays density =1.2 [index, etc.]

If the keyword **density** appears then the first number is the log of the cosmic ray density  $n(cr)$  [ $cm^{-3}$ ]. Expressions given in [Ferland and Mushotzky \(1984\)](#) convert this into an ionization rate.

<sup>2</sup>Before 2004 the code used a background ionization rate of  $7.4 \times 10^{-18} s^{-1}$  quoted by [Tielens and Hollenbach \(1985a, Table 10\)](#) and [McKee \(1999\)](#). The rate of  $2.5 \times 10^{-17} s^{-1}$  given by [Williams et al. \(1998\)](#) was used through version C10.

The second optional number is a power-law index  $\alpha$  that describes the variation of the cosmic ray density with radius, i.e.,

$$n(cr, r) = n(cr, r_o) \left( \frac{r}{r_o} \right)^\alpha [\text{cm}^{-3}]. \quad (11.2)$$

The default value of the index is  $\alpha = 0$ , corresponding to a constant cosmic-ray density. The third optional number is the log of the temperature of the fast electrons, if they are not relativistic. If this third number is specified then expressions from [Balbus and McKee \(1982\)](#) will be used to evaluate the electron heating rates. The options can be omitted from right to left.

### 11.6.4 Cosmic ray equipartition

The cosmic rays are assumed to be in equipartition with the magnetic field. Then the cosmic-ray density is given by

$$n(cr, B) = n(cr, B_0) \left( \frac{U(B)}{U(B_0)} \right) [\text{cm}^{-3}] \quad (11.3)$$

where  $U(B)$  and  $U(B_0)$  are the energy densities of the local magnetic field relative to the galactic background magnetic field. The **magnetic field** command sets  $B$ . [Webber \(1998\)](#) gives a cosmic-ray energy density of  $1.8 \text{ eV cm}^{-3}$ , which corresponds to a magnetic field of  $8.5 \mu\text{G}$  if equipartition holds. The background cosmic-ray ionization rate is scaled by the ratio of the magnetic energy densities to find a local cosmic ray ionization rate and energy density.

## 11.7 Failures 100 times [ map]

A converge failure occurs when the heating-cooling balance, the electron density, or the pressure, is not within the tolerance set by the **set convergence** commands. Normally CLOUDY will punt<sup>3</sup> after an excessive number of convergence failures (presently 20) occur. This command increases the number of allowed failures to the value entered as a parameter.

When CLOUDY stops because of excessive failures and the **map** option is specified<sup>4</sup> as a keyword on the **failures** command it first produces a map of (heating-cooling) versus temperature to give an indication of where the equilibrium temperature should have been. A section in Part 2 describes thermal failures in more detail and describes this output.

Failures most often occur near a thermal front. This occurs when the solution jumps over peaks in the cooling function that occur near  $\sim 2000 \text{ K}$  and  $\sim 10^5 \text{ K}$ . A warning will be issued at the end of the calculation if the global thermal balance is wrong.

It should not be necessary to use this command. Please post the example on the discussion board if you find a simulation where you need to increase the number of convergence failures.

## 11.8 Force temperature to 3400 K

This forces the initial estimate of the temperature of the first zone to the value entered. The temperature is interpreted as a log if it is  $\leq 10$  and the linear temperature otherwise. The keywords **log** and **linear** will override this.

<sup>3</sup>FAQ: Punt is a technical term from American football. It is something bad that happens when progress in advancing the ball is lacking.

<sup>4</sup>In versions 94 and before, the default was to produce the map, and the **no map** option turned this off. With version 95 the option is not to produce a map, and this must be requested with the **map** option.

This command is useful if more than one initial temperature solution is possible. It forces the first guess of the temperature to the specified value but *does not* hold the temperature constant. The temperature is determined by energy balance thereafter. (A constant kinetic temperature is set with the **constant temperature** command.)

CLOUDY may have trouble finding a valid first temperature if the initial solution is forced well away from the equilibrium value. This is an inevitable consequence of the complete linearization methods that are intrinsic to the code's solvers. If a large number of thermal failures or warnings result from the use of this command then it is likely that the code has been forced too far away from the solution. A better guess of the initial temperature would fix this problem.

## 11.9 Hextra -14 [depth, density, time, SS]

This includes extra heating due to some unspecified energy source. The first number  $H_0$  is the log of the volume-heating rate [ $\text{erg cm}^{-3}\text{s}^{-1}$ ]. Optional keywords specify how this heating depends on density, depth into the cloud, or time. If these optional keywords do not occur then the heating is constant.

### 11.9.1 Hextra -14 depth 18, thickness 12

The keyword **depth** makes the heating vary with depth into the cloud. The second number is the log of the scale radius  $r_{scale}$  [cm]. The extra heating rate varies as<sup>5</sup>

$$H = H_0 [\exp(-depth/r_{scale}) + \exp(T - depth)/r_{scale})] [\text{erg cm}^{-3}\text{s}^{-1}]. \quad (11.4)$$

The third optional parameter  $T$  is the total thickness of the slab. If this is given then the second exponential term will be added. This will mimic an external heat source that warms the cloud from both the illuminated and shielded faces. If the third parameter is not entered then the rightmost term is not included.

### 11.9.2 Hextra -13 density

The **density** option makes the heating scale with the hydrogen density. The heating will be given by

$$H = H_0 [n(\text{H})/n_0] [\text{erg cm}^{-3}\text{s}^{-1}]. \quad (11.5)$$

where  $n(\text{H})$  is the local hydrogen density [ $\text{cm}^{-3}$ ] and  $n_0$  is a scale density. The scale density is unity by default and is changed by specifying the optional second number, the log of the scale density.

### 11.9.3 Hextra time

If the **time** keyword appears then the variable scale factors that appear on the **time** command will multiply the heating rate specified with the **hextra** command. This makes it possible to follow the effects of time-dependent heating sources.

---

<sup>5</sup>In versions through 94.00 the heating rate varied as  $\exp[-r_{scale}/(r - r_o)]$  and went to infinity as the illuminated face. The radial dependence was changed to its current form in 94.01.

### 11.9.4 Hextra SS 0.2 1e8 3e17

When the keyword **SS** appears, the standard  $\alpha$ -disk model ([Shakura and Sunyaev \(1973\)](#)) will be used. The first parameter is  $\alpha$ , the dimensionless parameter of an  $\alpha$ -disk model. The second number is the mass of center black hole  $M$  in solar mass units. The last one is the distance [cm] from the center of the disk  $r$ . In this model, heating rate is calculated as

$$H = \alpha P \sqrt{\frac{MG}{r^3}} [\text{erg cm}^{-3} \text{ s}^{-1}] \quad (11.6)$$

where  $P$  is the local gas pressure [ $\text{erg cm}^{-3}$ ] and  $G$  is gravitational constant. All three parameters must appear. There are spaces to either side of “\_SS\_”.

### 11.9.5 Notes on the hextra command

The heating can only depend on depth or density but the **time** option can also be specified for each.

By default a calculation will stop when the kinetic temperature falls below 4000 K. It will be necessary to set other stopping criteria such as the cloud thickness if the extra heating keeps the gas warmer than this limit.

## 11.10 High temperature approach

This command tells the code to search for the first temperature by approaching the thermal solution from the high temperature extreme of  $10^6$  K. Normally the approach is from low temperatures. This can be useful when more than one thermal solution is possible. An example is shown in Figure 10 of [Ferland et al. \(2009a\)](#).

## 11.11 Magnetic field, log(B) = 5 [options]

Magnetic fields are not included by default. This specifies the strength and geometry of the magnetic field. A number, the log of the magnetic field strength in Gauss, is the first number on the line. The physical effects of magnetic fields are discussed in Part 3 of this document.

Ordered and tangled fields can be specified. The field is assumed to be tangled by default. If the keyword **ordered** appears then the angle between the radiation field of the central object and the magnetic field is also specified. This angle is zero if the field is in the outward radial direction. The angle is given in degrees by default but the **radian** keyword will cause it to be radians instead.

In the case of a tangled field the code will look for a second number, the index for the gamma-law relation between the magnetic field and the gas density. If a second number is not found then an index of  $\gamma = 4/3$ , appropriate for a tangled field, will be assumed. This index appears in the relationship

$$B_{\text{tangled}} = B_{\text{tangled}}^0 \left( \frac{\rho}{\rho_0} \right)^{\gamma/2} [\text{Gauss}] \quad (11.7)$$

where the term in parenthesis is the ratio of the current density to the density at the illuminated face of the cloud. For a spherical constant-velocity flow, where  $\rho/\rho_0 \propto (r/r_0)^{-2}$ , the field will vary as  $B/B_0 \propto (r/r_0)^{-\gamma}$ . This is in contrast with a dipolar field, in which the radial dependence is  $B/B_0 \propto (r/r_0)^{-3}$ .

Both ordered and tangled fields can be specified on separate commands. If more than one ordered or tangled field is specified then the second will take precedence over the first.

The major thermal effect of a field is to add cyclotron cooling. This is only important at very high temperatures.

Magnetic pressure and enthalpy terms corresponding to the magnetic energy density are included in the equation of state when a constant-pressure geometry is assumed. The magnetic pressure is

$$P_B/k \approx \frac{B^2}{8\pi k} \approx B_{100\mu G}^2 2.9 \times 10^6 [\text{cm}^{-3} \text{ K}] \quad (11.8)$$

where  $B_{100\mu G}$  is the magnetic field in units of  $100\mu G$ . The plasma  $\beta$  parameter, defined as the local ratio of thermal to magnetic energy densities,  $\beta = P_{\text{gas}}/P_{\text{mag}}$ , is printed in the summary of pressure contributions. The field affects the dynamics of the gas when  $\beta \leq 1$ .

Supersonic turbulence in rough energy equipartition with the magnetic field is often observed in the cold ISM (Heiles and Crutcher, 2005). The **turbulence** command has an **equipartition** option to set the turbulent velocity to a value in energy equipartition with the magnetic field. Although a general correlation is observed in the cold neutral medium of the ISM, it is not thought to be a fundamental relationship (see the Heiles & Crutcher paper).

## 11.12 Map, zone 4 [range 2000, 5000]

This computes the heating-cooling vs temperature relation (a “thermal map”) of the zone specified as the first number on the line. This is one way to check for the existence of more than one thermal solution. If no zone is specified, or if the zone is less than or equal to 0, then only a thermal map is produced for the illuminated face of the cloud and the calculation then stops. The calculation of the heating and cooling is self-consistent across this map. A section in *Problems* in Part 2 of this document explains how to interpret the map output.

The map produced by this command is not directly comparable to the more typical plot that shows the equilibrium temperature as a function of ionization parameter (Krolik et al., 1981). That map can be produced by successively calling CLOUDY with the same radiation field but different densities, say, with the **grid** command. In that second case each deduced temperature is a valid equilibrium temperature. In the map produced by the **map** command only one temperature, where heating and cooling are equal, is a valid equilibrium temperature. The map produced by this command is useful for checking for more than one thermal solution, to check that the heating and cooling curves smoothly flow as the temperature changes, or to investigate why the code had convergence problems (it was originally introduced for only this latter purpose).

The optional keyword **range** specifies the temperature range of the map. If this option is specified then the first number on the line must be the zone for the map, zero if only a map of the illuminated face, and the next two numbers must be the lower and upper temperature limits to the map. These temperatures will be interpreted as logs if the first temperature is  $\leq 10$ . Normally about 20 steps occur between the lowest and highest temperature in the map. The number of steps can be reset with the **set nmaps** command.

The thermal map can be saved as a separate file with the **save map** command. This produces output that is suitable for processing by other software.

The code stops when the map is complete since it is left in a disturbed state.

## 11.13 Neutrons -2 [efficiency =-2]

This adds energy deposition and ionization by secondaries due to the fast neutrons proposed by Sikora et al. (1989). The argument is the luminosity in fast neutrons expressed as a fraction of the *total* photon luminosity of the incident continuum. It is interpreted as a log if  $\leq 0$  and a linear scale factor if positive.

The second optional argument is the heating—ionization efficiency of the neutrons, unity by default. Both quantities are interpreted as logs if  $\leq 0$  and linear if positive.

## 11.14 Print coolants, zone 135

See the **print ...** commands below.

## 11.15 Print heating

See the **print ...** commands below.

## 11.16 Set temperature [floor, convergence]

See the **set temperature ...** commands below.

## 11.17 tlaw [DB96, SN99]

This specifies a temperature law. Two options currently are implemented.

The **DB96** option tells the code to use the temperature—column density law used by [Draine and Bertoldi \(1996\)](#):

$$T = T_0 / [1 + N(\text{H}) \sigma_{d,1000}] \text{ [K]} \quad (11.9)$$

where  $T_0$  is 500 K and  $\sigma$  is  $6 \times 10^{-22} \text{ cm}^{-2}$ .

The **SN99** option tells the code to use the temperature -  $\text{H}_2$  fraction relationship assumed by [Sternberg and Neufeld \(1999\)](#):

$$T = \frac{500}{1 + 9 [2n(\text{H}_2) / n(\text{H}_{tot})]^4} \text{ [K]}. \quad (11.10)$$



# Chapter 12

## CONTROLLING ATOMIC AND MOLECULAR MODELS

### 12.1 Atom overview

The **atom** commands change details of the physical treatment of several model atoms that are incorporated in the code.

### 12.2 The g-bar approximation

Many transitions do not have collision rates (collision rates are for more difficult to determine than radiative rates). We use various forms of the g-bar approximation to fill in missing data.

The **set gbar** (see page 241) controls aspects of the g-bar approximation.

### 12.3 Atom FeII [options]

This command adjusts details of the model Fe<sup>+</sup> ion. The default is to compute the lowest 16 levels, which produce IR emission, as in the real ion, but to do higher levels, which produce optical and UV emission, using the simplified and very fast scheme outlined by [Wills et al. \(1985\)](#) AGN3 describes Fe II emission in Section 14.5.

When any of the **atom FeII** commands are entered the Wills et al. scheme is turned off. A complete model, using 371 levels and described by [Verner et al. \(1999\)](#), is used instead. This is far more accurate but also *much* slower. [Baldwin et al. \(2004\)](#) show some examples of Fe II spectra of AGN.

*N.B.* the keyword is **FeII**, not **Fe2**, to avoid scanning the number 2 off the command line. Both **FeII** and **Fe II** (with a space) are accepted.

#### 12.3.1 Atom FeII levels

This changes the number of levels used by the model atom. The upper limit is 371 levels and is the default when the large Fe II model is used. When the large atom is not used the default is to compute the lowest 16 levels and treat the remainder of the levels with the [Wills et al. \(1985\)](#) simple model. Decreasing the number of levels will speed up the execution time [roughly proportional to  $n^2 \log(n)$ ] at the expense of a degraded simulation of the physics.

### 12.3.2 Atom FeII trace

This turns on debugging printout for each call to the model atom.

### 12.3.3 Atom FeII redistribution [options]

The keyword **redistribution** will change the form of the redistribution function for various lines within the model atom.

A keyword to specify which set of lines to change is required. This is either **resonance** (any line decaying to the ground term) or **subordinate** (transitions between excited levels). The type of redistribution function to use is also specified. The options are **PRD** (partial redistribution), **CRD** (complete redistribution with Doppler core only), and **CRDW** (complete redistribution with damping wings). (The underscore indicates a space.)

The keywords **redistribution show** tells the code to print the current default redistribution functions.

### 12.3.4 Atom FeII simulate

This will cause results from the atom to be simulated. The large model atom is not actually called. This is very fast and is a debugging aid.

### 12.3.5 Atom FeII slow

The keyword **slow** will cause the atom to always be reevaluated. Normally the code only reevaluates the atom when the local conditions have changed significantly.

### 12.3.6 Atom FeII output options

Fe II emission is an exercise in uncontrolled complexity. Hundreds of thousands of lines contribute to what often appears as a pseudo continuum. It is not practical to study the list of Fe II lines except in a few especially simple situations such as H II regions.

Three options are available for understanding output from the Fe II atom. Most often Fe II emission is seen as a blended continuum rather than individual lines. The general idea is to try to reduce the flood of information to a manageable level by distilling the emission into what an observer would actually see.

Fe II *bands in the main output*. A series of Fe II “bands” are automatically entered into the main emission-line output. Each band represents the total Fe II emission integrated over all lines that lie within a range of wavelengths. This emission appears in the output with the label “Fe2b” and a wavelength close to the center of the band. The bands are chosen to represent features that an observer might be able to measure.

The list of bands is contained in the file `FeII_bands.ini` which is included in the data directory. This file is intended to be easily changed by the user. It explains the format of the information that is needed. There is no limit to the number of Fe II bands that can be specified.

*The **save FeII** family of commands* are described on page 172 and provide a way to save some predictions. The following gives an overview of some of these commands.

**save FeII lines** This reports the intensities of all emission lines predicted by the model atom. The resulting file is very large and mainly useful for debugging the model atom or understanding where within the atom a particular feature originates.

**save FeII continuum** This reports the total Fe II emission as a continuous spectrum. Here a range of wavelengths is broken into a number of intervals and the total Fe II emission within each interval is added together. The result represents what would be observed by a spectrometer with a particular resolution and

was used to create the plots in [Baldwin et al. \(2004\)](#). Some details, such as the wavelength range and resolution, are changed with the **set FeII continuum** command described on page 239.

**atom FeII continuum from 1000Å to 7000Å in 1000 cells** This adjusts the lower and upper bounds and the resolution of the Fe II continuum saved with the **save FeII continuum** command. The numbers are the lower and upper limits to the wavelength range in Angstroms and the number of wavelength cell that occur over this range.

## 12.4 Atom H2 options

The large model of the H<sub>2</sub> molecule, described in [Shaw et al. \(2005\)](#), will be included if any of the family of **atom H2** commands appears. The much faster three-level model outlined by [Tielens and Hollenbach \(1985a\)](#), [Burton et al. \(1990\)](#), [Draine and Bertoldi \(1996\)](#), and expanded by [Elwert et al. \(2005\)](#), is used by default. The large molecule is represented by several thousand levels producing roughly half a million lines. AGN3 describes some properties of H<sub>2</sub> in section 8.3 and appendix A6.

*NB* The number “2” appears in the keyword for this command. Any numerical parameters that appear on the **atom H2** commands must appear after this two—the code will check that the first number parsed off the command line is the number 2.

### 12.4.1 The set H2 command

Some details of the physical treatment of the H<sub>2</sub> molecule can be changed with the **set H2** command.

### 12.4.2 H<sub>2</sub> output options

Strong H<sub>2</sub> lines will appear in the main emission-line output. The **save H2** command has many other output options. The section in Part 2 of this document describing calling the code as a subroutine describes several routines that will return predictions of the large molecule. The **set line precision** command will add more significant figures to the wavelengths printed in the main printout. This may help isolate a particular line.

### 12.4.3 Atom H2

With no options, the only effect is to include the large model of the H<sub>2</sub> molecule.

### 12.4.4 Atom H2 chemistry [simple; full]

This changes how the interactions between the H<sub>2</sub> molecule and the rest of the chemical network are treated. By default, or if the keyword **full** appears, then the fully self-consistent formation and destruction rates are used when the large H<sub>2</sub> molecule is enabled. If the keyword **simple** occurs then expressions from [Tielens and Hollenbach \(1985a\)](#) are used instead.

### 12.4.5 Atom H2 collisions [options]

These commands change various collisional processes within the H<sub>2</sub> molecule.

**atom H2 ortho para collisions on/off**

This turns off ortho-para changing collisions with gas particles.

**atom H2 orH2 collisions options**

**atom H2 paH2 collisions options**

These commands determine which of the  $\text{H}_2 - \text{H}_2$  collision data sets is used. The default is the [Lee et al. \(2008\)](#) set, which can also be chosen with the **ORNL** option. The keyword **Le Bourlet** selects the [Le Bourlot et al. \(1999\)](#) data set. The keyword **ohH2** adjusts the ortho data and the keyword **paH2** adjusts the para data set. One of these keywords must be specified. Both cannot be adjusted with the same command.

**atom H2 collisional dissociation on/off** turns on or off collisional dissociation. The default is to include it using the estimates given in [Shaw et al. \(2005\)](#). These rates are all only guesses and represent an uncertainty.

**atom H2 grain collisions on/off** turns off downward transitions induced by collisions with grains.

By default the code will use guesses of collisional rate coefficients using the g-bar method. Collisional deexcitation for the g-bar transitions are turned off with the **atom H2 gbar** command.

### 12.4.6 Atom H2 gbar [ off; on]

The g-bar approximation is a rough relationship between the energy of a line and its collision rate coefficient. This can be used to guess a collisional deexcitation rate coefficient when no real data exist. This command turns this guess off or on. It is on by default.

### 12.4.7 Atom H2 levels

This changes the number of electronic levels within the  $\text{H}_2$  molecule. The default is seven and includes the ground and first six bound singlet electronic states. This is also the largest number of levels. At minimum is three levels, which is sufficient to include the Lyman and Werner bands in the UV. This is a necessary minimum number of levels to include the correct photodissociation processes. If no number appears but the keyword **large** does then the code will use the upper limit.

### 12.4.8 Atom H2 limit -4

Calculating the level populations and line spectrum of the large  $\text{H}_2$  molecule is computationally expensive. The code tries to save time by not computing the populations when the abundance of  $\text{H}_2$  is negligible. This command changes the limit for the smallest  $\text{H}_2/\text{H}_{\text{tot}}$  ratio. The full model will be computed when the ratio is greater than this limit. The number is interpreted as the linear ratio if it is greater than zero and the log of the ratio if it is less than or equal to zero. The keyword **off** turns off the limit so that the large model of the molecule is always evaluated. The default limit is  $10^{-8}$ , small enough for the large molecule to be computed across the entire [Tielens and Hollenbach \(1985a\)](#) standard PDR model that is part of the code's test suite.

When the  $\text{H}_2$  abundance is below this limit the photodissociation, heating, and cooling rates, are evaluated using expressions in [Tielens and Hollenbach \(1985a\)](#).  $\text{H}_2$  level populations are set to their LTE value so that self-shielding in the electronic bands is still computed.

### 12.4.9 Atom H2 matrix 43

Populations of the lower ro-vibration states of the ground electronic level are determined by two schemes. The first, and most straightforward, is the solution of a complete set of balance equations by solving the system of balance equations with a master equation approach. The time needed to solve the linear algebra increases as a power of the number of levels so we need to keep the number of levels as small as possible. High levels are treated by back substitution, starting from the highest level with X and proceeding downwards. This command sets the total number of levels that are computed within the matrix. Levels higher than this will be treated with back substitution.

If the keyword **off** (note the leading space) or **none** appears, or if the number of levels is less than 1, the matrix will not be used. If the keyword **all** appears then all levels within X will be done this way.

### 12.4.10 Atom H2 noise [mean, standard deviation, seed]

This multiplies the rates for collisional processes within the H<sub>2</sub> molecule by a Gaussian random number so that  $r' = r \cdot 10^{\text{rand}}$ . Here  $r$  is the correct rate coefficient and **rand** is an Gaussian distributed random number. The first two optional numbers on the command line set the mean and standard deviation for the Gaussian random numbers. The first optional number is the mean, with a default of 0. The second optional number is the standard deviation with a default of 0.5. The last optional number is the seed for the random number generator, which must be an integer greater than 0. If the seed is not specified then the system time is used to generate a random seed.

### 12.4.11 Atom H2 thermal [simple; full]

This changes how the heating and cooling by the H<sub>2</sub> molecule are treated. By default, or if the keyword **full** appears, then the fully self-consistent heating and cooling rates are used when the large H<sub>2</sub> molecule is enabled. If the keyword **simple** occurs then expressions from [Tielens and Hollenbach \(1985a\)](#) are used instead.

### 12.4.12 Atom H2 trace [options]

This turns on trace information concerning the H<sub>2</sub> molecule. The optional keywords **full**, **iterations**, and **final** will give full information, an overview of iterations during the convergence, and only final results respectively. If the keyword **matrix** occurs the code will print the contents of the matrices that are used for solution of lower levels within the ground electronic state.

### 12.4.13 atom H2 output options

Roughly half a million lines are predicted when the large H<sub>2</sub> molecule is included. The main emission-line printout includes all significant lines produced in the ground electronic state but does not include electronic transitions. The **print line H2 electronic** command will include these lines. The family of **save H2** commands provides ways to save information such as column densities, the emission-line spectrum, and details of the effects of H<sub>2</sub> on the conditions in the cloud.

## 12.5 Atom [H-like | He-like] [element, options]

### 12.5.1 Introduction

These commands are used to change some details in the treatment of atoms of the H-like and He-like isoelectronic sequences.<sup>1</sup> Atoms of the H-like sequence have one bound electron and include H<sup>0</sup>, He<sup>+</sup>, Li<sup>+2</sup>, through Zn<sup>+29</sup>. Atoms of the He-like sequence have two bound electrons and include He<sup>0</sup>, Li<sup>+</sup>, through Zn<sup>+28</sup>.

This implementation of the H-like sequence was initially part of Jason Ferguson's PhD thesis and is described in [Ferguson and Ferland \(1997\)](#), [Ferguson et al. \(2001\)](#), and [Bottorff et al. \(2002\)](#). The physics

<sup>1</sup>This was the **hydrogenic** command in versions 90 and before.

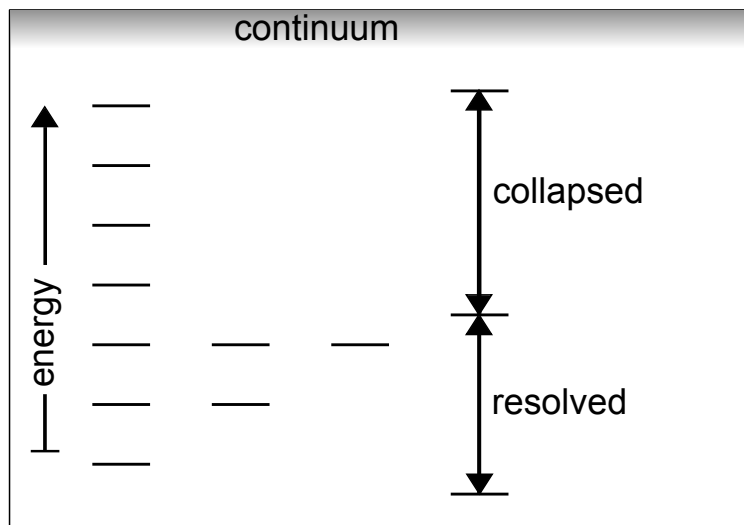


Figure 12.1: This shows resolved and collapsed levels for a typical H- or He-like species. The set of horizontal bars on the left are energy levels with principal quantum numbers ranging from 1 to 7, increasing from bottom to top. The lowest three configurations are resolved into  $nl$  terms while higher shells are treated as collapsed levels, in which the  $nl$  terms are assumed to be populated according to their statistical weight. The levels are adjusted with the **atom AA-like levels** command. This is a cartoon and does not represent any particular species.

was expanded to resolve  $nl$  terms by Ryan Porter during a visit to IoA Cambridge in Fall 2008, as was summarized in [Luridiana et al. \(2009\)](#). Any number of levels up to  $n$  of 400 can be computed.

The He-like sequence was developed by Ryan Porter as part of his thesis and it is described in [Bauman et al. \(2005\)](#), [Porter et al. \(2005\)](#), [Porter and Ferland \(2007\)](#), and [Porter et al. \(2012\)](#). Ryan Porter unified the two sequences and expanded the H-like sequence to include all of the physics included in the He-like sequence.

The two sequences are now unified so the same **atom AA-like** commands largely work for both.

The name of one of the iso-sequences must appear on the command line. The options are **H-like** and **He-like**. Only one iso-sequence can be modified with a single command. By default all ions of the iso-sequence are modified. If the keyword **element** and the name of an element appears then only that ion is modified. The following are some examples

```
# only change hydrogen itself
atom H-like element hydrogen levels 8
# change the entire He-like sequence
atom He-like levels 9
```

## 12.5.2 Structure of the model atoms

The model atoms include a certain number of resolved and collapsed levels as shown in Figure 12.1. The lower  $n_{\text{resolved}}$  levels are  $nl$  resolved. Another  $n_{\text{collapsed}}$  levels, which replace the  $nl$  terms with an  $n$  configuration, are above the resolved levels.

The physics of the resolved levels is exact while that of the collapsed levels is more approximate since the entire  $n$  configuration is treated as a single level assuming that the  $nl$  terms within the  $n$  configuration

are populated according to statistical weight. This is a good assumption at high densities, as shown by [Pengelly and Seaton \(1964\)](#).

The total recombination coefficient is the sum to over all possible bound levels. The model has a finite, often small, number of levels. Recombination coefficients to each level are derived from the photoionization cross section using the Milne relation (AGN3). The recombination to these levels is less than the total. We “topoff” the model by adding the remaining recombination coefficient to the model atom, as controlled with the **atom xx-like topoff** command.

By default only lines produced by resolved levels are included in the printout. The **print line iso collapsed** command, described on [154](#), will cause lines produced by the collapsed levels to be included in the printout. See the discussion of the **print line iso collapsed** command for more details.

### The H-like sequence

Figure [12.1](#) shows an H-like system. Resolved configurations are split into  $nl$  levels. Collapsed levels each represent one principal quantum number. By default there are 10 resolved and 15 collapsed levels for  $H^0$  and  $He^+$ , and 5 resolved and 15 collapsed levels for heavier elements.

The H-like iso sequence models atoms can extend up to any principle quantum number between the limits  $4 < n \leq 400$ . The size is limited mainly by the available memory and computer time. Increasing the number of levels allows a better representation of the collision physics that occurs within higher levels of the atom at the expense of longer execution times and greater memory requirements.

### The He-like sequence

The model atom resolves  $n$ -levels into  $nLS$  levels, and the  $2^3P$  term is split into three  $nLSJ$  levels. For a given maximum principal quantum number  $n_{\max}$ , there will be a total of  $n_{\max}^2 + n_{\max} + 1$   $nLS$  levels. The default number of resolved levels for  $He^0$  is 6, resulting in 43  $nLS$  levels, there are five resolved levels for C, N, O, Fe, and Zn, and three resolved levels for all remaining elements. Increasing  $n_{\max}$  allows a better representation of the atom’s emission, especially the collision physics that occurs within higher levels of the atom, but at the expense of longer execution times and greater memory requirements.

There are also 20 collapsed levels for  $He^0$  and one collapsed level for heavier elements. These collapsed levels bring together all of the individual  $nLS$  terms as one pseudo-level. The recombination coefficient into this pseudo-level is the sum of recombination coefficients into the individual terms plus the recombination topoff. Transition probabilities from this pseudo-level are calculated as follows.

$$A(n_u \rightarrow n_l L_l S) = \frac{\sum_{L_u=L_p m l} g_{L_u} S A(n_u L_u S \rightarrow n_l L_l S)}{\sum_{L_u=L_l \pm 1}}. \quad (12.1)$$

This causes the collapsed level to behave exactly as if it were a set of resolved terms populated according to statistical weight.

There is no limit to the number of levels other than computational resources like memory and time.

### 12.5.3 Atom H-like collisions...

Collisional processes, both between levels ionization, are turned off with this command. They are all on by default. This command is mainly used for debugging. Separate collisional processes can be turned off with the following options. Only one option is recognized per command line so multiple commands are needed to turn off several processes. If no sub-options are recognized then all collisional processes are disabled. This command turns off collisions for all elements along the H-like isoelectronic sequence.

**atom H-like collisions l-mixing off**<sup>2</sup> This turns off  $l$ -mixing  $2s - 2p$  collisions.

**atom H-like collisional ionization off** This command turns off collisional ionization by thermal electrons of all levels. Ionization by cosmic rays is not affected by this command.

**atom H-like collisional excitation off** This command turns off collisional excitation of all levels, except for  $2s-2p$ .

**atom H-like collisions off** All three collisional processes will be turned off if none of the three keywords are recognized.

*Warning!* The code will require a very number of zones if collisions are turned off in an optically thick cloud with a large ( $n \gg 15$ ) hydrogen atom. Collisions will normally hold populations of very highly excited levels to values very near LTE. The FIR and radio lines will have very small line optical depths due to the correction for stimulated emission. When collisions are absent, the normal tendency of departure coefficients to increase with principal quantum number means that FIR and radio lines will strongly maser. The code dynamically adjusts the zoning to prevent these maser optical depths from diverging to minus infinity. A very large number of zones will be required to spatially resolve the masing region. This is a totally artificial, not physical, effect. The solution is to not turn off collisions with a large atom when performing a simulation with more than a trivial thickness.

## 12.5.4 Atom He-like collisions ....

Collisional processes between levels and collisional ionization are turned off with this command. Separate collisional processes can be turned off with the following options. Only one option is recognized per command line so multiple commands are needed to turn off several processes. If no sub-options are recognized then all collisional processes are disabled. This command turns off collisions for all elements along the He-like isoelectronic sequence.

**atom He-like collisions l-mixing off** This command turns off all collisions within the same  $n$  level for all elements in the helium-like isoelectronic sequence. Both  $L$ - and  $S$ -changing collisions are turned off.

**atom He-like collisions l-mixing Pengelly [Vrinceanu]** This changes to the [Pengelly and Seaton \(1964\)](#) formalism rather than currently the default, based on [Vrinceanu and Flannery \(2001\)](#) for  $L > 2$ .

**atom He-like collisions l-mixing thermal [ averaging, no averaging]** The **no thermal averaging** option calculates the [Vrinceanu and Flannery \(2001\)](#) collision strengths at an impact energy equal to  $kT$ , rather than averaging over a Maxwellian distribution. This is the default when a small atom is used. Thermally averaged collision strengths are used when the atom is large.

**atom He-like collisions excitation** This command turns off collisional excitation, for all  $n_u \neq n_l$  transitions, for all elements in the helium-like isoelectronic sequence.

**atom H-like collisional ionization off** This command turns off collisional ionization by thermal electrons of all levels.

## 12.5.5 Atom [H-like | He-like] continuum lowering off

This command disables continuum lowering processes due to particle packing, Debye shielding, or Stark broadening. The processes are active by default and implemented following [Bautista and Kallman \(2000\)](#). This command applies to the entire isoelectronic sequence.

<sup>2</sup>This was the  $2s2p$  option in versions 94 and before. The  $2s2p$  option still exists for backward compatibility.

### 12.5.6 Atom [H-like] damping off

Rayleigh scattering, continuum scattering due to the extreme damping wings of hydrogen Lyman lines, is turned off with the **damping off** option. H I Rayleigh scattering is a significant opacity source in clouds that have large column densities of neutral material ( $N(\text{H}^0) > 10^{23} \text{cm}^{-2}$ ).

This only disables H I Rayleigh scattering. The **He-like** option is not supported.

### 12.5.7 Atom He-like dielectronic recombination [off]

This option turns dielectronic recombination off for the entire isoelectronic sequence. Dielectronic recombination is included by default. This command only turns off DR. It affects all elements of the He-like iso sequence.

### 12.5.8 Atom [h-like | he-like] error generation

Monte Carlo error analysis can be performed with this command. Randomly generated Gaussian errors are applied to atomic data. The parameter X is an integer used to set the seed of the random number generator.

The pessimistic option will choose the largest of two standard deviations for each piece of atomic data. The full command would look something like

```
atom he-like error generation pessimistic 5
```

where the number is the seed for the random number generator. Without the pessimistic keyword the default optimistic values are used.

### 12.5.9 Atom He-like FSM

For  $L > 2$ , levels with the same  $n$  and  $L$  but different  $S$  are strongly mixed due to the spin-other-orbit interaction. This option modifies transition probabilities to account for this fine-structure mixing. The effect on multiplet emissions is not large. See [Bauman et al. \(2005\)](#) for a discussion and calculation of this effect in a zero-density  $J$ -resolved helium atom.

### 12.5.10 Atom He-like gbar options

The code employs various forms of the  $\bar{g}$  approximation to fill in collision strengths for those transitions with no quantal calculations. This command changes which approximation is used. The options are **Vriens** for the [Vriens and Smeets \(1980\)](#) and **off** to set this to zero. This only exists for the He-like iso sequence.

### 12.5.11 Atom [h-like | he-like] levels options

This set of commands controls the model atomic structure shown in Figure [12.1](#).

The number of levels can only be set once at the very start of a calculation when space is allocated for the hydrogenic arrays. If the code is used to run a grid of models then only the first occurrence of **atom xx-like levels** is honored and all following occurrences are ignored.

### Atom He-like [resolved, collapsed] levels 4 [element iron]

One of the keywords **resolved** or **collapsed** must appear. This sets the number of resolved or collapsed levels. The argument gives the principal quantum number  $n$  for the number of levels. In the case of collapsed levels the number of added levels will be equal to the argument. In the case of resolved levels a large number of resolved terms may be needed to produce the requested number of principal quantum numbers.

The following sets most iso sequence models to a small number of levels but does a high quality simulation of the H- and He- like Fe ions.

```
% most ions have small models
atom H-like levels small
atom He-like levels small
% resolve the lowest n=10 shells, these take well more than 10 levels
atom H-like levels element iron resolved levels 10
atom He-like levels element iron resolved levels 10
% 15 collapsed levels on top
atom H-like levels element iron collapsed levels 15
atom He-like levels element iron collapsed levels 15
```

### Atom [h-like | he-like] levels LTE

This will set the level populations to their LTE values.

### Atom [h-like | he-like] levels print

This produces a summary of the number of levels for all ions of the iso sequences. It reports the highest principal quantum number of the resolved levels, the number of  $nls$  terms in these  $n$  configurations, and the number of collapsed levels.

### Setting the number of levels with keywords

If no numbers occur then we look for a keyword to specify preset sizes. The code will use the smaller of either the preset size or the current size.

*The H-like iso sequence.*

The keyword **large** or **small** specifies either 40 or 5 resolved levels. Ten collapsed levels are used for the **small** option.

The following would set the full H-like isoelectronic sequence to a small number of levels, then reset hydrogen, helium, and iron to a large number.

```
atom H-like levels small
atom H-like levels large element hydrogen
atom H-like levels large element helium
atom H-like levels large element iron
```

*The He-like iso sequence.* If no number appears on the command, but the keyword **large** or **small** does, then the number of levels will be large enough to extend to either  $n = 40$  or 3. Actually, the atoms are coded so that there is no limit to the number of levels that can be included, other than the memory and computer time requirements.

Use the **atom xx-like print** to confirm that you are using the expected number of levels.

*Warning!* Note that the command

```
atom H-like levels large
```

will set all 30 hydrogenic atoms to a large number of levels. This would require roughly half a gigabyte of memory for the H-like sequence along, and would be very slow on today's computers. It is best to set only the most important elements to large levels.

### 12.5.12 Atom [H-like | He-like] Lyman options

This set of commands changes the treatment of the Lyman lines. For this purpose, the Lyman lines are all resonance lines, lines whose lower level is the ground state, of the iso sequences. (Actually, only the H I resonance lines are Lyman lines.)

#### Atom [H-like | He-like] Lyman extra 1000

Atoms and ions of the H-like and He-like isoelectronic sequences use complete multi-level model atoms. The number of levels included is limited mainly by processor speed and available memory. Higher Lyman lines (used here to mean permitted lines that connect directly to ground) have little impact on emission since they scatter and are degraded into Balmer lines and  $L\alpha$ . However, an absorption spectrum will show them as a series of lines converging onto the photoionization continuum from the ground state. The code includes a large number of "extra" Lyman lines, included as absorbers with optical depths output with the **save line optical depth** command, but not treated as part of the multi-level atoms. The default number of higher Lyman lines is 100, and this can be changed to any number with this command.

This changes the number of extra levels for the entire iso-electronic sequence.

#### Atom H-like Lyman pump

These commands control how continuum fluorescent excitation, "line pumping", is treated. They only modify the treatment of H I so the **H-like** keyword must appear.

#### Atom H-like Lyman pumping off

This turns off continuum radiative pumping of the Lyman lines of H I. This is one way to take into account the possible presence of Lyman absorption lines in the incident continuum.

#### Atom H-like Lyman pumping scale 3

The continuum radiative pumping rate of the Lyman lines of H I will be multiplied by the scale factor that appears on the line. This is meant to take into account the possible presence of Lyman lines in emission or absorption in the incident continuum. The pumping rate is normally set by the intensity of the coarse continuum at the line wavelength. The number that appears on the command line is a scale factor that multiplies this continuum.<sup>3</sup> Numbers  $\leq 0$  are interpreted as a log and the **log** keyword will force interpretation as a log. A value of greater than 1 would correspond to Lyman lines in emission in the incident radiation field. A scale factor of 2 would simulate the presence of stellar Lyman emission lines with peak intensities twice those of the neighboring continuum.

<sup>3</sup>In versions C08 and before a value of 0 would produce black Lyman lines. Starting in C10 values  $\leq 0$  are interpreted as logs so a value of 0 will result in a scale factor of unity.

### 12.5.13 Atom [h-like | he-like] NO RECOmbination INTERp

The code normally derives recombination coefficients by interpolating on a table that lives in the data directory. This command tells the code to compute recombination coefficients on the fly by integrating over the photoionization cross section.

### 12.5.14 Atom [h-like | he-like] REDI

There are three options, PRD, CRD, and CRDW, representing partial redistribution, complete redistribution (doppler core only, no wings) and complete with wings, respectively. Additional options are ALPH (to set value for Lyman  $\alpha$ ), RESO (to set value for other resonance lines), and SUBO (to set value for subordinate lines). SHOW to prints diagnostic output to confirm selected options.

### 12.5.15 Atom [h-like | he-like] redistribution [options]

This changes the form of the redistribution function for various lines within the model atom. This command is only used if you are not happy with the default redistribution functions. The command changes the redistribution functions for entire iso-sequences.

A keyword to specify which set of lines to change is required. This is one of **alpha** (the H-like  $2p - 1s$  transition or the He-like  $2^1P - 1^1S$  transition)), **resonance** (any higher Lyman line decaying to the ground term), or **subordinate** (all Balmer, Paschen, etc lines). The type of redistribution function to use must also be specified. The options are **PRD** (partial redistribution), **CRD** (complete redistribution with Doppler core only), and **CRDW** (complete redistribution with damping wings). (The underscore indicates a space.)

The keyword **show** prints the current default redistribution functions at the time when the command is parsed.

There is at present a fundamental uncertainty in the computation of the line radiation pressure for transitions such as  $L\alpha$ . For a simple two-level atom with incomplete redistribution, it has long been known that the line-width is proportional to  $(a\tau)^{1/3}$  (Adams, 1972, Harrington, 1973;  $a$  is the damping constant). It is also easily shown that for complete redistribution and a frequency independent source function that the line width would be determined by inverting the Voigt function, and hence proportional to  $(a\tau)^{1/2}$ . Line interlocking, whereby scattered Balmer line radiation broadens the upper level of  $L\alpha$  (Hubbard and Puetter, 1985), can alter the line width, as can collisional effects when the density is high enough for distant collisions to broaden the line. These effects cause major differences in radiation pressure and emergent flux (factors of several) for  $L\alpha$ , which can easily have an optical depth of  $10^7$ – $10^9$ , when Balmer lines are also optically thick. This command determines which approximation is used. The default condition is incomplete redistribution, which minimizes the line width and radiation pressure. This issue is discussed further in Elitzur and Ferland (1986).

### 12.5.16 Atom [h-like | he-like] toff off

This turns top off off or on. The default is to be on and the keyword **off** disables toff. Toff is necessary to obtain the correct total radiative recombination rate coefficient with a finite number of levels. Because only a finite number of levels can be computed the sum of the total recombination coefficient will be less than the sum to infinity. This difference must be added somewhere to conserve the total recombination rate. This changes the entire iso-sequence.

## 12.6 Atom Chianti [ options ]

This controls the use of the Chianti database (Dere et al. (1997); Landi et al. (2012)). The **save chianti** command described on page 171 can be used to export parts of the Chianti data.

The Chianti database does not contain collision strengths for subordinate transitions. By default, CLOUDY will use the gbar approximation to estimate collision strengths for allowed transitions that do not have data. The **Set Gbar** command controls the use of gbar in Chianti and is described on page 241.

### 12.6.1 Atom Chianti "masterlist.ini"

By default, CLOUDY uses selected Chianti species between phosphorus and zinc, specifically including Fe VI through Fe XXIV. These species are listed in the `CloudyChianti.ini` masterlist file in the `data/chianti/masterlist` directory. Files in that directory give other sets of species.

If a double quote appears on the line then the filename between the pair of double quotes will be used instead of the `CloudyChianti.ini` file. This makes it possible to create masterlist files that select portions of Chianti. The code will search for the masterlist file in the current directory then in `data/chianti/masterlist`.

### 12.6.2 Atom Chianti off

will disable all of Chianti.

### 12.6.3 Atom Chianti hybrid

Hybrid, the merging of the Chianti data with the Opacity Project data, is on by default if Chianti is on. The **no hybrid** option disables the Opacity Project data and only uses Chianti.

### 12.6.4 Atom Chianti print

will print which Chianti ions are being used along with the number of levels.

### 12.6.5 Atom Chianti Levels

sets the maximum number of Chianti energy levels. Some ions have a very large number of levels. These have a significant impact on the execution time but produce only weak lines and have a minor effect on the cooling for photoionized clouds. By default we limit the number of energy levels for Chianti iron species to 25 and all other elements to 15. Plasmas in collisional equilibrium tend to be hotter, for a given stage of ionization, than a photoionized plasma. The **Coronal** command, described on page 104, is used for the collisional ionization case. The limits to the number of levels are then 100 for iron and 50 for all others. The **levels** option will overwrite these limits. The first number, i, is the iron level limit, while the second number, j, is for all other Chianti elements. If no numbers appear but the keyword **MAX** does, we use all of the available energy levels.

### 12.6.6 Atom Chianti [experimental theoretical]

By default we use experimental Chianti energies. The **theoretical** option causes CLOUDY to only use theoretical energies. This provides significantly more levels and transitions, however the error in wavelength is larger.

The **atom Lamda** command, described on page 126, and the **atom Stout** command, described on page 126, do similar work for the Lamda and Stout databases.

## 12.7 Atom Lamda [ON , OFF]

This enables or disables molecular models from Lamda, the Leiden Atomic and Molecular Database (<http://www.strw.leidenuniv.nl/moldata/>, Schöier et al. (2005)). Note that some molecules in LAMDA are not currently known to CLOUDY's chemistry. CLOUDY therefore has no means by which to predict the abundance of those molecules. In such cases, the LAMDA models are simply ignored.

The **atom Chianti** command, described on page 125, and the **atom Stout** command, described on page 126, do similar work for the Chianti and Stout databases.

## 12.8 Atom Stout [on , off, no hybrid][print][levels {j, MAX}]

The command controls the use of the Stout database.

### 12.8.1 Atom Stout [on off]

command will enable or disable the use of the Stout database. It is on by default.

### 12.8.2 Atom Stout "masterlist.ini"

The species included in the filename between quotes will be used. By default we use species listed in the `Stout.ini` file in the `data/stout/masterlist` directory. This makes it possible to create `ini` files that select portions of Stout. The code will search for the masterlist file in the current directory then in `data/stout/masterlist`.

### 12.8.3 Atom Stout hybrid

Hybrid, the merging of the Stout data with the Opacity Project data, is on by default. The **no hybrid** option disables the Opacity Project data and only uses Stout.

### 12.8.4 Atom Stout print

will print which Stout species are being used along with the number of levels.

### 12.8.5 Atom Stout Levels

This sets the maximum number of Stout energy levels. Some ions may have a very large number of levels. These have a significant impact on the execution time but produce only weak lines and have a minor effect on the cooling for photoionized clouds. By default we limit the number of energy levels for Stout species to 100. The **levels** option will overwrite the limit. A number following the **levels**, `j`, will limit the number of Stout levels to that number. If no numbers appear but the keyword **MAX** does, we use all of the available energy levels.

The **atom Chianti** command, described on page 125, and the **atom Lamda** command, described on page 126, do similar work for the Chianti and Lamda databases.

# Chapter 13

## DYNAMICAL & TIME-DEPENDENT CALCULATIONS


### 13.1 Overview

This section describes the dynamical and time-dependent calculations that can be done with the code. This physics was developed in collaboration with Robin Williams and Will Henney, and [Henney et al. \(2005\)](#) and [Henney et al. \(2007\)](#) describe first applications.

These calculations begin by doing several iterations to compute the static structure. This establishes the optical depth scale that is used in later calculations. The number of static calculations is 2 by default and is reset with the **set dynamics relax** command.

Advective terms are included in the balance equations by adding upstream quantities that are taken from the previous iteration. Problems would arise if we needed to look upstream beyond the outer edge of the computed radial grid. To prevent this the outer radius found in the static iterations will be the outer radius of later calculations. This overrides the behavior of the **radius** command.

**Warning!** The physics behind these commands is still being developed. The heuristics that are needed to control changes in the time steps or the advancing upstream parameters are not complete. Output options to capture the information in the flow or over time are not complete. All of this is an area of active development.

In the following discussion commands that are still under development are introduced by the  symbol and are in a grey box.

### 13.2 cosmology

This follows the time dependent recombination of the early universe. It was added by Ryan Porter. It has several options.

#### 13.2.1 cosmology omega

This specifies an omega parameter. It accepts the keywords **baryon**, **radiation**, **matter**, **lambda**, and **K**.

### 13.2.2 cosmology Hubble

This specifies the Hubble constant in units of  $100 \text{ km s}^{-1} \text{ Mpc}^{-1}$ .

## 13.3 A cooling or heating non-equilibrium gas

This case is a non-equilibrium gas that cools down or heats up after an initial state is established. The usual case is a grain-free gas which is not exposed to an external radiation field. A unspecified process has established the gas in an equilibrium state, and the gas is allowed to freely cool or heat. A recent paper which studied this case is [Gnat and Sternberg \(2007\)](#).

This calculation is set up by doing an equilibrium coronal equilibrium calculation with the **coronal 1e4 K init time** command described on page 104. This establishes an equilibrium collisionally ionized gas by doing two iterations with the kinetic temperature held fixed at the specified value.

The **iterate to convergence** tells the code to keep performing time steps until some stopping criterion is met. The **stop time when temperature below** command tells the code to stop when the lowest temperature falls below the specified value.

A simple input script, from the test case `time_cool_cd.in` in the test suite, follows.

```
title constant density cooling cloud
c
c commands controlling continuum =====
c 3 keV
blackbody 3.4e7 K
ionization parameter -10 time
coronal 3.4e7 K init time
c
c commands for density & abundances =====
c want nT = 2e6 K cm-3
hden 5.88e-2 linear
c
c commands controlling geometry =====
set dr 0
set nend 1
stop zone 1
c
c other commands for details =====
c the time dependent calculations will start on iteration 3
c first two are to relax the calculation
set dynamics relax 2
c number of time steps
iterate 300
stop time when temperature falls below 1e5 K
time first timestep 11.5
time 10 scale 0
time 11 scale=0 recombination
time 20 scale=0
end of times
cosmic rays background
c
c commands controlling output =====
print line faint 2 log
print line cumulative
print ages
save time dependent "time_cool_cd.tim" no hash
save overview "time_cool_cd.ovr" no hash
save cooling "time_cool_cd.col" no hash
save heating "time_cool_cd.het" no hash
save continuum units Angstroms "time_cool_cd.con"
save cumulative continuum units Angstroms last "time_cool_cd.concum"
c
c commands giving the asserts =====
c
c time_cool_cd.in
c class dynamics
c =====
c

test time dependent cooling at constant density
```

## 13.4 Time-variable incident radiation field

This follows the time-dependent evolution of a cloud near a variable continuum or heat source.

Time-dependent calculations are done by setting up an initial geometry using the usual commands that specify a cloud and the incident radiation field. The **time** keyword establishes which energy sources vary with time. The keyword can appear on any of the commands that specify the luminosity of the radiation field and on the **hextra** command. The **trace** option will turn on trace printout.

If a **time** command also occurs then all radiative and heat sources with the **time** keyword will change with time. The **time** command sets a time step and stopping time. Each iteration is a time step and the number of time steps is set with the **iterate** command. The calculation will stop when either the number of iterations or the stopping time is reached.

### 13.4.1 time command

The first argument on the **time** command is the log of the initial time step in seconds. The calculation starts at time zero and the first time step will be this long. Later time steps will have their size adjusted by the rate of change in conditions in the gas. The optional second number gives the log of the stopping time in seconds. The calculation will stop when either this time or the number of iterations is reached.

The **time** command is followed by a table giving the logs of the elapsed time (seconds) and the log of a scale factor giving the brightness of the variable radiation source relative to the value specified in the luminosity command.

The variation of luminosity is linearly interpolated between the points specified: the first point gives the initial scale factor. The code will not extrapolate to times beyond the end of the table, but for one exception. If the keyword **cycle** appears on any line specifying an elapsed time, the code will treat that time as a period and repeat all previous time steps with that period (the specified period must be greater than all previously-specified elapsed times). It will stop if it needs to look up times beyond the last tabulated value. The following is a simple example:

```
// set the continuum and a variable flux of H-ionizing photons
blackbody T=4e4 K
phi(H) 13.5 time
// set a limit of 50 time steps. The calculations will actually
// stop when we reach total age
iterate 50 times
// the time command sets a time step of 1e7 s and a stop time of 1e8 s.
// This requires ten time steps. We set 50 iterations above but the
// calculation will actually stop when the age of 1e8 s is reached.
// The time command is followed by a table giving the log of the age and the
// log of the brightness of the energy source relative to its initial value.
// The table ends with the line saying "end of times"
time steps=7 s stop at 8 s
age = 0 scale = 0
age = 7.3 scale = 0
age = 7.35 scale = 5
age = 7.5 scale = 5
age = 7.55 scale = 0
age = 10 scale = 0
end of times
// commands to set hydrogen density, only done one zone
```

```
hden 5
stop zone 1
```

In this example only one radiation field is given and the flux of hydrogen-ionizing photons varies with time. A constant time step of  $10^7$  s is used. The **time** command is followed by the series of lines giving the brightness of the incident radiation field as a function of time. The series ends with the line starting with **end**. Each of the lines in the age—brightness table starts with **age** but these characters are ignored. They are only present to improve readability.

### 13.4.2 Time-step size increment

```
c first set the continuum
blackbody T=4e4 K
c this continuum will vary with time
ionization parameter -2 time
c the CMB will be constant
CMB
c do 50 time steps
iterate 50 times
c the time command itself, followed by a table of times & continua
time 7.5
  7      scale= 0
  7.1    scale=-5 recombination
  9.3    scale=-5
  9.301  scale= 0 ionization, factor = 1.1
  20     scale= 0
end of time
c first set the continuum
blackbody T=4e4 K
c this continuum will vary with time
ionization parameter -2 time
c the CMB will be constant
CMB
c do 50 time steps
iterate 50 times
c the time command itself, followed by a table of times & continua
time 7.5
time = 7      scale= 0
time = 7.1    scale=-5 recombination
time = 9.3    scale=-5
time = 9.301  scale= 0 ionization, factor = 1.1
time = 20     scale= 0
end of time
```

In this example the incident radiation field is a blackbody with its intensity set by an ionization parameter. The code does fifty iterations with a time step of  $10^{7.5}$  s since this is specified on the initial **time** command line. In the table the blackbody is left at its initial brightness for the first  $10^7$  s then lowered to  $10^{-5}$  of the initial value for a total of  $10^{9.3}$  s when it is raised back to the initial value.

As given above, the time steps always have the same size, the size given on the initial **time** command. It is also possible to specify the size of the time step for each elapsed time that appears in the table that gives the continuum brightness. If all of the optional time-step sizes are specified then they are used in place of

the time step given on the **time** command. The time step sizes are multiplicatively increased by the time-step scale factor. It is also possible to give a time-step scale factor saying how to increase the time step.

If any are missing then the time step on the command is used and is kept constant. The table ends with a line saying **end**. If the optional end time is not specified on the **time** command then the calculation will continue until the specified number of iterations has been performed.

### 13.4.3 Keywords on individual time-step entries

Most of the letters on the lines giving the times and scale factors are totally ignored. They are there to make the table easier to read. There are keywords which indicate that a particular time step marks the start of a special case, such as the recombination of a highly ionized gas or the propagation of an ionization front into neutral gas.

The keyword **recombination** indicates that this time step is the first where the continuum source will be dramatically fainter. Certain heuristics are used to follow the recombination and cooling of the gas.

The recombination heuristics are not complete and the ionization heuristics do not exist..

### 13.4.4 Varying individual continua

The keyword **time** is used to specify which continua will be scaled with time and can appear on any of the luminosity / intensity commands given in Chapter 5. This makes it possible to vary only some of the continua while others are left constant. For instance, a constant CMB and a variable star can be treated. At least one of the luminosity commands must have a **time** keyword for time-dependent calculations to be done.

The **hextra** command includes the **time** keyword. The variable scale factor will apply to the extra heating in this case.

### 13.4.5 Controlling the number of time steps

Each iteration is a time stop. The **iterate to convergence** command has a special meaning in time-dependent calculations. In this case it tells the code to keep performing iterations, stepping through time, until one of the special criteria set with a **stop time** command is satisfied. The following **stop time** commands are implemented.

#### Stop temperature time [exceeds]

The **stop temperature** command is described on page 145. It has two forms. Usually it specifies the lowest temperature to allow in a calculation. If the keyword **exceeds** appears then it specifies the highest temperature to permit.

The **time** keyword tells the code to stop time when the highest or lowest temperature occurring anywhere in the computed structure is above or below the limits set with this command.

### 13.4.6 Other commands

The **coronal** command has the **time init** option. This will include thermal collisional ionization for the initial evaluations of the simulation. The kinetic temperature will be free when the time-dependent calculation starts.

### 13.5 Wind velocity=300 km/sec [mass =1.4 Msun, disk, ballistic, static]

The geometry will be a wind. The first number is the initial velocity in  $\text{km s}^{-1}$ . The second optional number is the central mass in solar mass units. Both are linear quantities. The previous form of this command without a **velocity** specification is now deprecated.

The equations of motion are solved including the inward pull of gravity. The gravitational acceleration in the default non-rotating case is evaluated as

$$g = -\frac{GM}{r^2} [\text{cm s}^{-2}]. \quad (13.1)$$

The mass of the central object is given in solar masses on the command line but is evaluated in gm within the code. If the mass is not specified then zero is assumed. If the mass is specified and the keyword **disk** also appears then the geometry is assumed to be a rotating disk. In this case the inward gravitational acceleration is

$$g = -\frac{GM}{r^2} \left(1 - \frac{r_o}{r}\right) [\text{cm s}^{-2}] \quad (13.2)$$

where  $r_o$  is the inner radius.

The line widths and escape probabilities are evaluated in the Sobolev or Large Velocity Gradient (LVG) approximation. The effective line optical depth is given by

$$\tau_{l,u}(R) = \alpha_{l,u} \min(r, \Delta r) \left( n_l - n_u \frac{g_l}{g_u} \right) \left( \frac{u_{th}}{\max(u_{th}, u_{exp})} \right) [\text{Napier}] \quad (13.3)$$

where  $u_{th}$  and  $u_{exp}$  are the thermal and expansion velocities respectively and the radius used is the smaller of the depth or the radius. This is necessary to keep the effective column density from becoming larger than the total cloud column density when the radius is large and the expansion velocity is small.

#### 13.5.1 Ballistic solutions

A **ballistic** flag (or *positive velocity* in the case with no **velocity** specification) indicates the hypersonic wind solution that has been a part of the code since its beginnings. (Note that the negative velocity case has however not yet been tested thoroughly.) The equations of motion of the gas are solved, not including forces due to material pressure gradients. Acceleration due to line and continuous opacity of the gas and deceleration due to the gravity of the central object are included. The calculation will stop if the gas comes to rest or if any of the other stopping criteria is met. The initial velocity must be above the sonic point. Further details are presented in a section in Part 2.

The first parameter is the expansion velocity  $u_o$  at the illuminated face of the cloud. The approximations used are only correct if the flow speed remains well above the sound speed throughout the structure. The initial velocity is entered in  $\text{km s}^{-1}$ . The density at the illuminated face of the cloud is entered with the **hden** command and the density is varied across the model to conserve mass flux (i.e., the product  $\rho(r)r^2u(r)$  is kept constant). Because of this a filling factor would not make physical sense and should not be used (although it can be). The optional second parameter is the mass of the central star in solar units; its default value is one solar mass.



Without a **ballistic** flag (or A *negative velocity* in the case with no **velocity** specification) the code simulates the flow including corrections due to pressure gradients in the flow, appropriate to a weak-D or D-critical H II region (Henney et al., 2005). (Note that the positive velocity case has however not yet been tested thoroughly.) This physics is currently under development in collaboration with Will Henney and Robin Williams. The central object mass is set to zero.

### 13.5.2 wind advection, velocity=-5 km/s

The **advection** keyword says to include the effects of advection on the thermal and ionization equations. Currently advection is only treated in the case where the velocity is negative, corresponding to a flow off a molecular cloud towards the source of ionizing radiation. The argument is the initial gas flow speed in  $\text{km s}^{-1}$ . This physics is being developed in collaboration with Robin Williams and Will Henney and is not yet mature.

The advection case has the following options. In all cases the numerical parameter follows the keyword. There can be many parameters on one command line.

**velocity-** The number following this keyword is the velocity in  $\text{km s}^{-1}$ . The following would specify a simple R-type front

**center, index-** A varying mass flux with depth into the grid is specified by a law  $\rho u = \Phi_o(r - c)^i$ . This gives the variation in flux with distance  $r$  into the grid as a function of value  $c$  given by the **center** parameter and the value  $i$  given by the **index** parameter. For example,

```
wind advection velocity -20 center 1e16 index -2
```

would correspond to a wind diverging spherically from a point  $10^{16}$  cm into the grid with a velocity of  $20 \text{ km s}^{-1}$  at the illuminated face. By default the mass flux is constant ( $i = 0$ ). If these are not specified then zero is assumed.

**dfdr-** This specifies the mass flux gradient,  $\Phi' = d\rho u/dr [\text{g cm}^{-3} \text{ s}^{-1}]$ , as an alternative to specifying the velocity. This is useful in the case in which the flow reaches stagnation at the surface of the model, in which case the velocity itself does not fully constrain the physical parameters.

**wind advection dfdr- 20.90 index 2**

The **set dynamics** command described below controls many details of the dynamics. The **set dynamics pressure mode** command tells the code whether it should search for globally subsonic or supersonic solution. If this is not specified the code will compare the ram and gas pressure at the illuminated face to try to determine whether a super- or sub-sonic solution is appropriate.

**Convergence-** the level of convergence can be estimated by comparing the discretization error and convergence error as a function of iteration, as shown in Figure 4 of Henney et al. (2005).

### 13.5.3 Wind 5 km/s no continuum

The **no continuum** keyword tells the code not to include continuous absorption in the calculation of the radiative acceleration.

The **no induced processes** command will turn off line radiative acceleration. It has other physical consequences since all fluorescent excitation processes are turned off.

## 13.6 Miscellaneous dynamics commands

### 13.6.1 Constant pressure time

This allows the pressure to vary with time. See Section 8.2.5 *Constant pressure timescale = 2.3e9 s, alpha=-1* for more details.

### 13.6.2 Set dynamics [options]

This changes some aspects of the dynamics solutions when advective winds are used.

**set dynamics advection length [fraction ]** This sets the look-back distance used for the advection terms in the initial iterations of the solutions. Its optimum value is determined by a compromise between speed of convergence (which is improved for large lengths) and accuracy (which is improved for small lengths). The code automatically cuts the look-back distance when good convergence is obtained so a reasonably large value can be assumed initially.

If the keyword **fraction** occurs then the number on the line will be the fraction of the total depth of the model. It is the log of the fraction if it is negative. If fraction does not occur then the number is the log of the scale length in cm.

**set dynamics antishock depth 16** would put an anti-shock at a depth of  $10^{16}$  cm.

**set dynamics antishock Mach 1.01** would put in an anti-shock when the mach number fell below 1.01.

**set dynamics population equilibrium** This uses the equilibrium solution rather than the non-equilibrium solution that is done in a dynamical or time-dependent model.

**set dynamics pressure mode** This changes some aspects of how the pressure solver deals with the sonic point. The options are: **original**, **subsonic**, **supersonic**, and **strongd**. The default chooses subsonic or supersonic based on a comparison of the ram pressure and gas pressure at the face. **Original** mode uses similar criteria to choose in each zone but is liable to oscillation. **Subsonic** and **supersonic** will force a globally subsonic or supersonic solution. **Original** and **strongd** can pass through a sonic point. **Strongd** does this by following the supersonic branch until there is no valid pressure solution, then following the minimum of the pressure-density relation until it can leave along the subsonic branch. By varying the face conditions, the depth of the internal region of unphysical solution values can be minimized, to converge on a physical strong-D type solution.

**set dynamics shock depth.** The argument is the log of the shock depth in cm.

**set dynamics relax 3.** This gives the number of static iterations to be performed before dynamical or time-dependent behavior begins. The initial iterations are done to establish the equilibrium geometry, optical depth scale, and other properties. The default is to do 2 iterations to relax the solution.

## 13.7 Useful output options

### 13.7.1 Print cumulative lines

This gives the time-integrated energy in the emission lines reported in the main printout. See page [153](#) for a description of this command.

### 13.7.2 Save commands, general comments

**Save** commands count every time step counting as an iteration. If you specify the **last** option you will only obtain save output for the last time step.

### 13.7.3 Save cumulative continuum

This gives the time-integrated cumulative energy in the spectrum reported in the **Save continuum** command. See page [167](#) for a description of this command.

### 13.7.4 Save time dependent

This gives some information about each time step. See page [195](#) for more information.

### 13.7.5 Set save hash options

The **set save hash** command (page [246](#)) has a **time** option to include the time on every time step in save output.



# Chapter 14

## STOPPING CRITERIA

### 14.1 Overview

CLOUDY will stop at some depth into the cloud. The physics that sets this depth is important since it can directly affect predicted quantities. This chapter describes various stopping criteria.

Two geometries, matter bounded and radiation bounded, can be identified for an ionized gas.

A radiation-bounded cloud is one where the outer edge of the emitting gas is a hydrogen ionization front. In this case the calculation stops because nearly all ionizing radiation has been attenuated and the temperature falls below 4000 K, the default lowest-allowed kinetic temperature. This choice of lowest temperature was made with optical emission lines in mind. Setting another outer limit is not necessary unless molecules or lines with very low ionization and excitation potentials (i.e., the [C II] or [O I] far infrared lines) are of interest. You lower the stopping temperature with the **stop temperature** command.

In a matter-bounded cloud the gas is optically thin to energetic radiation and the outer radius of the cloud must be specified. This could be a column density, physical thickness in cm, or optical depth. More than one stopping criterion can be specified and the calculation will stop when the first one is met.

CLOUDY will say why it stopped after the results of the last zone calculation are printed. It is very important to make sure that the calculation stopped for the reason you intended.

If no stopping criteria are set the calculation will usually stop because the default lowest temperature (4000 K) or the default greatest number of zones (1400) was reached.

### 14.2 Danger! Understand why the calculation stopped!

Sometimes the predicted emission-line spectrum will depend strongly on the thickness of the cloud. The cloud thickness is set by the stopping criteria. The predicted intensity will depend on thickness if the outer edge of the cloud is within a line's creation region. This is often the case for some lines in an X-ray irradiated gas and for any radiation field and molecular or low-ionization infrared lines.

There are several checks that should be made to confirm that the spectrum is the one expected and not an artifact of the cloud thickness or stopping criteria. The first and most important is to understand *why* the calculation stopped. This is explained in the first comment after the last zone is printed. First locate the print out for the last zone. The following example, from the `pn_paris` simulation, shows the printout that includes the last zone's results and the start of the calculation's summary. The first line after the ionization distribution of iron gives the title for the model and the line after that gives the reason that the calculation stopped. In this case the calculation stopped because the kinetic temperature fell below the lowest temperature, which was left at its default of 4000 K. This occurs very near the hydrogen  $H^+ - H^0$  ionization

front. Optical and UV lines form at higher temperatures so the calculation would include all contributors to the optical/UV spectrum. Lines such as [C II]  $158\mu$  or [Si II]  $34.8\mu$  form in cool neutral gas, so these lines would become stronger if the calculation went more deeply, into cold neutral gas.

```
####150 Te:3.978E+03 Hden:3.000E+03 Ne:1.276E+02 R:4.062E+17 R-R0:3.062E+17 dR:5.658E+13 NTR: 5 Htot:4.094E-19 T912: 9.97e+07###
Hydrogen 9.70e-01 2.97e-02 H+o/Hden 1.00e+00 3.57e-09 H- H2 1.57e-07 5.07e-10 H2+ HeH+ 8.59e-08 Ho+ CoId 3.27e+19 8.86e+20
Helium 8.77e-01 1.23e-01 1.81e-04 He I2SP3 4.78e-08 5.43e-16 Comp H,C 1.39e-26 3.59e-27 Fill Fac 1.00e+00 Gam1/tot 6.57e-01
Carbon 2.50e-04 9.97e-01 3.12e-03 0.00e+00 0.00e+00 0.00e+00 0.00e+00 H2O+O 0.00e+00 OH+/Otot 0.00e+00 Hex(tot) 0.00e+00
Sulphur 0 7.02e-05 9.64e-01 3.56e-02 2.36e-06 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00
Argon 0 7.82e-01 1.96e-01 2.24e-02 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00
Iron 0 9.25e-06 9.97e-01 2.80e-03 3.42e-06 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00 0.00e+00
parisprn.in Meudon Planetary nebula
Calculation stopped because lowest Te reached. Iteration 1 of 1
The geometry is spherical.
!Some input lines contained [ or ], these were changed to spaces.
!Non-collisional excitation of [OIII] 4363 reached 2.35% of the total.
!AGE: Cloud age was not set. Longest timescale was 3.68e+012 s = 1.17e+005 years.
Suprathermal collisional ionization of H reached 9.48% of the local H ionization rate.
Charge transfer ionization of H reached 8.94% of the local H ionization rate.
```

Left on its own, the code will probably stop when the temperature falls below the default lowest temperature of 4000 K. This is what happened in the preceding example. This temperature was chosen for two reasons; a) collisionally excited optical and ultraviolet lines generally form in gas hotter than this (but infrared lines will form at far lower temperatures) and b) more than one thermal solution is possible for temperatures around 3000 K (Williams, 1967), so thermal instabilities may result if the gas extends to cooler temperatures.

It is a good idea to check whether the predictions would change if the model were made thicker or thinner. It is safe to assume that a line's intensity does not depend on the thickness of the cloud if the final temperature is well below the excitation potential of the line or the gas is more neutral than the species of interest.

The chapter *Output* in Part 2 of this document lists all possible reasons for stopping.

## 14.3 Radius inner =18 [thickness =16; parsec; linear]

The optional second number on the **radius** command sets the thickness or outer radius of the cloud.

## 14.4 Stop AV 12.1 [point, extended]

This stops a calculation at a specified visual extinction  $A_V$ . The value is the extinction in magnitudes at the isophotal wavelength of the V filter (5500Å). The number is the linear extinction in magnitudes unless it is negative, when it is interpreted as the log of the extinction. Note that there must be spaces before and after the key “AV.”

Properties of grains are determined by the **grains** command. The distinction between the extinction for a point versus an extended source is described in section 7.6 of AGN3. By default the  $A_V$  specified with this command will be for a point source, which is the quantity measured in extinction studies of stars. The extended-source extinction, appropriate for extinction of a spatially-resolved emission-line region, is specified with the keyword **extended**.

## 14.5 Stop column density = 23 [neutral; ionized; total; ...]

This stops the calculation at the specified hydrogen column density  $N(\text{H})$  [ $\text{cm}^{-2}$ ]. There are several optional keywords which determine whether the column density is the total (the default), the ionized

hydrogen column density, the neutral hydrogen column density, or several other column densities. The default stopping column density is  $10^{30} \text{ cm}^{-2}$ .

By default the number on the line is interpreted as the log of the column density. The keyword **linear** forces that interpretation.

### 14.5.1 Stop column density 23

The number is the log of the total hydrogen column density (atomic, ionic, and all molecular forms), defined as the integral

$$N(\text{H}) = \int \left\{ n(\text{H}^0) + n(\text{H}^+) + 2n(\text{H}_2) + \sum_{\text{other}} n(\text{H}_{\text{other}}) \right\} f(r) dr [\text{cm}^{-2}] \quad (14.1)$$

where  $f(r)$  is the filling factor.

### 14.5.2 Stop neutral column density 23

The number is the log of the atomic hydrogen column density

$$N(\text{H}^0) = \int n(\text{H}^0) f(r) dr [\text{cm}^{-2}]. \quad (14.2)$$

### 14.5.3 Stop ionized column density 23

The number is the log of the ionized hydrogen column density

$$N(\text{H}^+) = \int n(\text{H}^+) f(r) dr [\text{cm}^{-2}]. \quad (14.3)$$

### 14.5.4 Stop atomic column density 21.3

In some PDR literature the atomic hydrogen column density is defined as the sum of  $\text{H}^0$  and  $\text{H}_2$ . This command allows the calculation to stop as this summed column density, defined as

$$N(\text{H}^0 + 2\text{H}_2) = \int [n(\text{H}^0) + 2n(\text{H}_2)] f(r) dr [\text{cm}^{-2}]. \quad (14.4)$$

This command was added by Nick Abel. Note that this counts each  $\text{H}_2$  as two hydrogen atoms.

### 14.5.5 Stop H/TSpin column density 17.2

This calculation stops at the specified integral

$$N(\text{H}^0) / T_{\text{spin}} = \int \frac{n(\text{H}^0)}{T_{\text{spin}}} f(r) dr [\text{K}^{-1} \text{cm}^{-2}]. \quad (14.5)$$

Note that  $T_{\text{spin}}$  is computed self-consistently including the effects of pumping by the background continuum (usually the CMB) and the local  $\text{L}\alpha$  radiation field.

### 14.5.6 Stop H2 column density 19.2

The calculation stops at the specified molecular hydrogen column density

$$N(\text{H}_2) = \int n(\text{H}_2) f(r) dr [\text{cm}^{-2}]. \quad (14.6)$$

The 2 in **H2** must come before the log of the column density in the command. This is really the H<sub>2</sub> column density, not twice it.

### 14.5.7 Stop CO column density 19.2

The calculation stops at the specified column density in CO

$$N(\text{CO}) = \int n(\text{CO}) f(r) dr [\text{cm}^{-2}]. \quad (14.7)$$

This command was added by Nick Abel.

### 14.5.8 Stop column density “OH” 19.2

The calculation stops at the specified column density in the species given in quotes. If the species is not recognized, the command will have no effect. This command is experimental.

### 14.5.9 Stop effective column density 23

This is actually a form of the **stop optical depth** command. Usually, low-energy cutoffs in X-ray spectra are parameterized by the equivalent column density of a cold neutral absorber with cosmic abundances. Actually what is measured is an optical depth at some energy, generally around 1.0 keV. If the gas is ionized then a much larger column density will be needed to produce the observed absorption. The difference can be more than an order of magnitude. This command stops the calculation when the incident continuum has been attenuated by the appropriate absorption at 1.0 keV. The calculation stops when the absorption optical depth at 1.0 keV (neglecting scattering opacities) reaches a value of

$$\tau_{abs}(1.0 \text{ keV}) = N_{effec} 2.14 \times 10^{-22} [\text{Napier}] \quad (14.8)$$

at 73.5 Ryd. The argument of this command is the log of the effective column density  $N_{effec}$ . The absorption cross-section per proton for cold neutral gas is taken from [Morrison and McCammon \(1983\)](#). Scattering opacities *are not* included in this optical depth. No attempt is made to use realistic physical conditions or absorption cross sections—this command follows the Morrison & McCammon paper.

If the gas is highly ionized then the actual column density will be greater than the effective column density. It will be less if the abundances of the heavy elements are greatly enhanced.

## 14.6 Stop continuum flux 200 micron 65 Jansky

This commands allows you to stop the calculation when an observed continuum flux or surface brightness at an arbitrary wavelength is reached. Note that both the keywords **continuum** and **flux** need to be present on the command line. The first parameter must be the wavelength or frequency of the observation. The

second must be the flux or surface brightness. The syntax for these parameters is exactly the same as for the **optimize continuum flux** command described in Section 16.4.3. If the flux is  $\leq 0$ , or the keyword **log** appears on the line, it will be assumed that the flux is logarithmic (but not the wavelength or frequency!).

The code will implicitly behave as if a **set nFnu add** command had been given, except that the **print continuum** output will not be turned on. Observed fluxes must be dereddened for any extinction inbetween the source and the observer. The same normalization will be used as in the rest of the Cloudy output. So if you include the **print line flux at earth** command, you should enter the observed flux at Earth here. See Section 15.21.7 for further details. See also Section 18.14.36 for a discussion of the components that are included in the continuum flux prediction.

There is no limit to the number of **stop continuum flux** commands. The following gives some examples of its use:

```
// make sure we normalize the flux as observed
print line flux seen at earth
// and set the distance
distance 980 linear parsec

// stop when a dust continuum flux, e.g. measured by IRAS is reached
stop continuum flux 60 micron 220 Jy

// stop when a measured radio continuum flux is reached
stop continuum flux 6 cm 50 mJy
// same for an OCRA measurement...
stop continuum flux 30 GHz 0.1 jansky

// this will stop on a flux of 1e-21 erg s^-1 cm^-2 Hz^-1 (100 Jy) at 100 micron
stop continuum flux 100 micron -21 erg/s/sqcm/Hz
```

## 14.7 Stop depth ...

This is another name for the **stop thickness** command described on page 145 below.

## 14.8 Stop eden 3 [linear]

The calculation stops when the electron density falls below the indicated value. The number is the log of the electron density [ $\text{cm}^{-3}$ ]. The optional keyword **linear** will force the argument to be interpreted as the quantity itself, not its log. This command is one way to stop constant-temperature models. For instance, the calculation can be forced to stop at the  $\text{H}^+ - \text{H}^0$  ionization front by setting the stopping electron density to approximately half of the hydrogen density.

The following examples show a case that will stop near the  $\text{He}^{2+} - \text{He}^+$  ionization front and a case that will stop near the  $\text{H}^+ - \text{H}^0$  ionization front for solar abundances.

```
//
// stop at the He++ - He+ ionization front
hden 9
stop eden 9.06 // stop when helium (10\% by number) is He+

//
// stop at H+ - H0 ionization front
hden 5
```

```
stop eden 4.5 // stop when electron dens falls below H density
```

The default is an electron density of  $-10^{30} \text{ cm}^{-3}$ . (The negative sign is not a typo.)

## 14.9 Stop efrac = 1.05

The model will stop when the electron fraction, defined as the ratio of electron to total hydrogen densities, falls below the indicated value. This is another way to stop calculations at ionization fronts. This is useful if the hydrogen density there is not known beforehand as occurs in constant-pressure calculations. The argument is the fraction itself if it is greater than zero and the log of the fraction if it is  $\leq 0$ .

The default is an electron fraction of  $-10^{37} \text{ cm}^{-3}$ . (The negative sign is not a typo.)

## 14.10 Stop line "C 2" 157.6m reaches 0.2 rel to "O 3" 5007

The calculation will stop when the emission line with the label given within the first pair of quotes and the wavelength given by the first number exceeds an intensity given by the second number, relative to an optional second emission line. In this example the calculation will stop when the intensity of [C II]  $158 \mu\text{m}$  reaches 0.2 relative to [O III]  $\lambda 5007$ . If a second optional line is not entered it will be  $\text{H}\beta$ <sup>30, 1</sup>. This can be a useful way to stop matter-bounded models. The results of this command are not exact; the final intensity ratio will be slightly larger than the ratio specified.

Intrinsic intensities are used by default. Emergent intensities will be used if the keyword **emergent** appears on the command line.

The line label and wavelength should be entered exactly as it appears in the emission-line output. The line label within the quotes must have the same number of spaces as in the output. "C 2" and "C 2" are not the same (the first has only one space and the second is correct with two spaces). The wavelength is assumed to be in Angstroms if no letter follows it. The wavelength can be changed to microns or centimeters by immediately following the wavelength with 'm' or 'c' so that the [C II]  $157.6\mu\text{m}$  would be written as "157.6m".

Up to 10 different **stop line** commands may be entered. If more than one **stop line** command is entered then the code will stop when any limit is reached.

## 14.11 Stop mass 32.98

The calculation will stop when the total mass of the computed structure exceeds the quantity entered. If the inner radius is specified (the luminosity case) then the entered number is the log of the mass in gm. If the inner radius is not specified (the intensity case) then it is the log of the mass per unit area,  $\text{gm cm}^{-2}$ .

At the current time no attempt is made to make the computed mass exactly equal to the entered number. The calculation will stop after the zone where the mass is first exceeded.

---

<sup>1</sup>The scaling of the line intensities can be changed with the **normalize** command. That command can change both the normalization line (usually  $\text{H}\beta$ ) and its relative intensity (usually 1). If the second line is not set with the **stop line** command then  $\text{H}\beta$  is the denominator in the ratio. The **stop line** command always uses the ratio of the two line intensities on the scale that is set with the **normalize** command. In versions C07.02 and before the **normalize** command did not interact with the stop line command.

## 14.12 Stop mfrac = 0.5

The calculation stops when the hydrogen molecular fraction, defined as  $2n(\text{H}_2)/n(\text{H}_{\text{tot}})$ , exceeds the indicated value. This is a way to stop calculations within a PDR. The argument is interpreted as the molecular fraction itself if it is greater than zero and as the log of the fraction if it is less than or equal to zero.

The default is a molecular fraction of  $10^{37} \text{cm}^{-3}$ .

## 14.13 Stop molecule depletion -2

Nick Abel incorporated the condensation of molecules onto grain surfaces. Currently CO, H<sub>2</sub>, and OH condensation are treated. The density of molecules on grains is given as a species with the molecule's usual label, "CO", "H2", or "OH", followed by the string "gr". The rates of UV and cosmic ray desorption along with accretion come from [Hasegawa et al. \(1992\)](#) and [Hasegawa and Herbst \(1993\)](#). The grain surface chemistry mentioned in these papers is not included so our treatment of condensation is closer to the work of [Bergin et al. \(1995\)](#), who also use the Hasegawa et al. rates. Use the **no grain molecules** command to turn off this condensation.

## 14.14 Stop nTotalIoniz 100

This is a way to stop a calculation while debugging and is not normally used. The variable with this name is incremented each time the ionization evaluation routine is called. This command will cause the calculation to abort after the specified number of calls.

## 14.15 Stop optical depth -1 at 2.3 Ryd

This command stops the calculation at an arbitrary continuum absorption optical depth. The first number is the log of the optical depth. The optical depth is interpreted as a log by default. If the **linear** keyword occurs then the number is interpreted as the linear value. The optical depth is only for absorption and does not include scattering opacities. The second number is the energy in Rydbergs. It is interpreted as a log if it is negative, as linear if positive, and must be within the energy bounds considered by the code (presently  $1.001 \times 10^{-8}$  Ryd to  $7.354 \times 10^6$  Ryd). At present only one stopping optical depth can be specified. If more than one is entered then only the last is honored.

It is traditional in X-ray astronomy to characterize low-energy cut-offs as the equivalent *completely neutral* column density for *solar* abundances. This is not correct when the gas is ionized (since the high-energy absorption opacity is diminished) or when the abundances of the heavy elements are enhanced (since the high-energy opacity is increased). For extreme cases these effects can change the opacity by more than an order of magnitude. The deduced column density is underestimated by the same amount. It is better to convert the deduced column density back into an optical depth at 0.5 or 1 keV (this is actually the observed quantity) and use this optical depth and energy as the stopping criteria than to use the deduced column density as a stopping criterion. Either this command, or the **stop effective column density** command (which is actually a form of the **stop optical depth** command) can be used to stop the calculation at an X-ray optical depth corresponding to a certain low-energy absorption.

The optical depth used in this command is the absorption optical depth and does not include scattering opacities. In general, the effects of scattering opacities are much more geometry dependent than absorption opacities.

### 14.15.1 Stop Balmer optical depth = -.3

This command is a special case of the **stop optical depth** command in which the energy does not need to be specified but the keyword **Balmer** is given. It will stop the calculation when the log of the absorption optical depth at the Balmer continuum threshold ( $\nu = 0.250$  Ryd) reaches the specified value. The default is  $\tau_{Bac} = 10^{20}$  and the optical depth is always interpreted as a log. This is the *total absorption* optical depth at the Balmer edge and includes all computed absorption opacity sources such as grains or free-free absorption, but neglects scattering.

### 14.15.2 Stop Lyman optical depth = 5

This is a special case of the **stop optical depth** command in which the energy does not need to be specified but the keyword **Lyman** is given. The number is the log of the Lyman limit optical depth,  $\tau_{12}$ . The default value is  $\tau_{12} = 10^{20}$ . The stopping criterion is *really* the *total* 912Å *absorption* optical depth and *not* the hydrogen Lyman limit optical depth at 912Å. These are not exactly the same, especially when grains are present or the abundances of the heavy elements are enhanced.

### 14.15.3 Stop 21cm optical depth = linear 3

This stops the calculation when the *line center* optical depth of H I  $\lambda 21$  cm reaches the entered value. The populations of the hyperfine levels are determined by solving the full level populations with the effects of pumping by  $L\alpha$  and the external continuum included. The calculation stops when the optical depth from the continuum source to the outer edge of the cloud exceeds the entered value. The actual optical depth will be greater than or equal to the indicated value.

Note that CLOUDY always uses the dimensionless *line center* optical depth. The *integrated* optical depth is the standard used in radio astronomy. The *integrated* optical depth is called the *mean* optical depth in optical spectroscopy. The dimensionless mean optical depth is  $\sqrt{\pi}$  larger than the line center optical depth. In radio astronomy, the integrated optical depth is often given in velocity units,  $\text{km s}^{-1}$ .

## 14.16 Stop pfrac = 0.23

The calculation will stop when the proton fraction, defined as the ratio of proton (ionized hydrogen) to total hydrogen densities, falls below the indicated value. This is another way to stop calculations at ionization fronts and is useful if the hydrogen density there is not known beforehand. This occurs in constant pressure calculations, for instance. The argument is interpreted as the fraction itself if it is greater than zero and the log of the fraction if it is less than or equal to zero.

The default is an proton fraction of  $-10^{37} \text{ cm}^{-3}$ . (The negative sign is not a typo.)

## 14.17 Stop radius 17.3 [parsec; linear; 17.6 on sec iter]

This sets an upper limit to the radius of the cloud. The argument is interpreted as the log of the radius unless the keyword **linear** appears. The default unit is centimeter but it will be interpreted as the log of the radius in parsec if the keyword **parsec** appears on the line.

The **stop radius** command has the same effect as the optional second number on the **radius** command.

Any number of radii may be entered on the command line. Each will be the ending radius for consecutive iterations. The limit to the number of stopping values is set by the limit to the number of iterations that can

be performed. If fewer numbers are entered than iterations performed then the last number will be used for all further iterations.

This command is useful if you want to vary the inner radius in an optimizer run, but want to keep the outer radius fixed. If you do so, make sure that you set the upper limit of the inner radius to a value less than the outer radius. You can do this with the **optimize range** command. If you did not set an upper limit and the optimizer would try to move the inner radius beyond the outer radius, the code would abort.

## 14.18 Stop temperature 1e3 K [linear, exceeds]

The calculation will stop when the kinetic temperature drops below  $T_{low}$ , the argument of this command. The argument is interpreted as the log of the temperature if  $\leq 10$  and as the linear temperature if  $> 10$  or if the **linear** keyword appears.

The default value is  $T_{low} = 4000$  K. Gas cooler than this produces little optical emission, but may be a strong emitter of infrared lines such as the [C II] 158  $\mu\text{m}$  or the [O I]<sup>3</sup>P lines. The lowest temperature allowed,  $T_{low}$ , should be adjusted with this command so that the excitation potential  $h\nu$  is  $\cong kT_{low}$  for the lowest excitation potential transition considered. Note that more than one temperature is sometimes possible when  $T \approx 10^3$  K (Williams, 1967) so thermal stability problems may develop if  $T_{low}$  is lowered below a few thousand degrees Kelvin. This issue is discussed further in the section *Problems* in Part 2 of this document.

If the keyword **exceeds** appears on the line then the specified temperature will be the highest allowed temperature. The calculation stops if the temperature exceeds the value on the command. This might be necessary when a grid of models is computed but those in the high temperature phase (i.e.,  $T > 10^5$  K) are not of interest. The other rules for the command are unchanged.

If no number appears on the command line, but the keyword **off** does, then temperature will not be used as a stopping criterion.

## 14.19 Stop thickness 9.3 [parsec; linear; 23 on sec iter]

This sets an upper limit to the thickness of the cloud. The thickness is the distance [cm] between the illuminated and shielded faces. The argument is interpreted as the log of the thickness unless the keyword **linear** appears. The default units are centimeters but it will be interpreted as the log of the thickness in parsec if the keyword **parsec** appears on the line.

The **stop thickness** command has the same effect as the optional second number on the **radius** command. This command makes it possible to set a cloud thickness when the inner radius is not specified, such as when the ionization parameter is given.

Any number of thicknesses may be entered on the command line. Each will be the ending thickness for consecutive iterations. The limit to the number of stopping values is set by the limit to the number of iterations that can be performed. If fewer numbers are entered than iterations performed then the last number will be used for all further iterations.

The keyword **depth** can be used instead of **thickness**.

## 14.20 Stop velocity < 1 km/s

The calculation will stop if the absolute value of the wind velocity falls below the value. The stopping velocity is entered in  $\text{km s}^{-1}$  but is converted to  $\text{cm s}^{-1}$  within the code.

## 14.21 Stop zone 123 [21 on sec iteration,...]

This sets a limit to the number of zones that are computed on each iteration. It is not normally used. In this example the calculation will stop after computing 123 zones. The default value is 1400. Any number of zones may be entered, each being the ending zone for consecutive iterations. This limit is set by the limit to the number of iterations that can be performed. If fewer numbers are entered than iterations performed then the last number will be used for all further iterations.

The code checks that it did not stop because the default number of zones was reached. A warning will be generated if this happens since it was probably not intended. Use the **set nend** command to increase the default number of zones while keeping this checking active.

The code allocates memory to store a great deal of information for the limiting number of zones. Increasing the number of zones will also increase the memory needed to run the code. Don't do this unless you really need to use the zones.

# Chapter 15

## CONTROLLING OUTPUT

### 15.1 Overview

CLOUDY is capable of generating lots of output although its default output is minimal. Commands that control the output are described here. Chapter 1 *OUTPUT* of Hazy 2 describes the meaning of the output.

### 15.2 No buffering

Output will be lost if the code crashes before ending because of the way that the C++ language handles file buffering. There is a **no buffering** command which forces output to be saved to disk as soon as it is created. This slows down the execution time considerably but may need to be used to save results when diagnosing a crash. If this command is used on most systems output will no go to `stdout` but will go to `stderr` instead. `stderr` can be directed to a file by redirection of 2 as in the following example

```
cloudy.exe < sim.in > sim.out 2> sim.err
```

or alternatively

```
cloudy.exe -r sim 2> sim.err
```

### 15.3 Normalize to “O 3” 5007 [scale factor = 100]

The strength of an emission line in the standard output will be given in intensity or luminosity units and as its intensity relative to a reference line. In the main printout each emission line has a label and wavelength, followed by the energy radiated in the line, ending with the intensity relative to a reference line.

Emission-line intensities are usually listed relative to the intensity of  $H\beta$   $\lambda 4861\text{\AA}$ , the default reference line. By default the reference line has an intensity of unity. This command can change the reference line to any of the other predicted lines and can change the relative intensity of the reference line to another value. The relative intensities of all lines in the spectrum will be relative to the intensity of the line whose label is within the double quotes and with wavelength given by the first number. The label must be the four-character string that identifies the line in the print out<sup>1</sup> and the wavelength must match the printed wavelength to all four figures. The wavelength units must appear if they are not Angstroms.

---

<sup>1</sup>The label was optional in versions 94 and before of the code, but now is required due to the large number of lines, making unique wavelengths unusual.

The optional second number sets the relative intensity of the reference line. If it is equal to 100, as in this example, then all intensities will be relative to a reference line intensity of 100. The default is for an intensity of unity. The example given above will cause the relative intensities to be expressed relative to an [O III]  $\lambda 5007$  intensity of 100. The scale factor must be greater than zero.

The code works by finding the first line in the emission-line stack whose wavelength and label matches the line on this command. There is a possible uniqueness problem since more than one line can have the same wavelength. This is especially true for XUV or soft X-ray lines and for H<sub>2</sub> lines.

The following shows some examples of the **normalize** command:

```
// normalize to spectrum to Pa
normalize to "H 1" 1.875m

// normalize spectrum to the [OI] IR line on a scale where it is
equal to 100 normalize to ``O 1'' 63.17m = 100
```

## 15.4 Plot [type, range]

Plots of several predicted quantities can be made.<sup>2</sup> One of the keywords described below must appear on the command line. Up to 10 plots can be generated. The keyword **trace** will turn on a great deal of information concerning the mechanics of generating the plot.

Publication-quality plots can be produced using the **save** commands (described below) to produce a file that can then be post-processed using other plotting software.

## 15.5 Plot continuum [\_raw, trace, range]

This plots the continuum. This energy range can be changed by entering the range key and the lower and upper limits. This is described below.

The default is to plot both the incident continuum (in units of  $\nu f_\nu$ ) (plotted as .'s) and the transmitted continuum (the o's). If the option **raw** is specified then the continuum in units actually used inside CLOUDY ( $\text{cm}^{-2} \text{s}^{-1} \text{cell}^{-1}$ ) will be plotted. If the keyword **photon** appears then the units of the plotted continuum will be photons  $\text{cm}^{-2} \text{s}^{-1} \text{Ryd}^{-1}$ .

### 15.5.1 Plot continuum keywords

It is possible to plot specific components of the continuum with the following series of keywords.

### 15.5.2 Plot diffuse continuum

This plots the diffuse emission per unit volume within the last computed zone. This gives emission by gas and grains in the optically thin limit and unity filling factor.

---

<sup>2</sup>Today most plots are generated by producing save output then post-processing that output in other software. The plot commands described here still function but are likely to be removed in a future version of the code.

### 15.5.3 Plot emitted continuum

The net integrated continuum produced by the cloud is plotted. This is the sum of the continua emitted in the inward and outward directions from the computed ionization structure and does not include the incident continuum.

### 15.5.4 Plot outward continuum

The contents of the *outcon* and *flux* arrays, multiplied by the local gas opacity, are plotted to indicate sources of ionization and heating.

### 15.5.5 Plot reflected continuum

The continuum emitted from the illuminated face of the cloud is plotted. This includes the back-scattered portion of the incident continuum along with the diffuse continuum emitted from the cloud in the direction towards the central object. This is possible only for non-spherical (open) geometries.

## 15.6 Plot opacity [type, range]

The opacity (total cross section per hydrogen atom) of the first and last zones is plotted. The full continuum predicted by the code, the range  $1.001 \times 10^{-8} \text{ Ryd} \leq h\nu < 7.354 \times 10^6 \text{ Ryd}$ , is plotted by default. This is changed by using the **range** option.

There are three optional keywords; **absorption**, **scattering**, and **total**, to change which opacity is plotted. If none appear then the total opacity is plotted.

### 15.6.1 Plot range options

The keyword **range** specifies the energy range of the **opacity** and **continuum** plots. If one number occurs on the line then it is the lowest energy in Rydbergs. If the first number is zero then it is replaced with the lowest energy in the continuum,  $1.001 \times 10^{-8} \text{ Ryd}$ . The optional second number is the highest energy shown on the plot. If it is omitted or zero then the high-energy limit of the code, presently  $7.354 \times 10^6 \text{ Ryd}$ , is used. If either number is negative then both are interpreted as the logs of the energies, otherwise they are assumed to be the linear energy. If the first number is zero (i.e., interpreted as the lowest energy considered by the code) then the second number is interpreted as the energy of the upper limit to the plot and not its log.

The following give specific examples of the range option.

```
// plots the absorption opacity between 0.1 to 10 Ryd.
plot absorption opacity, range=.1 to 10 Ryd
//
// plot the opacity between 1 Ryd and
// the high energy limit of the code.
plot scattering opacity, range=1
//
// the range will be the full energy limit of the code
plot opacity
```

## 15.7 Plot `_map [Tmin=3e3 K, Tmax=2e4 K, linear, range]`

The keyword `_map` (note the leading space) says to do a plot of the heating and cooling rates [ $\text{erg cm}^{-3}\text{s}^{-1}$ ] as a function of temperature for the last computed zone. The `save map` command saves this information in a file and is more useful.

### 15.7.1 Plot map range options

The high and low temperatures on the map are changed with the keyword `range` and one or two optional numbers. If no number appears then a temperature range of 10 K to  $10^9$  K is used. If only one number appears then only the lower temperature limit is changed. If two numbers appear then both lower and upper limits are changed.

If the first number is  $\leq 10$  then both numbers are interpreted as logs of the temperature. If the first number is  $> 10$  then both are interpreted as the temperature itself. If the keyword `linear` appears then both numbers are interpreted as the temperature itself no matter how large or small they may be.

The number of points on the map is set with the `set nmaps` command.

## 15.8 Print ages

The code normally assumes that the system is old enough for microphysical processes to have become time steady. This tells the code to print all of the timescales tracked by the code. These are the same timescales considered by the `age` command. Normally only the shortest timescale is printed at the end of the calculation.

If a physical process is not significant, for instance, the  $\text{H}_2$  formation timescale in a  $10^6$  K gas, the age is still computed but is set to a negative number. This retains the value while not including the process when the important timescales are determined.

## 15.9 Print arrays

This prints the array elements that enter into solution of the ionization balance. By default it will print this information for all elements. If the keyword `only` appears then it will also look for the name of an element and will only print the array elements for that element. `Print arrays only xxx` commands are additive. If more than one appears then only the information for the requested elements will be printed. This is a debugging aid.

## 15.10 Print citation

CLOUDY is a research project that involves the creative efforts of many people. It should be cited as follows: “Calculations were performed with version yy.mm.dd of CLOUDY, last described by Ferland et al. (yyyy).” The numbers represent the release date and the citation is to a review paper. The citation should mention the version of the code since some predictions changes as the atomic data and treatment of physical processes improve. Old versions of the code are never deleted from the web site so it is possible to recover a version that produced a given result.

This command will print the current version number of the code and give the full bibliographic citation for the review paper.

## 15.11 Print constants

The physical constants stored in the header file `physconst.h` will be printed along with sizes of some variables.

## 15.12 Print column densities [on; off]

This controls whether the column densities of the various constituents are printed. The keywords are `_ON_` and `_OFF`. The default is to print the column densities.

The column densities of several excited states within ground terms of some species are printed as well. The meaning of the labels for the excited states column densities is given in the discussion of *cdColm* in Part 2 of this document.

## 15.13 Print coolants, zone 135

This prints the coolants for the specified zone. If no zone number or 0 appears on the line then the coolants for *all* zones will be printed. The total cooling and the fractional contribution of the strongest coolants are printed. For each coolant a label gives an indication of the spectroscopic origin of the coolant and the following integer gives its wavelength, with a 0 to indicate a continuum. The last number of the group is the fraction of the total cooling carried by that agent.

## 15.14 Print continuum indices

The file created by the **save continuum** command identifies a line that occurs within each continuum bin. This can be used to understand what lines contribute to the predicted spectrum. The line label is for the first line that was entered in a particular cell. It is not the strongest line and there may be many lines contributing to a particular cell. This command will print the line energy (Rydberg), continuum array index, and the line's spectroscopic notation, for every line that is included in the calculation. The lines will be printed in the order in which they are entered into the continuum. The printout can then be sorted by energy or array index to discover all lines that occur within a particular cell. This is a debugging aid.

There are two optional numbers which give the lower and upper limit to the energy range (Rydbergs) to be printed. All lines are printed if these numbers do not appear then.

## 15.15 Print departure coefficients

LTE departure coefficients for levels within an element along the H-like or He-like isoelectronic sequences will be printed. The **print populations** command controls printing individual level populations.

If the keyword **He-like** appears then an element on the helium-like isoelectronic sequence will be printed. Otherwise an element of the H-like isoelectronic sequence is chosen. The code will search for the name of an element, and if it finds one, will print only that element. If no elements are recognized then departure coefficients for  $H^0$  (the H-like sequence) or  $He^0$  (the He-like) are printed.

## 15.16 Print errors

The code will always identify problems by either printing comments during the calculation or warnings after the calculation is complete. This says to also print these warnings to `stderr`. On many systems this output can be redirected to the screen. The **no buffering** command describes how to handle `stderr` output.

## 15.17 Print every 1000 [5 37 93]

This will be replaced with the **print zone** command.

## 15.18 Print heating

The relative heating due to each stage of ionization or physical process is printed. This is the fraction of the total heating due to this particular stage of ionization and is printed directly below the relative abundance of that stage.

## 15.19 Print populations [H-like carbon, to level 45]

Level populations are normally not printed for the atoms and ions of the H-like or He-like isoelectronic sequences. This will print them. If no numbers appear on the line then the first 15 levels will be printed. Enter the highest level to print on the line as an integer if more are desired.

If the keyword **He-like** appears then an element on the helium-like isoelectronic sequence will be printed. Otherwise an element of the H-like isoelectronic sequence is chosen. The code will search for the name of an element, and if it finds one, will print that element and isoelectronic sequence. If none are recognized then populations for H I are printed.

The departure coefficients are printed with the **print departure coefficients** command.

## 15.20 Print last

Normally results for every iteration are printed as they are computed. This command says to print only results for the last iteration.

## 15.21 Print line options

A large block of emission-line intensities is printed after the calculation is complete.<sup>3</sup> This controls details of that printout.

Some options change the layout of this information. These include options to print a single column, to sort the lines by wavelength or intensity, or to print only the strongest lines, or those within a certain wavelength range.

---

<sup>3</sup>In versions 87 and before, the code printed some relative line intensities for each zone. An extra line could be added with the **print line** command. This command, and that printout, no longer exists. Use the **save line intensities** command instead.

Other options indicate line-formation processes. A great deal of information about line formation and beaming is stored within the code but not normally printed to save space. The section of Part 2 of this document *The Emission Lines* gives more information.

Some spectra have so many lines that several different transitions may appear to have the same wavelength. This occurs to some extent for most H<sub>2</sub>, Fe II, and He-like spectra. The **set line precision** command allows you to change the number of digits in the printed line wavelength. It may be necessary to increase the wavelength precision if the default line wavelengths are ambiguous and more than one transition appears with the same wavelength.

### 15.21.1 Print line all

All of the contributions to line formation, including collisions, pumping, and heating, will be printed.

### 15.21.2 Print line cell xx

More than one line can occur within a continuum cell in the output produced by the **save continuum** command. This command will print the label for every line that falls into a particular continuum cell. The number of the cell, with the lowest energy cell being 1, must appear.

### 15.21.3 Print line collisions

Collisions are often the dominant contributor to an optically thick resonance line. This adds an entry with the label **Coll** followed by the wavelength and the collisional contribution.

### 15.21.4 Print line column [linear]

The main block of emission lines is normally printed with four lines across the page. This command says to print lines as a single column to make it easier to enter into a spreadsheet. The keyword **linear** will cause the intensities to be printed as the linear flux in exponential format rather than as the log.

### 15.21.5 Print line cumulative

In a time-dependent simulation the main block of emission lines give the emission for the current time step. This command says to also print the time-integrated line emission, referred to as the cumulative emission. This “spectrum” is the total energy emitted in the lines, with units  $\text{erg cm}^{-2}$ .

### 15.21.6 Print line faint -2 [\_off]

CLOUDY will normally print the intensities of all emission lines with intensities greater than  $10^{-3}$  of the reference line, which is usually H $\beta$ . This changes the limit to the relative intensity of the weakest line to be printed. The argument is either the log (if  $\leq 0$ ) or the linear (if positive) intensity of the weakest line to print, relative to the reference line. The **\_log** option will force interpretation as a log. The reference line is usually H $\beta$ , and can be changed with the **normalize** command. In the case shown here, only lines with intensities greater than 1% of H $\beta$  will be printed.

If no numbers are entered, but the keyword **\_off** appears then all lines are printed, even those with zero intensity.

### 15.21.7 Print line flux at Earth

If the distance to an object is set with the **distance** command and line luminosities are predicted then this command says to print the observed flux at the Earth rather than the line luminosity. The units are  $\text{ergs cm}^{-2}\text{s}^{-1}$ . (No correction for interstellar extinction is included, of course). Both the keywords **flux** and **Earth** must appear. This command can be combined with the **aperture** command to simulate observing only part of a spatially-resolved object.

### 15.21.8 Print line heat

Fluorescent excitation is included as a line formation process. If a line is radiatively excited but then collisionally deexcited it will heat rather than cool the gas. This option prints the heating due to line collisional de-excitation. The entry will have the label **Heat** followed by the wavelength.

### 15.21.9 Print line H2 electronic

By default only ro-vibrational lines within the ground electronic state of  $\text{H}_2$  are included in the emission-line printout when the large  $\text{H}_2$  molecule is included with the **atom H2** command. This command tells the code to also print electronic transitions.

### 15.21.10 Print line inward

Optically-thick emission lines are not emitted isotropically. The “inward” fraction of the line is the part that is emitted from the illuminated face of the cloud into the direction towards the source of ionizing radiation. This will generally be greater than 50% of the total intensity if the line is optically thick. This command prints this inward fraction with the label “Inwd” followed by the wavelength.

The optical depth scale must be fully converged for the inward intensity to be predicted. Use the **iterate to convergence** to do this.

### 15.21.11 Print line iso collapsed

The model atoms for the iso-electronic sequences have both resolved and collapsed levels. Only predictions from the resolved levels are printed by default. This command will also print predictions from the collapsed levels. The model atoms do not a good representations of lines that come from the highest collapsed level. Only lines coming from the lowest  $n - 1$  levels are printed at the end of the calculation.

### 15.21.12 Print line optical depths [\_off, faint]

Mean line optical depths are not printed by default<sup>4</sup>. The option tells the code to print them at the end of the iteration. There are two optional keywords.

If **\_off** appears then line mean optical depths will not be printed. This is useful if turned on in a previous iteration and no longer needed.

The keyword **faint** sets the smallest line mean optical depth to print. The default smallest mean line optical depth to print is 0.1. The log of the limit must be given. Optical depths for all lines that mase are printed.

---

<sup>4</sup>Line center optical depths were printed through version C10. Mean line optical depths are now reported. Line center optical depths are  $\sqrt{\pi}$  times smaller than mean optical depths.

### 15.21.13 Print line pump

All lines include fluorescent excitation by the attenuated incident continuum as a line formation process. Continuum pumping will often be the dominant formation mechanism for optically-thin high-excitation lines. This option prints an estimate of the contribution to the total line intensity from this process. The entry will have the label “Pump” followed by the wavelength.

### 15.21.14 Print line sort wavelength [range 3500A to 1.2m]

The output spectrum to be sorted by wavelength rather than by ion.<sup>5</sup> It was originally added by Peter G. Martin. If the **range** option appears then two more numbers, the lower and upper bounds to the wavelength range, must also appear. Each number is interpreted as the wavelength in Angstroms by default, but is interpreted as the wavelength in microns or centimeters if the wavelength is immediately followed by a “c” or “m.” The two wavelengths must be positive and in increasing wavelength order.

### 15.21.15 Print line sort intensity

The predicted emission lines will be sorted in order of decreasing intensity.

### 15.21.16 Print line sum

This prints the sum of the intensities of an arbitrary set of emission lines. This can be useful for applications such as the [Stoy \(1933\)](#) energy balance method of determining stellar temperatures, which rely on the sum of a set of observed line intensities relative to a recombination line (see also [Kaler and Jacoby, 1991](#) and section 5.10 of AGN3). The sum is printed as the last entry in the emission-line array as an entry with the label “Stoy” and a wavelength of 0.

Each emission line included in the sum is entered on its own line. This list begins on the line after the **print line sum** command and continues until a line with **end** in the first three columns appears. The line label must occur as the first four characters on each line and the line wavelength must appear as it does in the printout. The default units of the wavelengths are Angstroms and any other units must be specified. The following gives an example of its use.

```
print line sum
o 3 5007
totl 3727
o 1 6300
O 3 51.80m
S 3 18.67m
s 3 9532
end of lines
```

Up to 30 lines can be entered into the sum.

### 15.21.17 Print line surface brightness [arcsec]

By default the line intensities that are printed after the calculation is complete is given as  $L$  [erg s<sup>-1</sup>] for the luminosity case and  $4\pi J$  [erg cm<sup>-2</sup>s<sup>-1</sup>] for the intensity case. This command will change these intensities

<sup>5</sup>The **print sort** command existed but did not function between 1986 and 2001. It became functional again with version 96 but was moved to become an option on the **print line** command.

into surface brightness units. The default is per steradian but if the keyword **arcsec** appears then the surface brightness will be per square arcsec.

## 15.22 Print macros

This prints the name and status of the macros that are used in the `cddefines.h` header file. These macros are either set by the user at compiler time with the `-DMACRO` option on the compile command or by the compiler itself.

## 15.23 Print off

This turns off the print out, as with the **print quiet** command. This is normally paired with a later **print on** command to avoid printing parts of the output.

There is a possible problem. The code can read its own output as input, to make it easy to rerun a model. In many initialization files the following pair of commands appears:

```
print off
commands ....
print on
```

The resulting output will print the first **print off** command, but will not print the commands or the **print on** command. If this output is used as input no further output will be created for the new model. This problem will not occur if the **print off** command includes the keyword **hide**.

## 15.24 Print on

This command turns on printout. This is the opposite of the **print quiet** or **print off** commands.

## 15.25 Print only [header, zones]

The keyword **only** shortens the printout somewhat by stopping the calculation prematurely. If it appears then another keyword, **header** or **zones**, must also appear. The command **print only header** will cause the code to stop after printing the header information. The command **print only zones** will cause the code to return after printing the zone results on the first iteration. In both cases the calculation ends during the first iteration.

## 15.26 Print path

The path giving the location of the data files will be printed.

## 15.27 Print quiet

This sets CLOUDY's quiet mode, in which nothing is printed at all. Printing can be turned off and then restarted at a particular zone by using the **print starting at** command described below.

## 15.28 Print recombination

This reports the dielectronic and radiative recombination rate coefficients at the current temperature. An indication of the reference used for each ion is also give.

## 15.29 Print short

This shortens the detailed final printout. Only the emission lines and a short summary of some thermal properties of the model will be printed.

## 15.30 Print starting at 61

This option turns off *all* printout *until* the specified zone is reached. This should come last in the input stream since command lines appearing after it will not be printed.

## 15.31 Print version

This prints the code, compiler, and operating system versions, along with other information.

## 15.32 Print Voigt a=1.2e-3

This prints two forms of the Voigt function and their ratio. The damping constant must appear on the line.

## 15.33 Print zone 1000 [5 37 93]

CLOUDY will always print the results for the first and last zones. This command varies the number of zones printed between these two. If more than one number is entered then each applies to successive iterations. The example above will print every 1000 zones on the first iteration, every 5 zones on the second iteration, 37 on the next, etc. If there are fewer numbers entered than iterations performed then the last number entered will be used for all further iterations.

## 15.34 Save commands

### 15.34.1 Overview

**Save** commands save results into a file that can be used later. They are the primary output mechanism for CLOUDY. There are many options. For instance, physical quantities as a function of depth into the cloud, including temperature, ionization, and density, can be saved for later plotting. The emitted spectrum, or other quantities predicted by the code, can be output. The general idea is for the file produced by this command to then be post-processed by other plotting or analysis programs to produce final results.

One keyword must appear and only one keyword per line is recognized. Up to 100 **save** commands can be entered.

### 15.34.2 Save vs punch commands

In versions C08 and before the **save** command was called **punch**. “Punch” was an output option in FORTRAN IV and was implemented by machines that produced holes on [Hollerith cards](#). Those machines and cards now exist only in museums. This version of CLOUDY continues to accept **punch** as an alias for **save**.

### 15.34.3 An output file name must appear inside double quotes

Each **save** command must specify a file name<sup>6</sup> for the resulting output. This file name must appear between a pair of double quotes as in `"output.txt"`. It must be a valid file name for your operating system. The following is an example.

```
save overview "model.ovr"
```

The code will stop if a valid file name is not present.

### 15.34.4 Setting a prefix for all save files

A prefix can be set for all filenames with the **set save prefix** command (see Section [18.14.44](#)). This makes it possible to set a prefix only one time for several save files, as in

```
set save prefix "Den11"  
save overview ".ovr"  
save continuum units micron ".con"
```

The files `Den11.ovr` and `Den11.con` will be created.

### 15.34.5 The “last iteration” option

Each **save** command also has a keyword **last** that will cause the output to only be produced on the last iteration. If this keyword does not appear then output will be produced for every iteration. The results of each iteration are separated by a line of hash marks (“###”). In grid runs this behavior will be slightly modified. See the description in Section [17.3](#).

### 15.34.6 The “no buffering” option

If the option **no buffering** appears then file buffering will be turned off for that file. This slows down the output considerably but ensures that all output will exist if the code crashes. There is also a stand-alone **no buffering** command to turn off buffering for the code’s standard output.

### 15.34.7 The “clobber/no clobber” option

When the code is used as a stand-alone program to compute a single model it will open the save file at the start of the calculation and close it at the end. In a sequence of models as in an optimization run this will happen for each new model and so will overwrite results of all previous calculations.

---

<sup>6</sup>In versions 90 and before Fortran default save units, with names like `fort.9`, could be used for save output. The filename must be specified with versions 91 and later.

The **no\_clobber** keyword on the **save** command will produce one long file containing results of consecutive models. It tells the code to never close the file at the end of any but the last calculation and not try to reopen this file once it is open.

The default, with one exception, is to overwrite files. The **grid** command computes a series of simulations with a single input file. The entire set of output is usually needed so the default in this single case is to not overwrite files, but rather produce one large file.

Include the **clobber** keyword if you want to overwrite files, and the **no clobber** keyword if you want one large save file with successive predictions.

### 15.34.8 The “no hash” option

When more than one iteration is done the results of each iteration end with a series of hash marks, “###”, to make the start of each iteration easy to find in an editor. These hash marks can cause problems if the file is then read in by other programs. The hash marks will not be produced if the **no hash** keyword appears.

The character string that is printed between iterations can be changed with the **set save hash** command described on page 246.

### 15.34.9 The “title” option

The title<sup>7</sup> of the model and the version number of the code will be printed on the first line of the save file.

### 15.34.10 The “separate” option

The default behavior of the code is to concatenate save output from different models in a grid run into a single large file. The only exception to this is the **save FITS** command since it would violate the FITS standard to combine multiple FITS spectra into a single file. If the keyword **separate** is included on the save command line, each model in the grid will produce a separate save file. They will have names `grid0000000000_filename`, `grid0000000001_filename`, etc., where `filename` is the file name you supplied between double quotes. The meaning of the grid index embedded in the filename can be found with the **save grid** command described in Section 15.57. When the save output is split up, only the first file will contain the save header.

### 15.34.11 Depth versus radius

The code and this documentation make a consistent distinction between depth and radius. The **radius** is the distance from a point in the cloud to the center of symmetry, generally the center of the central object. The **depth** is the distance from a point in the cloud to the illuminated face of the cloud. In both cases the distance is to the center of the current zone.

The output from each **save** command is described in the following sections. In those cases where quantities are given as a function of position into the cloud, the first column will usually give the depth, not the radius. You need to add the inner radius of the cloud to the depth to get the radius.

---

<sup>7</sup>The title was printed by default in versions 95 and before of the code. The title was generally deleted so that the save file could be used to make plots so it is now missing by default.

## 15.35 Save abundances

The log of the gas-phase densities [ $\text{cm}^{-3}$ ] of the elements will be saved for each zone. This is the sum of the abundances of a chemical element in atoms, ions, molecules, and ices, but does not include grains. This provides a check for the effects of the **element table** and **fluctuations abundances** commands.

## 15.36 Save ages

The timescales for several physical processes will be saved as a function of depth.

## 15.37 Save agn [options]

This produces output files that were used to create data tables in the 2<sup>nd</sup> edition of *Astrophysics of Gaseous Nebulae*, referred to as AGN3 here. The options are the following: **charge** transfer, **recombination** coefficients, **recc** for hydrogen recombination cooling, **opacity**, **hemis**, and **hecs** (for He<sup>0</sup> collision strengths).

## 15.38 Save monitors

The **monitor** command provides an automated way to validate the predictions of the code. Normally the results from these checks will be printed on the standard output. If this command appears then the same output will also be sent to a file.

## 15.39 Save average ...

This reports averages of various quantities. It was included as a way to bring together information generated with the **grid** command.

The **save** command is followed by a series of lines which say which average to generate. These end with a line that starts with the word **end**. The following is an example:

```
save averages, file="hii.avr" last no clobber
temperature, hydrogen 1 over volume
ionization, helium 2 over radius
column density oxygen 3
end of averages
```

### 15.39.1 Temperature average

The keyword **temperature** begins the line. The average temperature can be weighted with respect to any atom or ion. The name of one of the elements and the ionization stage, 1 for the atom, 2 for the first ion, etc, then follow.

The code computes averages weighted over radius or over volume. If the keyword **volume** appears then the volume-weighted mean temperature will be reported. The default is weighting over radius. The log of the temperature is reported.

The command works by calling *cdTemp* described in Part 2 of this document. This command has all the options described there.

### 15.39.2 Ionization average

This reports the average ionization fraction of an atom or ion. The keyword **ionization** begins the line. It is followed by the name of one of the elements, then the ionization stage, 1 for the atom, 2 for the first ion, etc.

The code computes ionization fractions weighted over radius or over volume. If the keyword **volume** appears then the volume-weighted fraction will be reported. The default is weighting over radius. The log of the ionization fraction is reported.

The hydrogen molecular fraction  $2n(\text{H}_2)/n(\text{H}_{\text{tot}})$  can be obtained by asking for ionization stage 0 of the element hydrogen. This is a special case. Other molecular fractions cannot now be obtained.

The **save ionization means** command described on page 181 will save the mean ionization of all elements in the save form as that given at the end of the standard output.

### 15.39.3 Column density

The log of the column density of any atom or ion is reported. The keyword **column density** begins the line. It is followed by the name of one of the elements, then the ionization stage, 1 for the atom, 2 for the first ion, etc.

## 15.40 Save chemistry options

### 15.40.1 Save chemistry rates “filename” species “molecule”

This command saves rates for molecular reactions involving a specific species. Due to current design constraints, the molecule name must come second at present.

By default, all non-catalytic rates will be printed. There are several optional keywords to change this. The keywords **creation** and **destruction** select only those reactions which create or destroy the species, respectively. The keyword **catalytic** selects all reactions for which the specified species acts as a catalyst. Finally, the keyword **all** prints all reactions, including the catalytic ones.

## 15.41 Save column density

The column densities [ $\text{cm}^{-2}$ ] of the gas constituents are saved.

**save column density** will report column densities of all molecules and ions.

**save some column densities** allows you to specify which column densities to output. The code reads in a series of lines that give chemical elements and ionization stages. These end with a line that starts with **end**. The logs of the column densities of these species will be output in one line with each column density separated by a tab character. The following is an example:

```
save some column densities "test.col"
hydrogen 2
helium 2
carbon 2
end of column densities
```

The name of a chemical element must appear in the first four columns of each line and be followed by the ionization stage. One is the atom, 2 the first ion, etc.

The column densities in molecules or in levels within an ion can be obtained. The command works by saving the first four letters on each line together with the ionization stage. These are then passed as the first two arguments to *cdColm*, a routine described in Section 8.6.2 of Hazy 2 “*cdColm—the computed column densities*”. That section describes how to find molecular or state-specific column densities. If the ion stage is one or greater than the species will be interpreted as an atom or ion. An ion stage of zero indicates that one of the special cases listed where *cdColm* is described. As an example, the following will obtain the column densities of molecules and levels

```
save some column densities "test.col"
H2  0  // the hydrogen molecule
CO  0  // the carbon monoxide molecule
C11* 0  // the J = 0 level of atomic carbon
end of column densities
```

This command can be combined with the **save grid** command to save predictions from a series of grid calculations.

The **save FeII column density** command and **save H2 column density** commands are described elsewhere.

## 15.42 Save continuum

This command is a primary mechanism for saving the predicted spectrum.

### 15.42.1 Lines in the spectrum

Emission lines are included in the output for all **save continuum** commands except **save transmitted continuum**. They are visible in the net emitted continuum. Labels giving the strongest lines contributing to each wavelength are given in the third to last column in the save output. More than one line will contribute to many wavelength cells and the last column indicates the number of lines within that cell.

The **print continuum indices** command will list the labels for all lines that enter into each cell. This provides a way to see all lines that contribute. The **print line sort wavelength** can be used to understand the relative contributions when multiple lines contribute at a particular wavelength or energy.

Figure 15.1 shows the incident SED as the smooth red line, while the black line gives the net emission with a warm absorber long the line of sight.

### 15.42.2 Emission line - continuum contrast

In a real spectrometer the line-to-continuum contrast depends on the spectrometer resolution if a line is unresolved. The higher the resolution, the higher the line will appear in the spectrum. In CLOUDY, lines are unresolved on the coarse continuum mesh that is reported in most versions of the **save continuum** command. The default behavior of CLOUDY is to add the emission-line intensities directly to the continuum. This assures that the flux in the line is conserved.

Real spectrometers may have significantly higher or lower resolution than CLOUDY’s coarse continuum. The **set save line width / resolution** command, described on page 247, changes the lines relative to the continuum to make the spectrum look like that observed with a spectrometer with a resolution that is different from the coarse continuum. Changing the velocity width with the **set save line width** command has the same effect as changing the velocity resolution of a spectrometer measuring an unresolved line. Smaller velocity widths will make the line rise higher above the continuum. Alternatively

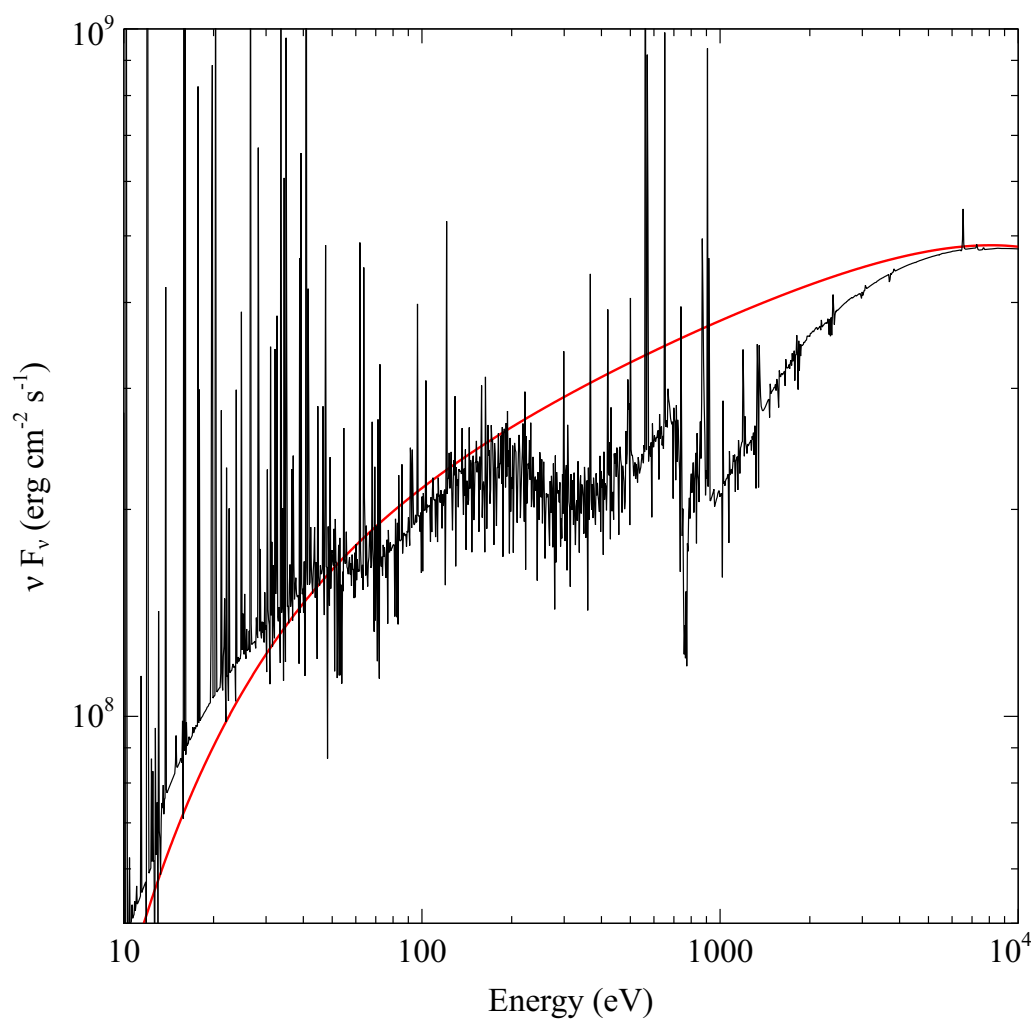


Figure 15.1: The predicted X-ray spectrum of a warm absorber in an Active Galactic Nucleus. Prominent emission and absorption lines are present along with broad UTA absorption features. The parameters are from Reynolds & Fabian (1995, MNRAS, 273, 1167).

you can also use the **set save resolution** command to specify the spectral resolution of a spectrograph. Higher values for the resolution will make the line rise higher above the continuum.

Note that this command will *only* adjust the height of the line, not the width. The latter will always be the width of one cell in the coarse continuum mesh (even if the line is broader than that cell). This implies that the line flux in the continuum array is artificially changed by the **set save line width / resolution** command. Changing the spectral resolution can be useful to emphasize weak lines in a plot, but should never be used when energy conservation is important, e.g. when you want to postprocess the file to fold the saved continuum with a photometric passband.

### 15.42.3 Pumped contributions to the lines

Continuum pumping and fluorescence are included as excitation processes for all lines. These contributions are usually not printed as a separate quantity but will be if the **print line pump** command is entered. Whether or not the pumped contribution actually adds to the observed line emission depends on the geometry. Continuum pumping increases the line emission if no related continuum absorption is seen by the observer. This will be the case if the continuum source is either not observed or not covered by absorbing gas on the observer's line of sight. If absorbing gas covers an observed continuum source then the situation is like the P Cygni problem, emission produced by absorption and pumping will not increase the total intensity of the line at all.

The line intensity includes fluorescent excitation unless the **no induced processes** command is entered. That command is unphysical since it turns off all induced processes. You can judge how great the contribution of the pumped part of the line is by printing it with the **print line pump** command.

In general the treatment of scattering is very geometry dependent. The output produced by the **save continuum** commands *does not* include the pumped part of the line contribution. This is correct if the continuum source is included in the beam, but is not if only the gas is observed.

### 15.42.4 The units option - changing the continuum units

By default, the energy units for the first column, which gives the wavelength or energy for each point in the continuum, are Rydbergs. The units can be changed to any of several energy or wavelength units with the **units** keyword that appears on a **save continuum** command. The following keywords are recognized: **\_micron**, **\_eV**, **\_keV**, **\_MeV**, **wavenumber**, **centimeter** (also **\_cm**), **\_mm**, **\_nm**, **Angstrom**, **\_Hz**, **\_kHz**, **\_MHz**, **\_GHz**, **Kelvin** (also **\_K**), **\_erg**, and **\_Rydberg**. Both the keyword **units** and one of these units must appear for the units of the energy scale to be changed.

### 15.42.5 Units of the save output

The units of the predicted continuum depend on whether the intensity or luminosity case is used. In the intensity case continua are given as the intensity per octave  $4\pi \nu J_\nu [\text{erg cm}^{-2} \text{s}^{-1}]$ . In the luminosity case they are  $\nu L_\nu / 4\pi r_0^2 [\text{erg cm}^{-2} \text{s}^{-1}]$  relative to the inner radius of the cloud so the monochromatic luminosity per octave is the predicted quantity multiplied by  $4\pi r_0^2$ .

### 15.42.6 Save continuum predictions

The **save continuum** command, with no other keywords, produces a file with the following information. The different contributors to the continuum are defined in the Chapter *Definitions*.

- Column 1.** The first column gives the photon energy in the units set with the **units** option. The default units are Rydbergs.
- Column 2.** This is the incident continuum at the illuminated face of the cloud.
- Column 3.** This is the transmitted incident continuum and does not include diffuse emission from the cloud.
- Column 4.** This is the outward portion of the emitted continuum and line emission. This includes a covering factor if one was specified. The total emission from the cloud will be this multiplied by the inner area of the cloud. This does not include the attenuated or reflected portions of the incident continuum.
- Column 5.** This gives the net transmitted continuum, the sum of the attenuated incident (column 3) and diffuse (column 4) continua and lines. This would be the observed continuum if the continuum source were viewed through the gas. It includes the covering factor.
- Column 6.** This is the reflected continuum and is only predicted for an open geometry.
- Column 7.** This is the sum of the transmitted and reflected continua and lines. The attenuated incident continuum is included.
- Column 8.** The sum of all reflected line emission.
- Column 9.** The sum of all outward line emission.
- Column 10 and 11.** Line and continuum labels indicate the lines and continuum edges that might contribute at that energy. The line label gives the label for the strongest line in the total spectrum (reflected plus outward) the line-center of which lies in that bin. (This is new in C10. All previous versions simply reported the first line encountered, as is still the case with the continuum label.) The continuum labels are established when the code is set up and they do not mean that the continuum feature is actually present in the spectrum.
- Column 12.** This gives the number of emission lines within that continuum bin, divided by the ratio of the energy width of the cell to the cell's central energy,  $dE/E$ . So this is the number of lines per unit relative energy.

### 15.42.7 What is observed

Figure 15.2 illustrates several possible geometries. Two lines of sight to the central object are shown, and two clouds are shown. Each cloud produces both a reflected and transmitted emission component.

Three possible geometries, indicated by the letter on the figure, occur depending on how we view the central source and clouds: a) we do not directly observe the central object although we may see it by reflection from the illuminated face of a cloud, b) we observe the transmitted continuum and the outward emission from the emitting cloud, and c) we observe the unattenuated continuum directly without absorption. Column 2 gives the unattenuated continuum, and column 3 gives the attenuated continuum.

There are also three possible situations for the line emission. First, we might only observe clouds that lie on the near side of the continuum source. In this case we see the “outward” line emission. Second, we might only observe clouds that lie on the far side of the continuum source. In this case we only see the “reflected” or inward component. Lastly, we might observe a symmetric geometry with reflected emission from the far side and outward emission from the near side.

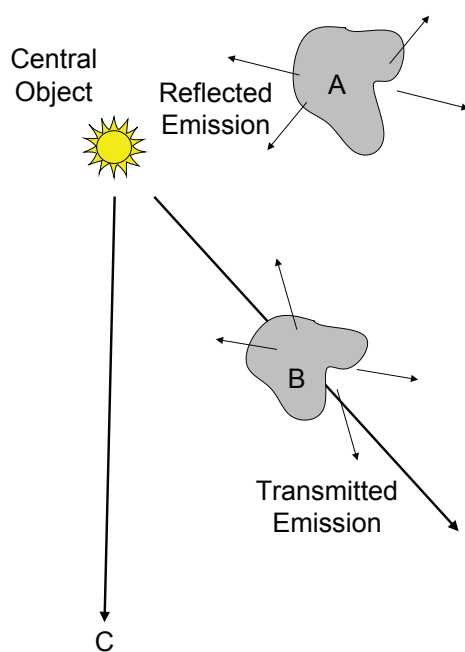


Figure 15.2: This figure illustrates several components of the radiation field that enter in the calculations.

In most cases an observer at large distance from the structure would observe *both* the central object and the cloud and would measure the quantity listed in column 5 (if only transmitted emission is detected) or column 7 (if both reflected and transmitted continua are seen). If the central object is not seen then the quantity in column 4 would be observed.

### 15.42.8 Save continuum bins

This saves the continuum energy bins. The first column is the center of the bin. The second column, which is nearly equal to the first, is the mean energy of the cell, weighted by the continuum shape. This has a slight dependence on the continuum shape. The last number is the cell width  $\delta\nu$ . The bin extends from  $\nu - \delta - \nu/2$  to  $\nu + \delta\nu/2$ .

### 15.42.9 Save cumulative continuum

This gives the continuum integrated over a time-dependent simulation. The usual **save continuum** command gives the continuum for the current time step in these calculations. The units of the usual **save continuum** command are flux per octave,  $\nu f_\nu$  [ $\text{erg cm}^{-2} \text{s}^{-1}$ ]. This command gives the time-integrated energy,  $\nu E_\nu$  [ $\text{erg cm}^{-2}$ ].

### 15.42.10 Save diffuse continuum

This reports the local diffuse line and continuous emission coefficient  $4\pi\nu j_\nu$  [ $\text{erg cm}^{-3} \text{s}^{-1}$ ]. Optical depth effects are not included.

By default this reports the diffuse emission from the last zone. The first column of the output gives the photon energy including the **units** option. The second column gives the diffuse continuous emission. The third column gives the line emission in the same units, including the effects of the **set save line width / resolution** command described on page 247 when appropriate. The last column gives the total.

If the keyword **zone** appears then the diffuse emission *from every zone* will be reported. The first row gives the wavelength or energy scale. The remaining rows give the total (line and continuum) emission coefficients  $4\pi\nu j_\nu$  at each energy.

### 15.42.11 Save continuum emissivity 12 [units micron]

This command will save the continuum volume emissivity  $4\pi\nu j_\nu$  (in  $\text{erg cm}^{-3} \text{s}^{-1}$ ), as well as the local absorption and scattering opacity (in  $\text{cm}^{-1}$ ) as a function of radius and depth (in cm). This output can be used by an external program to do more specialized radiative transfer, e.g. to determine the continuum flux through an aperture. To make this process second-order accurate, the radius and depth in the middle of each zone is reported. One number should be supplied on the command line, which is the wavelength / frequency at which the emissivity and opacity will be evaluated. You can use the keyword **units** as described in Sect. 15.42.4. By default the frequency is assumed to be in Rydberg.

### 15.42.12 Save emitted continuum

The continuum emitted and reflected from the nebula is saved. The first column is the photon energy. The second column is the reflected spectrum. The third column is the outward diffuse emission. The fourth column is the total emission (the sum of the inward and outward emission). This would be the observed emission from the nebula if the central continuum source was not in the beam but clouds uniformly cover

the continuum source. The last two columns are labels for lines and continua contributing at each energy. The attenuated incident continuum is not included in any of these components. All continua have units  $\nu f_\nu$  [erg cm<sup>-2</sup> s<sup>-1</sup>] at the inner radius.

### 15.42.13 Save fine continuum [range, merge]

The code transfers the continuum on a coarse mesh, needed for speed in evaluating photo-interaction rates, and on a fine mesh, needed for automatic treatment of line overlap. The coarse continuum is the one given in output from the **save continuum** command and it includes all the components shown in Figure 15.2. The fine continuum gives a normalized attenuated incident continuum and does not include diffuse emission from the cloud. This multi-grid approach is needed to combine precision and speed. This command will output the transmission coefficient,  $I_{transmitted}/I_{incident}$ , for the fine continuum.

The resulting output will be huge if the entire fine continuum is saved. The command accepts a **range** option to limit the size of the output file. If the keyword **range** appears then the lower and upper limits to the range of the fine continuum must be entered. The command also accepts a **units** option, described on 164, to change the units used in the specified energy range, and in resulting output. The optional third numerical parameter gives the number of fine continuum cells to average together, again with the intent of reducing the size of the output file. The default is to average over 10 cells. If the number of cells to be combined is specified then it must be the third number on the command line, following the limits of the range.

### 15.42.14 Save grain continuum

The thermal emission by grains is part of the emergent continuum. This command saves only the grain emission in the optically thin limit for the last zone. It is mainly intended as a debugging aid.

The first column gives the photon energy in the units specified with the **units** option. The second column gives the total emission from carbonaceous grains (including amorphous carbon and PAH's). The third column gives all emission from all constituents that are not carbonaceous. In practice this will be mainly the silicates. The last column gives the sum of the two.

### 15.42.15 Save incident continuum

The incident continuum, that emitted by the central object and striking the illuminated face of the cloud, will be saved. The two columns give the photon energy and the continuum  $\nu f_\nu$  [erg cm<sup>-2</sup> s<sup>-1</sup>].

### 15.42.16 Save interactive continuum

This gives the integral of the product of the internal radiation field times the gas opacity. The results are produced for each zone and give the attenuated incident continuum, the OTS line, the OTS continuum, the outward continuum and the outward lines. The first optional number is the lowest energy in the output. If missing or zero, the lowest energy considered by the code will be used. Numbers less than 100 are interpreted as the energy in Rydbergs and those greater than 100 as the cell number.

### 15.42.17 Save ionizing continuum [options]

This creates a file that can be used to indicate ionization sources. If the keyword **every** occurs then this is saved for every zone, otherwise it is only saved for the last zone.

The first optional number on the command line is the lowest energy to include in the output. If it is missing or zero then the lowest energy considered by the code will be used. It is interpreted as the energy in

Rydbergs if the number is less than 100 and as the cell number if it is greater than 100. The second optional number is the threshold for the faintest interaction to print. The default is one percent of the quantity given in the `rate/tot` column. Enter zero for this number if you want all interactions to be printed. The optional numbers may be omitted from right to left.

The first column in the resulting output is the cell number of the C scale, so the first cell is zero. Next comes the photon energy in Rydbergs unless changed with the **units** option. The third column, with the header `flux`, is the flux of photons within this frequency bin (*not* per unit frequency) with units  $\text{s}^{-1} \text{cm}^{-2}$ . The fourth column gives the photo-interaction rate, the product of the flux multiplied by the gas absorption cross section [ $\text{cm}^{-2}$ ] and so with units  $\text{s}^{-1}$ . The next five numbers are the fractions of this photo-interaction rate due to the attenuated incident continuum, the OTS line, the OTS continuum radiation fields, and the outward lines and continua. The 10<sup>th</sup> column, with the heading `rate/tot`, is the ratio of this photo rate to the total integrated radiation-field interaction rate. The next column, with the heading `integral`, is the integrated cumulative interaction, the integral of the previous column over energy. This makes it easy to identify the portions of the radiation field that have the dominant interaction with the gas. The last two labels on the line indicate which lines and continua contribute at that energy.

### 15.42.18 Save NLTE continuum

This saves a version of the emitted spectrum in the units required by the NLTE7 workshop. See Section [15.70](#) for more details.

### 15.42.19 Save outward continuum

The photon energy is followed by the attenuated incident continuum, the outwardly directed diffuse continuum, the outward lines, and the sum of the two. If the **local** keyword also appears then only the outward continuum produced in the last computed zone will be saved.

### 15.42.20 Save raw continuum

This saves the **raw** continua. This is exactly the continuum used within the code. The first number is the photon energy. The next columns are the contents of many of the continuum arrays at each energy. Consult the source to see which arrays are now saved. Each gives the number of photons stored in that cell with units  $\text{photons s}^{-1} \text{cm}^{-2} \text{cell}^{-1}$ . The last number is the number of lines within that cell.

### 15.42.21 Save reflected continuum

The reflected continuum is output if **sphere** is not set. The first column is the photon energy, the second the reflected continuum  $4\pi \nu J_\nu$  [ $\text{erg cm}^{-2} \text{s}^{-1}$ ] at that energy. The third gives the reflected lines and the fourth is the sum of these two. Someone who could only see the illuminated face of the cloud would observe this. The next column is the effective albedo of the cloud, the ratio of the reflected to incident continuum (the **save total opacity** command will give the true albedo). The last column gives the label for continuum processes with thresholds at each energy.

### 15.42.22 Save transmitted continuum

This saves the transmitted (attenuated incident and outward component of diffuse) continuum predicted at the end of the calculation.

This save file can be used as part of the incident continuum in a later calculation by reading it with the **table read** command. Three cautions apply when reading this file as an input continuum. First, if the keyword **last** does not appear on this command then the continuum from each iteration will be saved and the code will become confused when it tries to read this file. You should include the **last** option on the command since you only want results from the last iteration. Second, save output should not be written into the same file as the input file during the second calculation. The file containing the first continuum will be overwritten if this occurs. Finally, the first two lines contain header information and they are skipped. They should not be deleted.

The line-to-continuum contrast factor *Resolution* set by the **set save line width / resolution** command (see page 247) is not used in this command. This is to insure that lines have the correct intensity in the save file, as needed for energy conservation.

### 15.42.23 Save two photon continuum

This saves the total two-photon continuum and is mainly a debugging aid. The photon energy is followed by the number of photons emitted per Rydberg per second, then by  $\nu F_{\nu}$ . The details of two photon emission, including induced processes, are discussed by [Bottorff et al. \(2006\)](#).

## 15.43 Save convergence [reason, error]

These commands produce information about various aspects of the converged solution.

### 15.43.1 Save convergence base

This gives computed values of many quantities that are converged during a calculation. The values are given as they are at the exit to the base convergence routine. Depending on the convergence properties of the solution, there will be between only a few up to many dozens of evaluations in each zone.

### 15.43.2 Save convergence error

This will produce information concerning the quality of the converged pressure, electron density, and heating-cooling solution. The correct value, converged value, and percentage error,  $(\text{correct} - \text{converged}) \times (100/\text{correct})$ , will be produced for each zone.

### 15.43.3 Save convergence reason

This will save the reason the model was declared “not converged” at the end of each iteration when the **iterate to convergence** command is used.

## 15.44 Save cooling

This saves the cooling agents for each zone. The first number is the depth [cm] followed by the temperature [K]. The next two numbers are the total heating and cooling rates [ $\text{erg cm}^{-3} \text{s}^{-1}$ ]. The remaining labels indicate contributors to the cooling array and the fraction of the total cooling carried by that agent. The faintest coolant saved is normally 0.05 of the total and can be reset with the **set WeakHeatCool** command.

This is mainly used for debugging and its output is not well documented. The line labels may, or may not, correspond to labels used in the main emission-line output. The code adds individual coolants to the total cooling by calling routine *CoolAdd*. The arguments to that call include the string and a number that follows it. To discover the process for a particular label you will need to search over the entire code to find where that string occurs in a call to *CoolAdd*. The string will be within a pair of double quotes. As an example, two coolants that might appear are *dust 0*, and *H2cX 0*. A search on the string "H2cX" (include the beginning and ending double quotes) will find the string occurring in two places, where the cooling is added with the call to *CoolAdd* and another place where the cooling itself is evaluated. Comments around the call to *CoolAdd* indicate that *H2xC* is cooling due to collisional excitation within the ground electronic state of H<sub>2</sub>. A search on the string "dust " finds its call to *CoolAdd* with the comment that it is cooling due to grain recombination cooling.

Cooling due to the unified iso-electronic sequences is different since the label that occurs in the call to *CoolAdd* is generated by the routine that evaluates the cooling and does not explicitly occur in the source. The iso-electronic cooling labels begin with "IS", followed by a string indicating the process, and followed by strings giving the iso-electronic sequence and the element. Search for the start of the string but not for the element name. An example might be the string "IScIonH H". The "IS indicates that it is cooling due to an ion along the iso-electronic sequences and the two ending H's indicate that the coolant is H-like hydrogen. The string "IScIon" occurs in the source and comments indicate that the process is collisional ionization cooling. The iso-electronic cooling strings do not include a pair of double quotes in the source since the ending double quote occurs after the element names. You would search for the string "IScIon".

### 15.44.1 Save cooling each

If keyword **each** appear after **save cooling** command, the cooling of each element and for certain special cases will be saved for each zone. The unit of the cooling rate is [erg cm<sup>-3</sup> s<sup>-1</sup>]. Notice that bremsstrahlung cooling includes H, He, and metals. The cooling due to molecules is listed separately.

## 15.45 Save charge transfer

Charge transfer recombination and ionization rate coefficients [cm<sup>3</sup>s<sup>-1</sup>] for hydrogen onto heavier elements will be output. The rates will be evaluated at the temperature of the last computed zone. Rates for recombination ( $A^{+x} + H \rightarrow A^{+x+1} + H^+$ ) are first, followed by the rates for the opposite ionization process. The first number is the atomic number of the species.

## 15.46 Save Chianti

This saves collision strengths for Chianti transitions over a certain temperature range. The output gives species, lower level, upper level, wavelength in Angstroms, and collision strengths for each temperature given in the header row. This reports data for all active Chianti species in that particular run.

## 15.47 Save dr

The logic behind the choice of zone thickness will be described.

## 15.48 Save dynamics options

This produces some information concerning the dynamics solutions.

### 15.48.1 Save dynamics advection

This produces information about advection terms.

## 15.49 Save element *name*

This will save the ionization structure of any element. The output will have one line per zone giving the ion fraction<sup>8</sup> of each successive stage of ionization. The keyword **element** must be followed by the element name.

The first number on the resulting output is the depth [cm] into the cloud. The remaining lines give the relative ionization fraction of the  $n + 1$  possible stages of ionization where  $n$  is the atomic number of the element. These may be followed by some of the more abundance molecules.

If the keyword **density** appears on the command line then the density [ $\text{cm}^{-3}$ ] will be given rather than the dimensionless fraction.

## 15.50 Save enthalpy

The file will list the depth into the cloud, followed by the total enthalpy, and various contributors to it.

## 15.51 Save execution times

The code will output the zone number, the time required to compute that zone, and the elapsed time since the start of the calculation. This is intended as a mechanism to identify zones that require large amounts of work to converge. This command is being superseded by the **save performance** command.

## 15.52 Save FeII [options ...]

This produces some information about the Fe II atom. The atom is only included when the **atom FeII** command, described on page 113, is included.

Both “**FeII**” with no spaces and “**Fe II**” with a space are accepted. The following examples show the first style but both are correct.

### 15.52.1 Save FeII column densities

This gives the excitation energy of the levels [wavenumbers], their statistical weights, and the column densities [ $\text{cm}^{-2}$ ].

---

<sup>8</sup>Before version 96 the ionization fractions only included atoms and ions. They now include molecules. The sum of the atomic and ionic fractions will not add up to unity if a significant fraction of the element is in molecules.

### 15.52.2 Save FeII continuum

This reports the pseudo-continuum of Fe II lines produced by the large Fe II atom.

Each output file begins with the photon energy at the center of each continuum bin. This is given in Rydbergs by default but the **units** option can be used to change to other units. The intensities are the integrated intensity or luminosity of Fe II emission over each band. The units of the intensity in the intensity and luminosity cases follow those for the **save continuum** command (page 162).

The output can distinguish between the total, inward, and outwardly directed Fe II emission. This is discussed for the case of quasars by [Ferland et al. \(2009b\)](#).

The **set FeII continuum** command, described on page 239, can be used to adjust the lower and upper bounds to the energy range and the number of bins that occur over this range.

#### The default four-column output

By default the photon energy and the total, inwardly directed, and outwardly directed components are given as four columns.

#### The row option

If the keyword **row** appears then the photon energy will be given in the first row and the intensities will be given in a single row with a large number of columns. This **row** option is more suitable for large grids of calculations.

By default this reports the total Fe II emission. It will give the inward emission if the keyword **inward** appears and the outward emission if the keyword **outward** appears.

The **set FeII continuum** command, described on page 239, can be used to adjust the lower and upper bounds to the energy range and the number of bins that occur over this range.

### 15.52.3 Save FeII departure

The departure coefficients will be saved. This is normally only listed for selected levels. All levels will be saved if the keyword **all** appears.

### 15.52.4 Save FeII levels

A list of the energy levels in the large Fe II atom will be produced. The first column gives the energy of the level [wavenumbers] above ground and the second column gives the statistical weight of the level.

### 15.52.5 Save FeII lines [faint=0.1, range 0.1 to 0.3 Ryd]

This gives the intrinsic intensities of all  $\sim 10^5$  lines predicted by the large Fe II atom at the end of the calculation. The upper and lower level indices are given on the physics, not C, scale, so the lowest level is one. Next is the line wavelength in Angstroms, followed by the log of the intensity or luminosity of the corresponding Fe II line. This is followed by the linear intensity relative to the line set with the **normalize** command. The optical depth is given in the last column. If the keyword **short** appears then the relative intensity and the optical depth are not saved.

Three optional numbers can appear on the command line. The first is the intensity of the faintest line to be saved. This is relative to the normalization line which is usually H $\beta$ . The second and third optional numbers are the lower and upper limits to the range of line energies in Rydbergs. Both numbers are interpreted as logs if either is negative. These optional numbers can be omitted from right to left.

### 15.52.6 Save FeII optical depths

The optical depths of all lines in the large Fe II atom will be produced. The first two columns give the index of the lower and upper levels on the physics (not C) scale, the third column gives the wavelength of the transition in Angstroms, and the last column gives the optical depth.

### 15.52.7 Save FeII populations

The level populations [ $\text{cm}^{-3}$ ] for selected levels of the large Fe II atom are saved by default. All levels will be saved if the keyword **all** appears. If the **range** keyword appears then a pair of numbers, the lower and upper indices for the levels, will be read. The populations are per unit volume by default. If the keyword **relative** appears then they will be given relative to the total  $\text{Fe}^+$  density.

## 15.53 Save FITS

This command produces photon energies and transmitted continuum into a two-column file in FITS (Flexible Image Transport System) format. FITS is a standard format used in astronomy, and endorsed by both NASA and the International Astronomical Union. The most current definition of the FITS format is by [Hanisch et al. \(2001\)](#). This was added by Ryan Porter and its first application is given in [Porter et al. \(2006\)](#).

Since only one spectrum can be stored in a FITS file, the command will implicitly behave as if the keyword **last** was included on the command line.

The following creates a FITS file with a blackbody continuum

```
blackbody 1e5 K
ionization parameter -2
save FITS "filename"
```

This command is often used with the **grid** command which creates grids of calculations. In this case, the command produces separate FITS files for each grid point. They will have names

`grid000000000.filename`, `grid000000001.filename`, etc., where `filename` is the file name you supplied between double quotes. The meaning of the grid index embedded in the filename can be found with the **save FITS** command described in [Section 15.57](#).

## 15.54 Save gammas

This gives the photoionization rates for all subshells of all ions for the last zone. The numbers are the element, ion, and subshell numbers, followed by the photoionization and heating rates from that subshell. The remaining numbers are the fractional electron Auger yields.

### 15.54.1 Save gammas element oxygen 1

If the **element** keyword appears then the detailed contributors to the photoionization rate for the valence shell of a particular element will be produced by calling *GammaPrt*. The ionization stage must also appear, with 1 the atom, 2 the first ion, etc.

## 15.55 Save gaunt factors

This produces a table showing the free-free gaunt factors as a function of photon energy and temperature.

## 15.56 Save grains [options]

These commands give grain properties. Several grain species are usually included in a calculation. Often there are several size bins per grain type. These commands will print a line giving a list of the grain labels, followed by a line giving the grain radius in  $\mu\text{m}$ . The following lines then give the individual grain properties (temperature, potential, etc) for each size and type.

Details of the grain physics are given in [Baldwin et al. \(1991\)](#), [Weingartner and Draine \(2001a\)](#), [van Hoof et al. \(2004\)](#), and [Weingartner et al. \(2006\)](#).

### 15.56.1 Save grain abundance

The grain abundance [ $\text{g cm}^{-3}$ ] for each grain bin and the total grain abundance is given as a function of depth.

### 15.56.2 Save grain charge

The first number is the electron density [ $\text{cm}^{-3}$ ] contributed by grains. A positive number indicates that grains where a net source of electrons so they have a net positive charge. The remaining columns print the charge of each grain size and type, in number of elementary charges per grain, for each zone.

### 15.56.3 Save grain continuum

This is listed in the *save continuum* section.

### 15.56.4 Save grain D/G ratio

The dimensionless dust to gas ratio for each grain bin and the total grain abundance is given as a function of depth.

### 15.56.5 Save grain drift velocity

The drift velocity [ $\text{km s}^{-1}$ ] of each grain species is printed for each zone.

### 15.56.6 Save grain extinction

The grain extinction at the  $V$  filter will be saved as a function of depth. This extinction only includes grains, although they should provide nearly all the extinction when they are present. The first column gives the depth into the cloud [cm], the second is the extinction [mag] at the  $V$  filter for an extended source, like a PDR, and the third number is the extinction for a point source like a star. This distinction is discussed in Sections 7.2 and 7.6 of AGN3. The extended source extinction discounts forward scattering by writing the scattering opacity as  $\sigma(1 - g)$ , where  $\sigma$  is the total scattering opacity and  $g$  is the grain asymmetry factor. The quantity in the last column does not include the  $(1 - g)$  term.

### 15.56.7 Save grain H2rate

The grain  $\text{H}_2$  formation rate is given for each size and type of grain and for each zone.

### 15.56.8 Save grain heating

The grain heating [ $\text{erg cm}^{-3}\text{s}^{-1}$ ] is output for each zone.

### 15.56.9 Save grain opacity

This gives the grain opacity as a function of the photon energy in the last zone of the model. The first column is the photon energy in the units set with the **units** option, the second the total (absorption plus scattering) cross section, followed by the absorption and scattering cross sections. These are the summed cross section per proton for all grain species in the calculation. Column 5 is the pure scattering cross section summed over all grains and column 6 is the grain albedo. Columns 2, 4, and 6 use the scattering cross section multiplied by  $(1-g)$ , while column 5 does not. The opacities have units [ $\text{cm}^2 \text{H}^{-1}$ ] using the actual grain abundance from the last zone.

### 15.56.10 Save grain potential

The grain floating potential [eV] is output for each grain size bin and each zone. The grain potential is defined as

$$\phi_g = \frac{(\langle Z \rangle + 1) e^2}{a} \quad (15.1)$$

where  $\langle Z \rangle$  is the average grain charge of the grain size bin. In reality there is a distribution of grain charges in each bin, so this quantity does not relate to any individual grain. It is approximately the amount of energy needed to move an electron from the grain surface (after it has been lifted out of the grain potential well) to infinity, averaged over all charge states. [Weingartner and Draine \(2001a\)](#), [van Hoof et al. \(2004\)](#) and [Weingartner et al. \(2006\)](#) provide further details.

The grain potential given here and the (average) grain charge (see **save grain charge**) differ only by constants. It is probably best to use the latter since that quantity will be far easier to define. Refer to [Weingartner and Draine \(2001a\)](#) and [van Hoof et al. \(2004\)](#) for more details.

### 15.56.11 Save grain qs

The photon energy is followed by the absorption and scattering  $Q$ s for each grain species. These are defined in Chapter 7 of AGN3.

### 15.56.12 Save grain temperature

The temperature of each grain species is printed for each zone.

## 15.57 Save grid

This is used with the **grid** command to create a file giving the parameters for each simulation in a large grid of calculations. This can be combined with other **save** commands to create files giving the derived quantities for a large set of calculations.

The first row gives tab-separated column titles. The column title for the parameters that are varied will give the first few characters of the command line for that parameter. Each of the following lines summarizes a particular grid point. The first column gives the index number in the grid. This is useful if you have separate output for each grid point (e.g. from the **save FITS** command). The index number will be part of

the file name in that case. It is also useful for finding back the output from a particular grid point in a save file (see Section 17.3 for more details). The next two columns indicate whether the calculation had a failure or had any warnings. A successful calculation will have “F” (for false) indicating no failure or warning occurred. If either of these is “T” (for true) then that simulation had major problems. The following column is a string giving a bit more detail about the exit code. It says “ok” if everything went fine and “warnings” if warnings were present in the run, but nothing more serious. If the simulation failed completely, you could see strings like “cloudy abort” or “early termination”. You should look at the detailed output to find out what went wrong. The next two columns give the number of the MPI rank that executed the simulation (will be zero in non-MPI runs) and the sequence number of the simulation on that rank (they are executed in random order). These numbers are used for debugging the code. The next columns give numerical parameters for each simulation in the grid. The last column gives all the grid parameters as a single string. Many plotting programs will allow you to add this string next to each of the plotted data points.

This command does not produce any output if the **grid** command is not used. In grid runs it is highly recommended to always include this command. It allows you to see in one glance if the run was successful and where the problems are in case it was not. It is also useful to include this output in case you want to file a bug report.

## 15.58 Save heating

The code will save the heating agents for each zone. The two columns give the depth [cm] and temperature [K]. The next two columns give the total heating and cooling rates [ $\text{erg cm}^{-3}\text{s}^{-1}$ ]. This is followed by a set of labels for various heat sources and the fraction of the total heating carried by that agent. The faintest agent saved is normally 0.05 of the total and can be reset with the **set WeakHeatCool** command.

The heating labels will probably not correspond to any entries in the emission-line list. If the identification of a heat source is in question the best recourse is to search for the heating label over the entire code.

## 15.59 Save [option] history

### 15.59.1 Save pressure history

This follows the pressure and density convergence history.

### 15.59.2 Save temperature history

This follows the temperature and heating—cooling convergence history.

## 15.60 Save H2

Some details of the large  $\text{H}_2$  molecule are output as a save file. One of the following options must appear. The large  $\text{H}_2$  atom is not included by default but is turned on with the **atom H2** command.

Many studies of  $\text{H}_2$  properties will use plots showing populations as a function of excitation energy. The slope gives a population temperature, which may be related to the kinetic temperature under some circumstances. Theoretical plots can be made using the **save H2 column density** or **save H2 populations** commands described below. The level energy in K, given in the save output, is the x-axis and the column density or population in each level is the y-axis.

The **save grain H2rate** command gives the H<sub>2</sub> formation rate for each of the grain species included in the calculation.

### 15.60.1 Save H2 column density

This saves the column density of ro-vibrational states within the ground electronic state. This command recognizes the same options as the **save H2 populations** command.

The file begins with the total H<sub>2</sub> column densities in the ortho and para forms, followed by the total H<sub>2</sub> column density. The remainder of the file gives the  $\nu$  and  $J$  quantum indices, followed by the excitation energy of the level in K, the total column density in that level, and finally the column density divided by the statistical weight of the level.

### 15.60.2 Save H2 cooling

This produces a file containing heating and cooling rates [ $\text{cm}^{-3} \text{ s}^{-1}$ ] as a function of depth.

### 15.60.3 Save H2 creation

This command has been superseded by the **save chemistry rates** command.

### 15.60.4 Save H2 destruction

This command has been superseded by the **save chemistry rates** command.

### 15.60.5 Save H2 heating

This produces a file containing the depth, total heating rate [ $\text{erg cm}^{-3} \text{ s}^{-1}$ ], and H<sub>2</sub> heating predicted by an expression in [Tielens and Hollenbach \(1985a\)](#), together with the heating predicted by the large model of the H<sub>2</sub> molecule.

### 15.60.6 Save H2 levels

This creates an energy-ordered list of the levels within X. The first column gives the energy in wavenumbers relative to the lowest level, the second gives the statistical weight, and the next two columns give the vibration and rotation quantum numbers. The sum of the transition probabilities is given, followed by the critical density of the level for each of the colliders included in the calculation.

### 15.60.7 Save H2 lines

The intensities of all significant H<sub>2</sub> emission lines that are produced within the ground electronic configuration are given. The file also gives the information needed to convert an emission-line spectrum into a level population vs excitation energy diagram.

Each line of output begins with a spectroscopic designation of the line, followed by the upper and lower electronic, vibration, and rotation quantum numbers. This is followed by the wavelength of the line in microns. The line wavelength is then printed as it appears in the output. The log of the intensity or luminosity in the line (depending on whether the intensity or luminosity case is specified), and the intensity of the line relative to the normalization line, follow. The excitation energy of the upper level of the

transition in Kelvin and the product  $g_u h\nu A_{ul}$  for each line are also given. This product is needed to convert intensities into excited-state column densities.

Only lines brighter than  $10^{-4}$  of the reference line are given by default. The intensity of the faintest line, relative to the normalization line, is set with the first optional number that can appear on the command line. If the number is negative then it is interpreted as the log of the limit.

By default only lines within the ground electronic system are saved but this can be changed if the keyword **electronic** appears on the command line. If the keyword **all** also appears then lines within all electronic systems are saved. If the keyword **ground** appears then only lines the ground system are saved. This is the default. If a number appears then it is the number of electronic systems to be saved, 1 for only the ground electronic state. If the number of systems is specified then it must be the second number on the line—the first being the intensity of the faintest line to print.

The following give examples. The first sets the faintest H<sub>2</sub> line to save. Only lines within the ground electronic system will be produced.

```
save H2 lines, faintest -4 "filename"
```

This sets the faintest line, and also requests all lines produced by all electronic configurations.

```
save H2 lines, faintest -4 all "filename"
```

This example requests only lines for the lowest three electronic configurations.

```
save H2 lines, faintest -4 electronic 3 "filename"
```

### 15.60.8 Save H2 populations

The level populations for the ground electronic state are given for the last computed zone. The populations are relative to the total H<sub>2</sub> abundance.

There are several optional parameters. The quantum numbers of the highest vibrational and rotational levels to save can be specified as consecutive numbers on the command line. These occur in the order  $v$  then  $J$ . If no numbers occur, or if a limit that is less than or equal to zero is entered, then populations of all levels will be saved.

If the keyword **zone** appears then the level populations will be saved for every zone. These are all given along one long line, a format that is different from the other output options. Otherwise the populations are only saved at the end of the iteration using the output options described next.

If output is only saved for the last zone then it can be in either a triplet format, with the vibration and rotation quantum numbers followed by the population, or as a matrix, with all populations of a given vibration quantum number lying along a single row. The triplet form is done by default, and the second will occur if the keyword **matrix** occurs on the command line.

The **save H2 column densities** command provides similar output options but for integrated column densities.

### 15.60.9 Save H2 PDR

The output contains useful information regarding conditions within a PDR.

### 15.60.10 Save H2 rates

The output contains useful information regarding H<sub>2</sub> formation and destruction rates.

### 15.60.11 Save H2 Solomon

The output will give the total rate for photo-excitation from the ground to electronic excited states and then identify those levels which are the dominant contributor to the total rate.

### 15.60.12 Save H2 special

This provides infrastructure to save debugging information. It can be easily changed to suite particular needs.

### 15.60.13 Save H2 temperatures

The depth [cm], 21 cm spin temperature [K], gas kinetic temperature [K], and several temperatures derived from relative populations of  $J$  levels within the  $H_2 v = 0$  ground electronic state [K], are saved for each zone.

### 15.60.14 Save H2 thermal

A variety of heating—cooling processes involving  $H_2$  are given for each zone.

## 15.61 Save helium [options..]

### 15.61.1 Save helium line wavelengths

This gives wavelengths of lines from  $n = 2$  levels of He-like ions.

## 15.62 Save hydrogen

### 15.62.1 Save hydrogen 21 cm

This gives some information related to the spin temperature of the 21 cm line. The keyword is either **21 cm** or **21cm**. The level populations within 1s are determined including radiative excitation by  $L\alpha$ , pumping by the external and diffuse continua, collisions, and radiative decay. Several of the resulting populations and temperatures are included in the output.

### 15.62.2 Save hydrogen conditions

This gives the physical conditions and populations of various forms of hydrogen are given as a function of depth. The depth [cm], temperature [K], hydrogen density [ $\text{cm}^{-3}$ ], and electron density [ $\text{cm}^{-3}$ ] are followed by the densities of  $H^0$ ,  $H^+$ ,  $H_2$ ,  $H_2^+$ ,  $H_3^+$ , and  $H^-$  relative to the total hydrogen density.

### 15.62.3 Save hydrogen ionization

This gives rates for processes affecting the hydrogen ionization as a function of depth. The columns give the ground state photoionization rate [ $\text{s}^{-1}$ ], the total and Case B recombination coefficients [ $\text{cm}^3 \text{s}^{-1}$ ], the predicted ratio of  $n(H^+)$  to  $n(H^0)$ , and the theoretical ratio for the simple case. Finally, contributors to the ground state photoionization rate are produced with a call to *GammaPrt*.

### 15.62.4 Save hydrogen lines

The upper and lower quantum indices, the line energy, and the optical depth in the line, will be saved.

### 15.62.5 Save hydrogen Ly $\alpha$

This produces some information related to the excitation, destruction, and escape of the Ly $\alpha$  line of hydrogen. The optical depth from the illuminated face to the outer edge of the current zone is followed by the excitation temperature, electron kinetic temperature, and the ratio of these.

### 15.62.6 Save hydrogen populations

This gives the depth [cm], the densities of H<sup>0</sup> and H<sup>+</sup> [cm<sup>-3</sup>], followed by the level population densities [cm<sup>-3</sup>] for the levels in the order  $n = 1, 2s, 2p, 3, 4, 5, \dots$  for each zone.

## 15.63 Save ionization means

The mean<sup>9</sup> ionization of all elements included in the calculation will be output. The format is exactly the same as the mean ionization printout produced at the end of the standard output.

The **save averages** command described on page 160 can save the average ionization fraction for a particular species.

## 15.64 Save ionization rates carbon

The total ionization and recombination rates for a specified element will be saved as a function of depth. The name of an element must appear on the command line. Each line of output will have the depth [cm], electron density [cm<sup>-3</sup>], and the sink timescale for loss of particles due to advection out of the region [s<sup>-1</sup>]. The remaining numbers give quantities for each possible stage of ionization of the element. For each ionization stage the set of numbers that are printed give the density of atoms in that ionization stage [cm<sup>-3</sup>], the total ionization rate [s<sup>-1</sup>], the total recombination rate [s<sup>-1</sup>], and the rate new atoms are advected into the region [s<sup>-1</sup>].

## 15.65 Save ip

This gives the ionization potentials of all shells of all ions and atoms of the 30 elements included in the code. The first row is the spectroscopic designation of the ion. Each additional row gives the subshell and ionization potential of that subshell in eV.

## 15.66 Save Leiden

This command produces an output file designed for the comparison calculations presented in the 2004 Leiden meeting on PDR calculations (Röllig et al., 2007).

<sup>9</sup>Before version 96 the ionization fractions only included atoms and ions. They now also include molecules. The sum of the atomic and ionic fractions will not add up to unity if a significant fraction of the element is in molecular form.

## 15.67 Save lines, options

This set of commands will save some details about line formation.

### 15.67.1 Save lines, array

This gives the intensities of all lines in a form in which they can easily be plotted by other software. The first column lists the line energy in Rydbergs. The next gives the spectroscopic designation of the ion. The following two columns give the log of the intrinsic and emergent intensities or luminosities of the line. Only lines with non-zero intensity are included. All lines that appear in the CLOUDY output will also appear in the resulting output file.<sup>10</sup>

Lines energy are in Rydbergs by default. This command recognizes the **units** option.

### 15.67.2 Save lines, cumulative

This option tells the code to save the log of the cumulative intensity of up to 100 emission lines as a function of depth into the cloud. The emission lines are specified on the following input lines and end with a line with the keyword **end** in columns 1–3.

The code distinguishes between intrinsic and emergent line intensities. This command reports the intrinsic line intensity by default. If the keyword **emergent** appears then it will report the emergent line intensity.

The label used by CLOUDY to identify each line in the main emission-line output must appear in column 1–4 of the line and the line wavelength appears as a free-format number in later columns. These must match the label and wavelength used by the code exactly. You can obtain this either from the main printout or from the output of the **save line labels** command.

The line labels and wavelengths are followed by the depth into the cloud and the integrated intensities of the lines [ $\text{erg cm}^{-2}\text{s}^{-1}$ ] for each zone. This information can be used to follow the build up of emission lines across a computed structure.

The following illustrates its use;

```
save lines, cumulative, "lines.cum"
totl 4861
o 3 5007
totl 3727
o 1 6300
end of lines
```

If the optional keyword **relative** is specified then the quantities will be given relative to the normalization line. The default is to give the intensity  $4\pi J[\text{erg cm}^{-2}\text{s}^{-1}]$ .

The **save lines cumulative** and **save lines emissivity** commands use the same line array so both commands cannot be used in the same calculation.

### 15.67.3 Save line data

This saves some atomic data for all lines included in the line transfer arrays. It can be used to generate a table listing many lines and their atomic parameters. The code will stop after the data have been saved since it is left in a disturbed state.

<sup>10</sup>In versions 90 and before of the code, only the level 1 and level 2 lines were output by this command.

The first set of lines consists of recombination lines from [Nussbaumer and Storey \(1984\)](#) and [Pequignot et al. \(1991\)](#). For these the spectroscopic designation and wavelength are given followed by the log of the recombination rate coefficient.

The remaining sets of lines are those that are treated with full radiative transfer. The first are the *level 1* lines, those with accurate atomic collision data and wavelengths. The next *level 2* lines have many more lines and uses Opacity Project wavelengths and various g-bar approximations to generate approximate collision strengths. These are followed by the hydrogen and helium iso-electronic sequences, then the  $^{12}\text{CO}$  and  $^{13}\text{CO}$  lines. The  $\text{H}_2$  and Fe II lines come last if these large atoms are included.

By default the atomic parameters will be evaluated at a temperature of  $10^4$  K. Other temperatures can be selected by entering a **constant temperature** command. The number of H-like, He-like, CO,  $\text{H}_2$ , and Fe II lines that are printed is controlled by the size of the relevant atoms when the **save line data** command is executed.

This command recognizes the **units** option. The line can be given in any of the wavelength or energy units it understands.

### 15.67.4 Save lines, emissivity

This saves the emissivity of up to 100 emission lines as a function of depth into the cloud. This information can then be used by other codes to reconstruct the surface brightness distribution of a resolved emission-line object. The *emissivity* is the net emission  $4\pi\bar{J} = n_u A_{ul} P_{ul} h\nu$  [erg cm $^{-3}$  s $^{-1}$ ] produced at a point and escaping the cloud. This includes the escape probability  $P_{ul}$ .

The code distinguishes between intrinsic and emergent line intensities. This command reports the intrinsic line intensity by default. If the keyword **emergent** appears then it will report the emergent line intensity.

The emission lines are specified on the input lines that follow the command and end with a line with the keyword **end** in columns 1–3. The label used by CLOUDY to identify each line (use the **save lines labels** command or look at the main emission-line intensity printout to obtain a list of lines) must appear in column 1–4 of the line and the line wavelength appears as a free-format number in later columns. The easiest way to obtain this information is to copy and paste the line identification and wavelength from a CLOUDY output. The label and line must match exactly.

The save output begins with emission-line labels and wavelengths. The remaining output gives the emission structure. The first column is the depth [cm] into the cloud. The remaining columns give the volume emissivity [erg cm $^{-3}$  s $^{-1}$ ] for each line. The intensity is for a fully filled volume so the saved intensity should be multiplied by the filling factor to compare with observations of a clumpy medium.

The following illustrates its use;

```
save lines, emissivity, "lines.str"
totl 4861
o 3 5007
totl 3727
o 1 6300
end of lines
```

The **save lines cumulative** and **save lines emissivity** commands use the same line array so these commands cannot be used in the same calculation.

### 15.67.5 Save lines, intensity [every 5 zones]

This gives the intrinsic or emergent intensities of all lines with intensities greater than zero in the format used for the final printout (line label, wavelength, intensity).

The default is to give the intrinsic intensities. If the keyword **emergent** appears then those will be given instead.

The default is for this to be done only after the last zone is computed. Results for intermediate zones can be saved if the additional keyword **every** appears. In this case the first number on the line is the interval between zones to save, as in the **print every** command.

The save output will have the line information spread over 6 columns. For some data base applications it would be better to have a single column of results. If the keyword **column** appears then a single column is produced.

Lines with non-zero intensities are reported by default. If the keyword **all** appears then all lines are reported.

### 15.67.6 Save line labels

This creates a file listing all emission-line labels and wavelengths in the same format as they appear in the main output's emission-line list. This is a useful way to obtain a list of lines to use when looking for a specific line. The file is tab-delimited, with the first column giving the line's index within the large stack of emission lines, the second giving the character string that identifies the line in the output, and the third giving the line's wavelength in any of several units. The line ends with a description of the line.

There are a vast number of emission lines predicted by the code and many lines will have the same wavelength. The line label can usually be used to distinguish between various lines with the same wavelength. This is seldom the case for contributions to the line however. The line index can be used to resolve this degeneracy in cases where you want to obtain a line's intensity with a call to a routine. Routine *cdLine.ip* (described in the header file *cdDrive.h* and also in Part 2 of this document) uses the line index to find the relative intensity and luminosity of a particular line. But note that this index is not necessarily the same in different calculations. It will always be the same for a particular set of input conditions but it depends on the sizes of various atoms and which chemical elements are used in the calculation.

Most emission lines in the code share a common structure. Each of these lines will enter the following into the emission-line stack:

```
532 H 1 6563A predicted line, all processes included
533 Inwd 6563A predicted line, all processes included
534 Coll 6563A predicted line, all processes included
535 Pump 6563A predicted line, all processes included
536 Heat 6563A predicted line, all processes included
537 H 1 4861A predicted line, all processes included
538 Inwd 4861A predicted line, all processes included
539 Coll 4861A predicted line, all processes included
540 Pump 4861A predicted line, all processes included
541 Heat 4861A predicted line, all processes included
```

The entries marked "Inwd", "Coll", "Pump", and "Heat" indicate the inward fraction, the collisional and radiative pumped contribution to the line, and the line heating. All of these entries will occur in the file if the keyword **long** appears. By default these contributions to the line are now given so the above would appear as

```
532 H 1 6563A predicted line, all processes included
537 H 1 4861A predicted line, all processes included
```

### 15.67.7 Save line list [absolute]

This reads in a list of emission lines from a file and reports the predicted line intensities. It is designed as a way to obtain predictions for a subset of the lines that are predicted during a series of calculations. It is

often used together with the **grid** command when doing grids of calculations or with the **time** command when following the evolution of a time-varying continuum source.

*Filenames* These are tricky since two filenames appear in this command. All **save** commands have the name of an output file in double quotes. This is the first filename on the command line. The file containing the list of emission lines is within the second pair of quotes. In the following example

```
save linelist "output.txt" "LineListHII.dat"
```

the save output will go to `output.txt` and `LineListHII.dat` contains the set of emission lines. Predicted intensities for the list of lines contained in the second file will be output into the first file.

This command works by calling routine `cdGetLineList` which is described in Part 3 of this document. The filename within the second pair of quotes is sent to this routine. You can build your own file and several sample files giving lists of emission lines are included in the data directory. They have names that are of the form `LineList*.dat` and are intended for different circumstances. `cdGetLineList` will first look for the list of emission lines in the current directory and then search the data directory.

By default results are presented as rows of emission lines. The output file will have the list of emission-line labels in the first row. The first column gives the iteration number and the remaining entries across the row give the line predictions. The **column** option will produce columns instead.

*Units of the line brightness* Intrinsic line intensities are given by default. The keyword **emergent** will give those instead. The lines will be relative to the reference line by default. If the keyword **absolute** appears then they will be given in absolute units, the same units as the third column in the main emission-line output. By default these are  $\text{erg cm}^{-2} \text{s}^{-1}$  for the intensity case and  $\text{erg s}^{-1}$  for the luminosity case. The **print line surface brightness** command, described on page 155, can change the absolute units for all the lines to surface brightness, either  $\text{sr}^{-1}$  or  $\text{arcsec}^{-2}$ .

*The ratio option* If the keyword **ratio** appears then the ratio of adjacent lines will be output. There must be an even number of lines in the line-list file. The output will have the ratio of the intensity of the first divided by the second, the third divided by the fourth, etc. This provides a quick way to look at line ratios as a function of other parameters. The **grid** command can produce grids of calculations. Suppose the file `linelist.dat` contains the following:

```
o 3      5007
totl     4363
```

This specifies the [O III]  $\lambda 5007$  and  $\lambda 4363$  lines. The following input script uses the **grid** command to predict the [O III] line ratio as a function of  $n$  and  $T$ .

```
c produce the save output
save line list "O3.pun" "linelist.dat" ratio no hash
save grid "O3.grd"
c following three commands do H and O-only, and set O
c ionization so that little O+3 is present (to prevent
c formation of 4363 by recombination).
init ``honly.ini``
element oxygen on
element oxygen ionization 1 1 1 0.01
c set the continuum
blackbody 4e4 K
ionization parameter -2
c next 4 commands vary Te and n
constant temperature 4 vary
grid 4000 17000 3000
hden 4 vary
```

```
grid 2 6.1 1
c must stop this constant Te model
stop zone 1
```

This produces two output files, `03.grd` containing the densities and temperatures, and `03.pun`, containing the ratio  $I(5007)/I(4363)$  for each density and temperature. These could be plotted to show this line ratio as a function of density and temperature, as shown in the Figure [15.3](#).

### 15.67.8 Save line optical depths, limit=-2

This gives the total optical depths for all lines. By default all lines with optical depths greater than 0.1 will be included. The lower limit can be reset with the optional number that appears on the line—it is the log of the smallest optical depth to be printed. This command recognizes the **units** option so the line wavelengths can be in any of the wavelength or energy units understood by this option.

The line identification, element and ion, starts the output line, in the form used in the usual emission-line printout. Next follows the line's wavelength or energy. Finally the line's optical depth and damping constant are printed.

Results are reported for the last computed zone unless the **every** option appears.

### 15.67.9 Save line pressure.

This produces a list of the most important contributors to the line radiation pressure for each zone.

### 15.67.10 Save line populations, limit= -2

This will output some information concerning the atomic parameters and level populations for all lines that are transferred.

By default all transitions with upper level densities greater than zero will be included. The lower limit to the density threshold can be reset with the optional number that can appear on the line—this is the log of the smallest population density [ $\text{cm}^{-3}$ ] to be printed. This can be used to make the print out somewhat shorter. If the keyword **off** appears then the limit to the smallest population to print will be turned off. All populations will be reported.

The first block of information gives an index to identify each line. This is followed by the line's label. This will usually be the spectrum, as in "H 1" followed by the wavelength, as in "1215A". The lower and upper statistical weights are next, followed by the energy of the line in wavenumbers and the  $gf$  value for the transition.

The population densities for each zone follow this block of information. Each line begins with the index used for that line in the atomic parameter list. This is followed by the populations of the lower and upper level of the transition [ $\text{cm}^{-3}$ ].

### 15.67.11 Save line RT

This produces a file containing information concerning line radiative transfer. A series of lines that specify which emission lines to produce follow the command. The line label is in columns one through four and is followed by the line wavelength. They end with a line that starts with **end**.

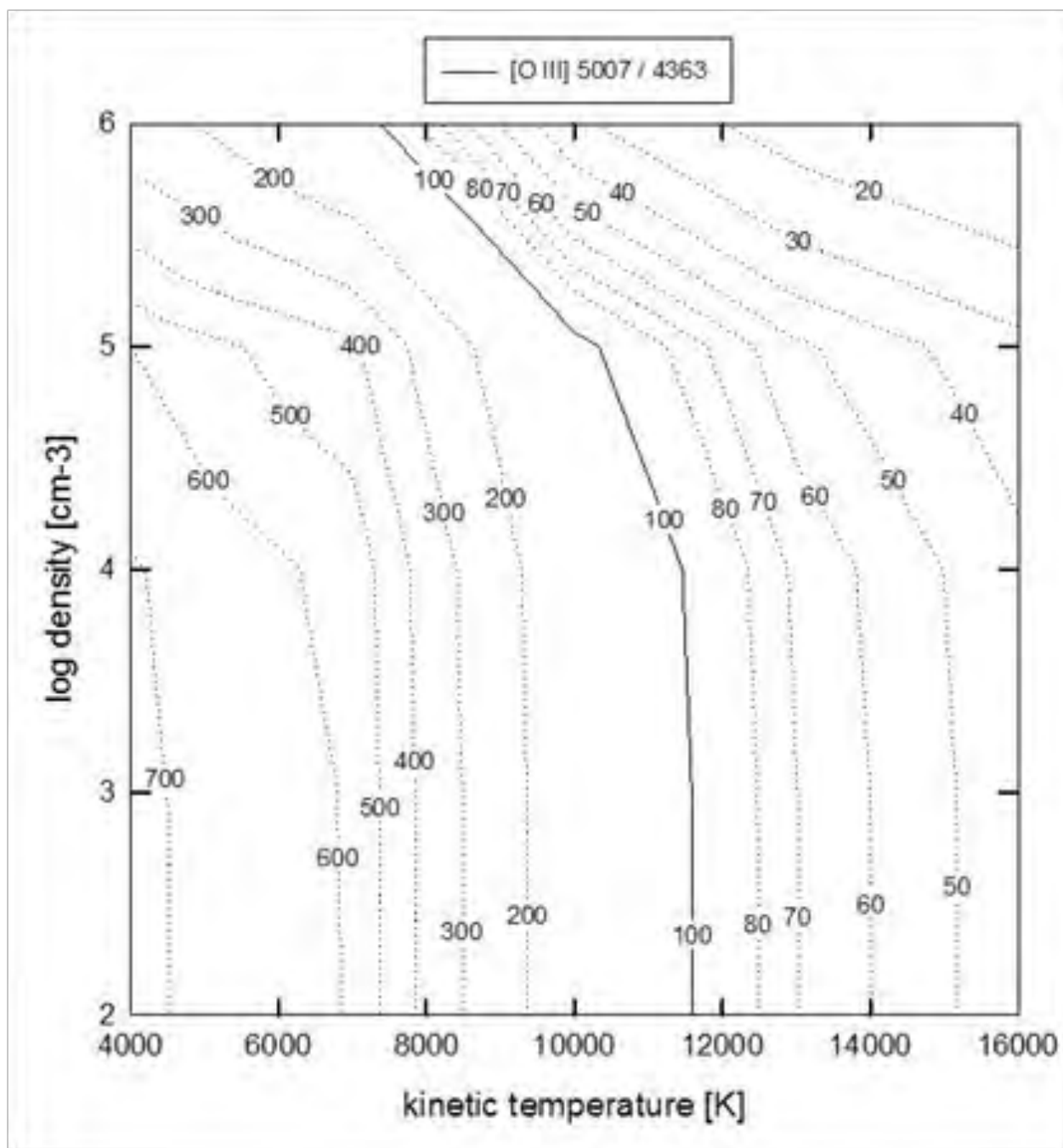


Figure 15.3: The [O III] line ratio as a function of density and temperature.

## 15.68 Save map, zone 3 [range 3999 to 4500]

This produces a map of the heating and cooling rates as a function of temperature. The details of the map are described in the description of the **map** command. The first number is the zone for the map, zero if only a map of the first zone

The optional keyword **range** specifies the temperature range of the map. If this option is specified then the zone number must come first and is followed by the lower and upper temperature limits to the map. Both temperatures will be interpreted as logs if the first number is  $\leq 10$ . The keyword **linear** will force that interpretation. If the temperature range is specified then there must be three numbers on the line—the stopping zone number followed by the lower and upper limits to the temperature.

Normally 20 steps occur between the lowest and highest temperature in the map. The number of steps is reset with the **set nmaps** command.

## 15.69 Save molecules

The densities [ $\text{cm}^{-3}$ ] of all molecules will be saved. The depth and the point and extended visual extinction into the cloud are given in the first three columns. The first line of the output gives header labels for the molecules.

## 15.70 Save NLTE

This command saves some averages reported for the NLTE7 Workshop, <http://nlte.nist.gov/NLTE7/>. You must enable the **USE\_NLTE7** macro when compiling to use this feature. To do so, add **EXTRA="-DUSE\_NLTE7"** to the end of the **make** command used to build the code in the **sys.XXXX** directory that you want to use. A typical example might be

```
make -j 4 EXTRA="-DUSE_NLTE7"
```

## 15.71 Save opacities [total, grain, element]

This gives some of the opacity sources considered by the code. The photon energy is given in the first column and the opacities are in the columns that follow. This command recognizes the **units** option to change the energy scale. One of the keywords described in the following sections must appear.

The opacities are only defined over the energy range over which the incident radiation field is defined. The resulting opacities will not extend to high energies for softer continua. A hard continuum such as **table agn** should use used in the input stream to obtain the opacities over the full energy range.

Results are reported for the last computed zone unless the **every** option appears.

### 15.71.1 Save total opacity

If the keyword **total** appears then the total opacity  $\kappa$ , the absorption cross section multiplied by the density of the absorber, summed over all constituents, will be saved. This has units  $\text{cm}^{-1}$ . The optical depth would be  $\kappa$  multiplied by a physical depth. This opacity includes all constituents, gas phase and grains, for the last computed zone, with unit filling factor. The first column is the photon energy and the second is the total opacity. The absorption and scattering opacities follow. The fifth column gives the albedo, the ratio  $\kappa_s/(\kappa_s + \kappa_v)$ . The  $\kappa$ 's are the scattering and absorption parts of the total continuous opacity. The last column is a label indicating the ionization edge for each species included in the calculation.

### 15.71.2 Save grain opacity

The total grain opacity (all grain types that are included) will be saved after the last zone is calculated. Successive columns give the photon energy, the total (absorption plus scattering) opacity, the absorption opacity, and the scattering opacity. The total and scattering opacity discount forward scattering so are for the extended source case. The last column gives the scattering opacity with forward scattering included so is for the stellar case.

### 15.71.3 Save fine opacities range 0.7 to 1 Ryd, coadd 15 cells

The code's execution time is partially set by the resolution of the continuum mesh due to the need for frequent reevaluations of opacities and rates. A very fine continuum mesh, with resolution of  $1 \text{ km s}^{-1}$  or better, is used to automatically treat line overlap. The main opacity array cannot use this resolution because single models would then have *very* long execution times. Instead, the code uses a multi-grid approach where a coarse continuum is used for most integrated quantities but a fine continuum grid is also present to handle the line overlap problem. This command will output the current contents of the fine opacity array. This only includes lines, not the continuum.

Only cells with non-zero opacity will be output. Even then, the file will be huge. If the keyword **range** occurs then the first two numbers on the command line are the lower and upper bounds to the energy range in the output. If neither is specified then the full energy range is reported. The **units** keyword, described on [164](#), can be used to change the units of the range and the resulting output. The last optional number says how many neighboring cells to co-add. If no number appears then 10 are coadded to reduce the amount of output.

### 15.71.4 Save element opacity [name]

If neither the **total** or **grains** keywords appear then the name of an element must be specified. The keyword consists of the first four characters of any one of the 30 elements now incorporated in the code. The photon energy (eV) and total photoionization cross section (Megabarns [ $10^{-18} \text{ cm}^{-2}$ ]) for all stages of ionization of the specified element will be saved. A save file name must still be specified to get past the command line parser but is totally ignored.

The photoionization cross section of each stage of ionization is saved in a series of files. The name of the file will start with the first four characters of the element's name, followed by the stage of ionization (the atom is one), ending with `.opc`. Examples are `CARB1.opc` or `CARB6.opc`.

The code stops after producing these files. Only one element can be treated at a time because of this. If you want to examine the opacity files for more than one element you will need to run the code one time with each element.

This version of the **save opacity** command is misnamed. It actually saves the photoionization cross section, not the opacity due to the element.

### 15.71.5 Save opacity figure

This version of the command creates the file needed to generate one of the figures used in another Part of HAZY. The output gives the energy in Rydbergs, then keV, following by the hydrogen, helium, and total gas opacities. The opacities are in units of  $10^{24} \text{ cm}^{-2}$  and have been multiplied by the cube of the energy in Rydbergs.

### 15.71.6 Save opacity shell 26 5 3

This saves the state-specific photoionization cross section for a subshell of any species. The first number is the atomic number of the element, the second number the ionization stage, 1 for an atom, and the third number the subshell, between 1 and 7 representing  $1s, 2s, 2p$ , etc. The save file will contain the incident photon energy in Rydbergs followed by the cross section [ $\text{cm}^2$ ].

## 15.72 Save optical depths

This gives the total, absorption, and scattering continuum optical depths for the computed geometry. For a spherical geometry this is the optical depth from the illuminated face to the outer edge of the cloud and not the total optical depth. The photon energy is followed by the total absorption and scattering optical depths. This command recognizes the **units** option to change the energy scale.

### 15.72.1 Save fine optical depths

The code's execution time is partially set by the resolution of the continuum mesh, due to frequent reevaluations of opacities and rates. For problems related to line overlap, a very fine continuum mesh, with resolution of  $1 \text{ km s}^{-1}$  or better, is used. The main continuum array cannot use this resolution because single models would then have *very* long execution times. Instead, the code uses a multi-scale approach, where a coarse continuum is used for most integrated quantities, but a fine continuum grid is also present to handle the line overlap problem. This command gives the current contents of the fine optical depth array. This only includes lines, not the continuum.

Only cells with non-zero opacity will be output. Even then, the file will be huge. If the keyword **range** occurs then the first two numbers on the command line are the lower and upper bounds to the energy range to be output. If neither is specified then the full energy range is output. The **units** keyword, described on [164](#), can be used to change the units of the range and the resulting output. The last optional number says how many neighboring cells to co-add. If no number appears then 10 cells are averaged together to reduce the size of the output.

## 15.73 Save OTS

The line and continuum on-the-spot fields will be saved.

## 15.74 Save overview

This option saves an overview of the thermal and ionization structure of the cloud and is a major output mechanism for the code. The first numbers are the depth [ $\text{cm}$ ], temperature [ $\text{K}$ ], local heating [ $\text{erg cm}^{-3} \text{ s}^{-1}$ ], total hydrogen density [ $\text{cm}^{-3}$ ], and electron density [ $\text{cm}^{-3}$ ]. All are given as logs except for the depth.

These are followed by various ionization fractions, also given as logs of the quantity. The  $\text{H}_2$  molecular fraction is expressed as  $2n(\text{H}_2)/n(\text{H})$ . Neutral and ionized hydrogen fractions are followed by the ionization fractions for the three stages of ionization of helium, the carbon molecular fraction  $n(\text{CO})/n(\text{C})$ , the first four stages of ionization of carbon, and the first six stages of oxygen. The last column gives the visual extinction (for point and extended extinction) from the illuminated face to the current position.

## 15.75 Save PDR

This gives some quantities relevant to a photodissociation region (PDR). The first column gives the depth into the cloud [cm]. The second is the total hydrogen column density [ $\text{cm}^{-2}$ ]. The gas kinetic temperature follows. These are followed by the ratios of densities of  $\text{H}^0$ ,  $2\text{H}_2$  and  $2\text{H}_2^*$  to total hydrogen,  $\text{C}^0$  and CO to total carbon, and water to total oxygen. The next number is the (dimensionless) intensity of the UV continuum relative to the Habing background. The last columns give the total extinction in magnitudes in the  $V$  filter measured from the illuminated face of the cloud for a point and extended source.

## 15.76 Save performance

The code will output the zone number, the time required to compute that zone, the elapsed time since the start of the calculation, and the number of times per zone that the most nested (ionization) solver was called. This is intended as a mechanism to identify zones that require large amounts of work to converge.

## 15.77 Save pointers

This gives the element number, ion stage, and the shell number, for all shells of the elements heavier than helium. This is followed by the energy of the lower and upper ranges of this shell and the photoionization cross sections at these bounds.

## 15.78 Save physical conditions

The physical conditions as a function of depth will be saved. The depth into the cloud [cm] is followed by the temperature [K], hydrogen and electron densities [ $\text{cm}^{-3}$ ], heating [ $\text{erg cm}^{-3} \text{s}^{-1}$ ], the radiative acceleration [ $\text{cm s}^{-2}$ ], and filling factor.

## 15.79 Save pressure

Various contributors to the total pressure in the gas equation of state will be saved. Pressures are given in dynes  $\text{cm}^{-2}$ . Successive columns give the following:

*depth* is the depth [cm] from the illuminated face to the center of the current zone.

*Pcorrect* is the correct pressure at the current position. This is the sum of all contributors to the total pressure. This may include, among other terms, gas, radiation, turbulent, magnetic, and ram pressure.

*Pcurrent* is the current pressure. It will be equal to the correct total pressure, the previous term in the output, if the pressure has been converged. The tolerance on the pressure convergence is controlled with the **set pressure convergence** command.

*PIn+Pinteg* is the sum of the gas and radiation pressure due to the incident continuum evaluated at the current position. In a hydrostatic model, such as the Orion model proposed by [Baldwin et al. \(1991\)](#), this will be the total pressure and will be equal to the sum of the gas pressure at the illuminated face and the momentum absorbed from the incident continuum.

*Pgas(r0)* is the gas pressure at the illuminated face of the cloud.

$P_{gas}$  is the current gas pressure.

$P_{ram}$  is the current ram pressure. This is only non-zero if the gas is moving, which only occurs when the wind geometry is computed.

$Prad(line)$  is the current line radiation pressure.

$P_{integ}$  is the current integrated pressure due to attenuation of the incident continuum.

$V(wind\ km/s)$  is the wind velocity in  $km\ s^{-1}$ . This is only non-zero for a wind geometry.

$cad(wind\ km/s)$  is adiabatic sound speed in  $km\ s^{-1}$ .

$P(mag)$  is magnetic pressure at the current position.

$V(turb\ km/s)$  is the turbulent velocity in  $km\ s^{-1}$ .

$P(turb)$  is the turbulent pressure.

$int\ thin\ elec$  the integrated radiation force for electron scattering opacity only, in the absence of any absorption.

$conv$  This is “T” if the pressure is conserved and “F” if it is not.

## 15.80 Save qheat

The probability distribution for the grain temperatures is saved. The first column is the grain temperature and the second column gives  $dP/d\ln T$  as defined using the nomenclature of [Guhathakurta and Draine \(1989\)](#). Peter van Hoof added this command.

## 15.81 Save radius

The zone number is followed by the distance to the central object, the depth to the illuminated face of the cloud, and the zone thickness, all in cm. If the keyword **outer** appears then it will only write this information for the outer radius.

## 15.82 Save recombination [option]

### 15.82.1 Save recombination coefficients

Total recombination coefficients, the sum of radiative, dielectronic and three-body, will be produced for all elements in the code. These rate coefficients [ $cm^3 s^{-1}$ ] are evaluated at the current electron temperature.

### 15.82.2 Save recombination efficiency

This gives the recombination efficiency for hydrogen, singlet helium and the helium ion.

## 15.83 Save results

The intrinsic intensities of all emission lines with non-zero intensities, and all column densities, can be saved at the end of the calculation by entering the command **save results last iteration**. This is one way to save the results of a grid of models. The resulting file contains the entire input stream as well.

The resulting save output will have the line information spread over 6 columns. For some data base applications it would be better to have a single column of results. If the keyword **column** appears then a single column is produced. If no keyword occurs, or the keyword **array** does, then the wide format is produced.

## 15.84 Save secondaries

The rate of secondary ionization of  $H^0$ , dissociation of  $H_2$ , and excitation of  $H\ I\ L\alpha$ , are given as a function of depth into the cloud.

## 15.85 Save source function [depth, spectrum]

### 15.85.1 Save source function, spectrum

The continuum source function for the local diffuse radiation field will be saved. The first column is the photon energy. The second column is the diffuse radiation field at that energy, in units of photons per second per Rydberg. Column three contains the total absorption opacity [ $\text{cm}^{-1}$ ] at that energy. Column 4 contains the source function, the ratio of the diffuse field to opacity (both have the units described above). The last column gives this ratio relative to the Planck function at the local electron temperature.

The last column is a measure of the local source function relative to the local Planck function. This will generally be nearly unity for a thermal plasma close to LTE. Ground states of atoms of hydrogen and helium generally have departure coefficients greater than unity so this ratio will be less than unity at energies when their emission dominates. The helium ion can have departure coefficients much smaller than unity for nebular conditions so the source function at helium-ionizing energies can be greater than the Planck function.

### 15.85.2 Save source function, depth

The source function of the diffuse field at an energy slightly greater than the Lyman continuum edge will be saved for all depths into the cloud. All quantities are evaluated at the lowest energy continuum cell that lies within the Lyman continuum. The first column gives the integrated optical depth from the illuminated face of the cloud to the current position. The second is the ratio of the diffuse field (photons per Rydberg per second) to the absorption opacity. The third is the OTS continuum at this frequency, and the last is the ratio of the OTS continuum to the opacity, a photon measure of the OTS source function.

## 15.86 Save species [options]

These commands provide information about the molecules, atoms, and ions that are treated by a unified “species” approach.

Several molecule models in the third-party database LAMDA separate species into ortho- and para-systems. The **save species** command in this version of Cloudy has the limitation that only the last system in

the LAMDA masterlist will be reported in the output. This affects only the output of these commands. All recognized systems will be included in the simulation.

### 15.86.1 Specifying a particular species

By default the **save species populations** and **save species column densities** commands report details about all species that exist during a calculation. If a string appears in double quotes, such as "He+2" or "H2O", only results for that particular species, in this case He<sup>2+</sup> or water, will be given. The string must match one of the species labels, which are listed with the **save species labels** command. The species label must appear after the output file name, as in the following example:

```
% save water column density
save species column density "pdr.col" "H2O"
```

### 15.86.2 Save species column densities

This reports the column densities [ $\text{cm}^{-2}$ ] for all species, at the end of the iteration. At low temperatures the highest levels may have no population so only the lower levels with positive populations are printed.

### 15.86.3 Save species energies

This reports the level energies for all species. The default is to give level energies in Rydbergs but this can be changed with the **units** keyword.

### 15.86.4 Save species labels

This gives a list of the species labels, a useful way to find out how we refer to a particular atom, ion or molecule.

### 15.86.5 Save species levels

This reports the number of levels used for each species, for each zone. If a species is not resolved, that is, it has no internal structure, the number of levels will be given as zero.

### 15.86.6 Save species populations

This reports the level population [ $\text{cm}^{-3}$ ] for all species, for all zones. The depth, species, and column densities for each level are given. At low temperatures the highest levels may have no population so only the lower levels with positive populations are printed.

## 15.87 Save special

If **special** is specified then routine *SaveSpecial* will be called. This routine can be changed to fit the circumstances.

## 15.88 Save tegrid

The history of the last *NGRID* evaluations of the heating and cooling will be saved. *NGRID* is set in a header file. This is one way to evaluate the stability of the thermal solutions.

## 15.89 Save temperature

The radius is followed by the temperature and the derivative of the cooling with respect to temperature  $dC/dT$ . Next come the first and second spatial derivatives of the temperature with respect to depth,  $dT/dr$  and  $d^2T/dr^2$ . These derivatives set the rates of conductive heat flow and heat loss respectively.

## 15.90 Save time dependent

This gives some information on a time-dependent model.

## 15.91 Save TPredictor

The code estimates the temperature of the next zone from the changes in temperature that have occurred in previous zones. This is only attempted in a constant density geometry. This output gives the old temperature, the estimated new temperature, and the final equilibrium temperature.

## 15.92 Save XSPEC [atable/mtable]

This command produces a file in FITS format for input into the spectral analysis program XSPEC ([Arnaud, 1996](#)). This command was added by Ryan Porter and its first application is given in [Porter et al. \(2006\)](#).

Either **atable** or **mtable** must be specified. These keywords refer to additive and multiplicative tables respectively. This command is used with the **grid** command to produce grids of calculations. The file produced by this command contains predictions pertaining to the last iteration of each of the simulations (i.e. the keyword **last** is implicitly in effect). A file produced with **mtable** contains the energy bins and total optical depth,  $\exp(-\tau)$ , from the illuminated face to the last zone of each simulation in the grid. A file produced with **atable** contains the energy bins and some component of the spectrum, as determined by the following options:

**total** - saves the sum of the outward spectrum and the reflected spectrum, including diffuse and incident, lines and continua.

**[attenuated/reflected** incident continuum -] saves the incident continuum, the attenuated incident continuum or the reflected incident continuum;

**[reflected** diffuse continuum -] saves the outward diffuse continuum or the reflected diffuse continuum;

**[reflected** lines -] saves outward lines or reflected lines; and

**[reflected** spectrum -] saves the total outward spectrum or the total reflected spectrum.

By “reflected” we mean components escaping into the  $2\pi$  sr subtended by the illuminated face toward the continuum source. If no options are specified for the **atable** command then the transmitted spectra will be saved. Note that the command can be specified multiple times, allowing the user to individually save any or all of the separate components of the predicted spectra.

By default the full spectral range will be saved. The **range** option will limit the range. Both lower and upper limits must be specified. The energies must be in keV.

In the example below we specify that a blackbody is to be varied. The number on the **blackbody** line is ignored. The **range** command specifies that the log of the temperature of the blackbody will range from 4 to 6. The **grid** command specifies that we are calculating a regularly spaced grid with 1 dex steps between 4 and 6. In this case since we only have one parameter varied with the **vary** keyword, there will only be one dimension in the grid and only three simulations. Each of the two **save xspec atable** commands produces a FITS format file. The first file, named `filename1`, will contain the incident continuum for each of the three simulations. The second file, named `filename2`, will contain the transmitted spectrum for each of the three simulations. The commands are as follows:

```
blackbody 1e5 K vary
grid range 4 to 6 in 1 dex steps
save xspec atable incident continuum "filename1"
save xspec atable spectrum "filename2"
```

### 15.93 Save wind

The radius and depth [cm] are followed by the velocity [ $\text{cm s}^{-1}$ ], total radiative acceleration [ $\text{cm s}^{-2}$ ], the accelerations due to lines and continua alone, and the dimensionless force multiplier. If the keyword **terminal** appears then this is only produced for the last zone, otherwise it is for every zone. This option can be combined with the **save grid** command to save predictions from a series of grid calculations.

### 15.94 State [get; put] “filename”

This command either saves or recovers the conditions computed in a previous calculation. In both cases the name of a file must appear between two double quotes. If the keyword **get** appears then the file is opened for reading. It must contain the state variables for a previous iteration of the same simulation. If the keyword **put** appears then the file is opened for writing and the code’s state at the end of the calculation is saved in the file. If the keyword **print** appears on the command line then a detailed printout of the contents of the state file is produced.

This is intended as a debugging aid for dynamics simulations which require many dozens of iterations to approach a solution. It is under development and is not ready for use.

### 15.95 Title “This is a title”

The argument is a title for the calculation and can be useful for organizing the models. The preferred form is a quoted string, but if this is not present, the whole of the line after the command will be used for backward compatibility.

The title is reprinted several times to label output.

Table 15.1: Trace convergence keywords and routines

Keyword	Routine
<b>pressure</b>	ConvPresTempEdenIoniz
<b>temperature</b>	ConvTempEdenIoniz
<b>eden</b>	ConvEdenIoniz
<b>ionization</b>	ConvIoniz

## 15.96 Trace zone 94 [iteration 2; options . .]

This command turns on *trace* information to follow the logical flow within CLOUDY. The code uses adaptive logic to control the calculation and this option provides a way to follow these internal decisions.

The trace begins *after* the zone given by the first number on the line. If the zone is zero, or if no numbers occur on the line, then the trace is turned on at the beginning of the calculation. The second (optional with default of 1) number is the iteration on which the trace should be started. It should be set to 2 to turn on the trace for the second iteration. So the command **trace 0 2** would start the trace at the beginning of the second iteration.

Table 15.1 lists the trace keywords in the first column. The four-character part of the key that must be matched is capitalized. The purpose of each is indicated in the last column.

A string including the word `DEBUG` is printed when the **trace** command is parsed. This will not be printed if the option **no print** occurs on the **trace** command.

### 15.96.1 Trace convergence level

This is a special form of the **trace** command that prints an overview of the decisions made during the calculation. The physical state of the gas is determined by nested pressure, temperature, electron density, and ionization solvers. This **trace** option makes it possible to view the decisions made by any of these solvers.

The code will check for one of the keywords **pressure**, **temperature**, **eden**, or **ionization**, and produce output explaining the decisions made by that solver and all higher ones. With no keyword all levels are printed. Successively deeper layers are obtained with the keywords listed in Table 15.1.

There are further keywords that create additional printout. The **OTS** keyword will identify source of OTS fields. The **ESOURCE** option will identify sources of free electrons.

### 15.96.2 Trace H-like [element name, full]

This turns on extensive printout describing the physics of one of the model hydrogenic atoms. The same code is used to compute atomic properties for all hydrogenic species. If the keyword **full** appears then the printout will be far more detailed. If no element is specified then this will only be for hydrogen itself. If the name of any other element appears then the printout will be for that element.

### 15.96.3 Trace He-like [element name, full]

This turns on extensive printout describing the physics of one of the model helium-like sequence atoms. The same code is used for all helium-like species. If the keyword **full** appears then the printout will be far more detailed. If no element is specified then this will only be for helium itself. If the name of any other element appears then the printout will describe that element.

Table 15.2: Trace Keywords and Effects

Keyword	Quantity traced
BETA	OI 8446-L $\alpha$ problem
CARBon	carbon ionization equilibrium
CALCium	calcium ionization balance
COMPTon	Compton heating, cooling, and ionization
CONTinuum	prints out photon arrays, pointers
CONVergence	convergence loop, no other printout
COOLants	cooling
DIFFuse fields	sum of recombination coef in DIFFEM
DR	choice of next zone thickness
EDEN	changes in electron density
GAUNT	the free-free gaunt factors
GRAIN	details dealing with grain treatment
HEATIng	heating agents
HEAVies	heavy element balance
HELIum	helium ionization equilibrium
HELIum ATOM	Helium singlets ionization equilibrium
HELIum IONized	helium ion ionization equilibrium
HELIum SINGlet	Helium singlets ionization equilibrium
HELIum TRIPlEt	helium ion ionization equilibrium
HYDRogen	Minimal trce of the H ionization
IRON	Fe abundance, K-alpha emission
LINEes	line pointers, opacity. A's, etc
leveln	LevelN n level atom routine
Ly BETA	L $\beta$ - OI 8446 pumping problem
MOLEcules	rate coefficients for molecules
NEON	recombination, ionization for neon
OPTICal depths	inner, outer optical depths in STARTR
OPTIMizer	Steps in optimize command driver
OTS	ots ionization rates
POINters	pointers for element thresholds
THREe body	three-body recombination rates for metals
TWO photon	induced two photon processes
WIND	Wind geometry

# Chapter 16

## THE OPTIMIZE COMMAND

### 16.1 Running the optimizer

If you want to run the optimizer, it is *mandatory* to use one of the following commands

```
// non-MPI runs
cloudy.exe -r optrun
// alternative
cloudy.exe -p optrun

// MPI runs
mpirun -np <n> /path/to/cloudy.exe -r optrun
// alternative
mpirun -np <n> /path/to/cloudy.exe -p optrun
```

This assumes that the input script is in the file `optrun.in`. The normal input and output redirection shown elsewhere will not work in this case and CLOUDY will stop with an error message if you try to use it. The command line switches are described in Section 7.2 of HAZY 2. Using the **-r** or **-p** command line switches is necessary because the code needs to know the name of the input script in order to generate intermediate files with its name embedded. It is also necessary for the correct functioning of the code in MPI mode. Running in MPI mode is described further in Section 16.5.1.

### 16.2 Overview

The **optimize** command and its keywords tell the code to vary one or more parameters to try to reproduce e.g. an observed emission-line spectrum, line flux or luminosity, a set of column densities, or temperatures, etc. R.F. Carswell wrote the original code and first implemented the method in CLOUDY and Peter van Hoof extended the methods. The user can choose a minimization method (see Section 16.5) to obtain a best fit to a set of observed quantities. The latter are specified by a series of **optimize** commands. These are described in Section 16.4. The keyword **vary** can appear on many of the commands used to specify physical parameters (Table 16.2). This indicates that this parameter is to be varied in order to obtain a best fit to the observed quantities, and also sets the initial value for the parameter. Section 16.9 below discusses details of some commands. Other commands exist to influence the behavior of the optimizer, e.g. to set the initial stepsize, limit the range of a physical parameter, set the convergence tolerance, etc. See Section 16.6 for more details.

Table 16.1: Commands with vary option. Entries “var” are explained in Section 16.9.

Command	Quantity varied	Min	Max	Inc.
abundances starburst	metallicity	-3	$\log(35.5)$	0.2
atom H-like Lyman pumping scale	line blocking scale factor	$-\infty$	$+\infty$	0.1
blackbody	temperature	$-\infty$	$+\infty$	0.5
bremsstrahlung	temperature	$-\infty$	$+\infty$	0.5
constant pressure set	pressure	$-\infty$	$+\infty$	0.1
constant temperature	temperature	$\log(2.8)$	10	0.1
coronal equilibrium	temperature	$\log(2.8)$	10	0.1
cosmic rays	cosmic ray density	$-\infty$	$+\infty$	0.2
distance	distance	$-\infty$	$+\infty$	0.3
dlaw	first dlaw parameter	$-\infty$	$+\infty$	0.5
element ...	abundance of an element	$-\infty$	$+\infty$	0.2
energy density	energy density temp	$-\infty$	$+\infty$	0.1
filling factor	filling factor	$-\infty$	0	0.5
fudge	first fudge factor	$-\infty$	$+\infty$	var
globule	density	$-\infty$	$+\infty$	0.2
grains	grain abundance	$-\infty$	$+\infty$	1.0
hden	hydrogen density	$-\infty$	$+\infty$	1.0
hextra	extra heating	$-\infty$	$+\infty$	0.1
illuminate	Angle of illumination	0	$\pi/2$	0.1
intensity	intensity of source	$-\infty$	$+\infty$	0.5
ionization parameter	ionization parameter	$-\infty$	$+\infty$	0.5
luminosity	luminosity of source	$-\infty$	$+\infty$	0.5
magnetic field ...	magnetic field	$-\infty$	$+\infty$	0.5
metals	metallicity	$-\infty$	$+\infty$	0.5
phi(H)	photon flux	$-\infty$	$+\infty$	0.5
power law	see below	var	var	0.2
Q(H)	no. of ionizing photons	$-\infty$	$+\infty$	0.5
radius	inner radius	$-\infty$	$+\infty$	0.5
ratio	intensity ratio	$-\infty$	$+\infty$	0.2
ratio alpha <sub>ox</sub>	power-law index	$-\infty$	$+\infty$	0.2
set H2 Jura scale	scale factor for Jura rate	$-\infty$	$+\infty$	0.3
set temperature floor	lowest allowed temperature	$\log(2.8)$	10	0.3
stop ... column density	column density	$-\infty$	$+\infty$	0.5
stop mass	total mass	$-\infty$	$+\infty$	0.5
stop optical depth	optical depth at specified energy	$-\infty$	$+\infty$	0.5
stop radius	outer radius	$-\infty$	$+\infty$	0.5
stop thickness	cloud thickness	$-\infty$	$+\infty$	0.5
table Draine	scale factor	$-\infty$	$+\infty$	0.2
table ISM	scale factor	$-\infty$	$+\infty$	0.2
table star ...	usually temperature	var	var	0.1
turbulence	turbulent velocity	$-\infty$	$+\infty$	0.1
xi	ionization parameter	$-\infty$	$+\infty$	0.5

## 16.3 What must be specified

At least one observed quantity must be given, e.g. the desired emission-line spectrum, a line luminosity, kinetic temperature, or a column density. You also specify which physical parameters should be varied. These parameters are specified by a keyword **vary** which may appear on any of the commands listed in Table 16.2. Up to 20 parameters may be varied at a time. Note that it makes no sense to vary more parameters than the number of observables. In that case there will be multiple solutions and the optimizer will not be able to converge. Preferably you should have significantly more observables than quantities to vary so that observational errors do not unduly influence the optimization process. The physical quantities are actually varied as logs within the code and increments (the first steps away from the initial guess) are also logarithmic. The only exceptions to this rule are the **illuminate** command, and commands taking varying a power-law index (**power law** and **ratio alphox**). They are varied as linear quantities. The parameters of the **dlaw** and **fudge** will have the meaning given to them by the user and may be either linear or logarithmic (though the user is strongly encouraged to make them logarithmic).

Several examples of the **vary** option in action are given in the `optimize_*.in` simulations in the test suite. A typical input stream follows:

```
// tell the code to vary the ionization parameter
// and hydrogen density
blackbody, 5e4 K
hden 4 vary
ionization parameter -2 vary
stop zone 1
//
// the following specifies the observed emission lines, order is
// label, wavelength, intensity relative to H-beta, tolerance
optimize lines
O 3 5007 intensity =13.8 error =0.1
totl 3727 < 2.1 (only upper limit)
end of lines
//
```

This example tells the code to vary the density and ionization parameter to reproduce the observed intensities of two emission lines.

Information concerning the optimization process is fed to the code as a series of keywords on the **optimize** command. These are described next. Only one keyword will be recognized per **optimize** command.

## 16.4 Observed quantities

This section describes how to specify the observed properties we want to match.

### 16.4.1 Optimize column density

This specifies a set of column densities. A series of column densities, ending with a line with the keyword **end** in columns 1 to 3, will be read in from subsequent lines. One column density is entered per line and there is no limit to the number of entries. Columns 1 to 4 of the column density lines must contain the first four characters of the name of the element spelled as in the output from the zone results. The first number on the line is the ionization stage, 1 indicates Atom I, 3 indicates Atom III, etc. The second number on the line is the log of the column density [ $\text{cm}^{-2}$ ] and the last optional number is the relative uncertainty. It has a

default of 0.05 (5 percent). A column density can be specified as an upper limit by entering < anywhere on the line after column 4.

The following gives an example of its use:

```
optimize column densities
hydrogen 1 < 17 // make optically thin in H0 Lyman continuum
carbon 4 17.4 error =.001 // match the C+3 column density closely
silicon 3 14.6 // The Si+2 column density
end of column densities
```

**Molecular and level column densities: how this command works:** The label and ion that are parsed from the lines giving the column densities are simply passed to routine *cdColm*. That routine is described in Part 2 of this document in Section 8.6.2 *cdColm—the computed column densities*. This optimization command accepts any species that *cdColm* recognizes. Column densities of molecules and excited states of some ions can be specified by entering an ion stage of zero and one of the strings that is described where *cdColm* is described. The first four characters of the label given on the input line must agree with those listed there.

The following shows some examples of optimizing molecular and state column densities:

```
optimize column densities
H-    0 < 17 // The H- column density is a limit
H2     0 17.4 error =.001 // Match the H_2 column density exactly
H2+    0 14.6 // The H2+ molecular ion
O11*   0 16.3 // This is an excited level within the O0 ground term
end of column densities
```

Note that extra spaces were placed after the labels for the molecules to pad out the needed four-character label. The ion, the first number after the four-character label, is always zero

## 16.4.2 Optimize, [intensity, luminosity]=36.425 [error =0.1]

This specifies the luminosity or intensity of a line. The code will try to match the predicted intensity or luminosity of the normalization line (usually H $\beta$  and set with the **normalize** command) match this value. The sub-keyword is either **intensity** or **luminosity** and both have exactly the same effect. The number is the log of either the intensity or luminosity of the line in the same units as found in the third column of the final print out. The second (optional) number is the fractional error for the fit between the observed and computed values. If a tolerance is not specified then a fractional uncertainty of 0.05 is assumed.

By default the intrinsic luminosity of the line will be matched. If the keyword **emergent** appears then the emergent luminosity will be considered.

Comments may be entered by placing any of the special characters described on page 17 in column 1.

The following gives some examples of its use:

```
// this will request an H beta intensity of 0.5 erg cm-2 s-1
// it applies to Hbeta since this is the default normalization
// line
optimize intensity -0.3

// the following resets the normalization line to 5007, then
// asks the code to reproduce its luminosity
normalize to "O 3" 5007
// we want a 5007 luminosity of 1034.8 erg / s
optimize luminosity 34.8
```

### 16.4.3 Optimize continuum flux 350 micron 126 Jansky [error =0.1]

This command allows you to optimize an observed continuum flux or surface brightness at an arbitrary wavelength. Note that both the keywords **continuum** and **flux** need to be present on the command line. The first parameter must be the wavelength or frequency of the observation. The syntax for this parameter is exactly the same as for the **set nFnu add** command described in Section 18.14.37. The code will implicitly behave as if a **set nFnu add** command had been given, except that the **print continuum** output will not be turned on. The second parameter on the command line is the observed flux. The unit of the flux should also be supplied. There are many choices. You can supply any combination of the following keywords separated by slashes: **erg/s** or **W** for the power unit, and **sqcm** ( $\text{cm}^{-2}$ ) or **sqm** ( $\text{m}^{-2}$ ) for the surface area unit. This will define a flux per decade  $\nu F_\nu$ . If you want to supply a flux density  $F_\nu$ , you can combine this with the keyword **Hz**, while for  $F_\lambda$  you can use **A** ( $\text{\AA}$ ), **nm** or **micron** ( $\mu\text{m}$ ). If you want to supply a surface brightness you can combine this with **sr** or **sqas** (square arcsec), otherwise it will be assumed to be the intensity radiated into  $4\pi$  sr. Some examples of valid units would be **erg/s/sqcm/Hz**, **W/sqm/A**, or **W/sqcm/micron/sr**. Alternatively the following keywords are also recognized: **Jansky** or **Jy** (Jy), and **mJy** (mJy) for supplying a flux density  $F_\nu$ , while the keyword **MJy/sr** can be used for supplying a surface brightness. A keyword for the unit must be present. If the flux is  $\leq 0$ , or the keyword **log** appears on the line, it will be assumed that the flux is logarithmic (but not the wavelength or frequency!). Observed fluxes must be dereddened for any extinction inbetween the source and the observer. The same normalization will be used as in the rest of the Cloudy output. So if you include the **print line flux at earth** command, you should enter the observed flux at Earth here. See Section 15.21.7 for further details. See also Section 18.14.36 for a discussion of the components that are included in the continuum flux prediction. The third (optional) parameter on the command line is the relative uncertainty in the flux. If it is not specified then an uncertainty of 5% is assumed. The optimizer will print both the model and observed flux in the same units as were used on the command line. A continuum flux can be specified as an upper limit by entering **<** anywhere on the line after column 4.

For wavelengths longer than 1 mm this command is counted in the absolute flux category, for shorter wavelengths in the photometry category (see Section 16.7). This distinction is useful so that you can use a radio continuum flux measurement (e.g. at 6 cm) as a replacement for the  $H\beta$  intensity, while you would not want the same to be done for dust continuum measurements since the latter do not scale with the number of ionizing photons.

There is no limit to the number of **optimize continuum flux** commands. The following gives some examples of its use:

```
// make sure we normalize the flux as observed
print line flux seen at earth
// and set the distance
distance 980 linear parsec

// optimize a dust continuum flux, e.g. measured by IRAS
// this will be counted in the photometry class
optimize continuum flux 60 micron 220 Jy error 0.10

// optimize a 6 cm radio continuum measurement
// this will be counted in the absolute flux class
optimize continuum flux 6 cm 50 mJy
// an OCRA measurement...
optimize continuum flux 30 GHz 0.1 jansky

// this will set an upper limit of  $1\text{e-}21 \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Hz}^{-1}$  (100 Jy) at 100 micron
optimize continuum flux < 100 micron -21 erg/s/sqcm/Hz
```

### 16.4.4 Optimize lines

This command tells the code to read a list of observed lines that it will try to reproduce. There is no limit to the number of lines that may be entered.

```
//
// the following specifies observed emission lines, order is
// label, wavelength, intensity relative to H-beta, tolerance
optimize lines
O 3 5007 intensity =13.8 error =0.1
totl 3727 < 2.1 (only upper limit)
O 3 88.33m 1.2
end of lines
//
```

One emission line is specified per line and the line must contain information in a specific order. Columns 1 to 4 list the label and is followed by the wavelength of the line. Both must match the identifications printed in the emission-line output. The code will stop if it cannot find an exact match. The third quantity is the observed relative line intensity. This will be in the same units as the relative intensities printed at the end of the calculation. Intensities are normally given relative to  $H\beta$ , but can be changed to other reference lines with the **normalize** command. The last (optional) number is the relative error in the observed line. If an error is not specified then a fractional uncertainty of 0.05 (5%) is assumed. A line can be specified as an upper limit by entering < anywhere on the line after column 4. The default is to use the intrinsic line intensities. If the keyword **emergent** appears then those will be used instead.

The emission lines end with a line that has the keyword **end** in columns 1 to 3. If this end does not appear correctly then the code will continue reading lines until the end-of-file is encountered.

Comments may be entered using any of the special characters in column 1 that were described on page 17.

### 16.4.5 Optimize temperature

This specifies a set of observed mean temperatures. Each of the lines that follow gives a species, ion stage, mean temperature, an error, and a specification of whether to weight the temperature with respect to radius or volume. The following is an example:

```
optimize temperature
Hydrogen 1 36200K volume
H2 0 150K radius
end of temperatures
```

This behaves as do the previous commands. The “<” option is recognized. Numbers  $\leq 10$  are interpreted as logs of the temperature. The keywords **volume** and **radius** specify how to weight the mean temperature. The default is to weight over radius and will be used if no keyword is recognized. The label for the element must appear in the first four columns. The ion stage follows with the temperature and an optional error coming next. An ion stage of zero indicates a molecule.

This command simply copies the labels and parameters on the each line and passes them to *cdTemp*, a routine that determines the mean temperature and is described in Hazy Part 2 Section 8.6.17 *cdTemp—the computed mean temperature*. That documentation describes how to request mean temperatures for various ions, molecules, and derived quantities.

### 16.4.6 Optimize diameter

The specifies the (angular) diameter of the nebula, defined either as 2 times the Strömgren radius for an ionization bounded nebula, or 2 times the outer radius for a density bounded nebula. If the distance to the object is set with the **distance** command, the number will be interpreted as a linear diameter in arcsec. If the keyword **cm** is present, the number will be interpreted as a linear diameter in cm. The keyword **log** can be used to force interpretation as a logarithmic quantity. If the distance to the object is not set, the number will always be interpreted as a diameter in cm. A diameter can be specified as an upper limit by entering < anywhere on the line after column 4.

## 16.5 Optimization methods

Two optimization methods are in CLOUDY. The *phymir* method (van Hoof, 1997) is the default.

### 16.5.1 Optimize phymir [sequential mode] [8 cpu]

This uses Peter van Hoof's *phymir* optimization method (van Hoof, 1997). In particular it tries to avoid being upset by the inevitable numerical noise that is present in any simulation. It has the further option of being able to run on multiple CPUs on multiprocessor UNIX machines, or in an MPI environment. This optimizer is the default.

*Phymir* by default runs in parallel mode (using more than one CPU) on UNIX systems and in sequential mode on non-UNIX systems. When the code is compiled with MPI support enabled (see Section 7.4 of Hazy 2), it will also run by default in parallel mode on any (distributed) MPI cluster. The keyword **sequential** forces *phymir* to sequential mode. On most systems *phymir* will be able to detect the number of available CPUs. By default it will use all these CPUs. The command parser searches for a number on the line. If one is present this will be the maximum number of CPUs that are used simultaneously. In MPI runs the number of CPUs will be picked up automatically from the MPI environment. In this case setting the number of CPUs on the command line will have no effect.

*The continue option.* The *phymir* method includes an option to restart the optimization. During an optimization run, the code's state is regularly saved. The optimization can be restarted using this state file by including the command **optimize continue** described below.

### 16.5.2 Optimize Subplex

This uses the Rowan (1990) implementation of the subspace-searching simplex optimization method. This method does not support the **continue** option described above.

## 16.6 Controlling the optimizer

These commands change the behavior of the optimizer.

### 16.6.1 Optimize file= "best.in"

At the end of the optimization process the derived input parameters are written into a file for later use.<sup>1</sup> The default filename is "**optimal.in**" but can be changed with this command. The file name must be valid for the

<sup>1</sup>This replaces the **optimize save** command, that was in versions 90 and before.

system in use and must be enclosed in double quotes.

It is possible to use this file to do later calculations in which various quantities might be saved for plotting. Also it is generally a good idea to confirm that a single run with CLOUDY does reproduce the same results as the many calls of the code made by the optimizer. The two should agree *exactly* but might not if the code became corrupted during the many calls made during the process.

### 16.6.2 Optimize increment = 0.5 dex

Increments are the logarithmic quantities that will be added to or subtracted from the initial guess as the optimizer makes the first steps away from the initial value. The default increments preset in the code and listed in Table 16.2 were chosen with typical conditions in mind. It may be necessary to change these if the process is unable to identify a solution. If a zero or no number is entered as an increment then the default increment will not be changed.

The increments entered with this command affect *only* the *previously* entered **vary** command. The following gives some examples of changing the increments.

```
hden 4 vary
optimize increments .1 // this sets .1 dex changes in hden
brems 6 vary           // increments left at default
radius 13.6 vary
optimize increments .05 // this sets changes in radius
```

### 16.6.3 Optimize, iterations = 1200

This specifies the upper limit to the number of iterations to be performed. The default is 400. This command is quite similar to the **stop zone** command in that it is a fail-safe method to prevent runaway infinite loops. The optimization process should not stop because of this limit. It may be necessary to increase the limit if the process is still making progress at the end of the calculation.

The number of iterations that the optimizer needs depends on the number of parameters that are varied. To work well there must be enough iterations to allow each of the free parameters to be varied over a wide range. Make sure that this happens by looking at why the optimization process ended. If it ran out of iterations then you should check whether all of the parameters been varied over a significant range. If they have not then you should increase the number of iterations or vary fewer parameters. If you are using the *phymir* method, it is possible to salvage a prematurely terminated run by increasing the number of iterations and adding the **optimize continue** command described below. CLOUDY will then continue where the previous run stopped.

### 16.6.4 Optimize range -2.3 to 3.9

The preset limits to the range over which parameters can be varied are indicated in Table 16.2.

It is sometimes necessary to establish physical limits to parameters. For instance metallicities may be limited to the range  $-1 \leq \log(Z) \leq 0$  by observations or physical plausibility. This command sets the bounds that the optimizer will use. The arguments are the lower and upper limit to the range of variation of the *previously* entered **vary** commands. Examples follow.

```
hden 4 vary
// the following sets limits to range of density
optimize range from 3 to 5
// There will be no range for this one
```

```
brems 6 vary
radius 13.6 vary
// this sets limits to radius
optimize range from 13 to 14
```

If the optimizer tries to go outside of the allowed range, a very large  $\chi^2$  is returned without actually calculating the model. This should steer the optimizer back to the allowed range.

### 16.6.5 Optimize tolerance = 0.02

The tolerance is a measure of the desired fractional accuracy of the parameters that are varied and is set with this command. The default value of 0.10 should be sufficient for initial trial runs but the final values should be made lower for more precision.

### 16.6.6 Optimize continue

The *phymir* method includes an option to restart the optimization. During an optimization run, the code's state is regularly saved in the file `continue.pmr`. The optimization can be restarted by including the command **optimize continue**. In this case it does not start from scratch, but re-starts using information in the file `continue.pmr` instead. This can be useful when your machine crashed during a lengthy run, you hit the maximum number of iterations before the optimization was finished, or if you want to continue optimizing with a tighter tolerance. The code will be in exactly the same state when it continues as when it wrote the last state file. So in general you will need to edit the input script before you restart the calculation. For instance, the first optimization may have ended because it hit the limit to the number of iterations. If you restart an optimization with a `continue.pmr` file you will need to increase the maximum number of iterations in the input script. Otherwise the code would stop immediately, thinking it was already at the iteration limit.

When you start a run with the **optimize continue** command, the code will immediately rename the file `continue.pmr` to `continue.bak` to avoid it being overwritten by the state files that are produced by the new run. So if you make a mistake, you can rename `continue.bak` to `continue.pmr` and try again.

The **optimize continue** command is *only* supported by the *phymir* optimizer.

## 16.7 Convergence criteria

Observables are placed into one of six categories - “relative flux,” “column density,” “mean temperature,” “absolute flux”, “photometry”, and “diameter” (see [van Hoof, 1997](#)). For the  $i^{th}$  observable the error estimate is

$$\chi_i^2 = \left( \frac{F_i^m - F_i^0}{\min(F_i^m, F_i^0) \sigma} \right)^2 \quad (16.1)$$

where  $F^m$  and  $F^0$  are the model and observed values and  $\sigma$  is the relative error in the observed value. The uncertainty  $\sigma$  is specified when the observed quantities are entered and has a default value of 0.05. The average of the error estimate is computed for each category. The error estimate summed over all categories is minimized.

## 16.8 Other optimizer commands

### 16.8.1 No vary

It is sometimes useful to be able to turn off the optimizer for a given input stream without having to change the (possibly many) occurrences of the **vary** keyword. If the **no vary** command is entered then the **vary** keyword on the other commands will be ignored and a single model will be computed.

The **no vary** command can also be used with the **grid** command to tell the code to ignore the **grid** command and **vary** options.

### 16.8.2 Optimize, trace start 4

This turns on trace printout for the  $n^{\text{th}}$  time the code is called by the optimizer. Specific aspects of the trace are still controlled by the **trace** command.

### 16.8.3 Optimize, trace flow

This turns on trace to follow the logical flow within the optimizer.

## 16.9 Notes concerning commands with vary option

The keyword **vary** can appear on the commands in Table 16.2. All other keywords of the command (except **trace**) are supported (though in some cases there may be an implicit unit conversion, e.g. if you supply a radius in parsec, the optimizer will vary the equivalent radius in cm). If multiple parameters are entered on the command line, only the first parameter will be varied while the rest will be held fixed. The parameter will be varied as a logarithmic quantity. Any exceptions to these rules will be noted below.

### 16.9.1 Cosmic rays

All keywords except **equipartition** are supported.

### 16.9.2 Dlaw

The first parameter will be varied as entered by the user (i.e. no log will be taken). The user is however strongly encouraged to use logs in the definition of the command if the parameter is not of order 1.

### 16.9.3 Element

Only the keywords **scale** and **abundance** are supported.

### 16.9.4 Fudge

The first parameter will be varied as entered by the user (i.e. no log will be taken). The user is however strongly encouraged to use logs in the definition of the command if the parameter is not of order 1.

The initial increment is set to 20% of the initial estimate, or to 1 if the initial estimate is zero. Use the **optimize increment** command to override this default.

### 16.9.5 Illuminate

The illumination angle is varied as a linear quantity in radian.

### 16.9.6 Metals

The **grains** option can be used to vary the grain abundance with the metallicity. The keyword **depletion** is not supported.

### 16.9.7 Power law

The **vary** keyword appears in three forms, **vary**, **varyb**, and **varyc**. If **vary** appears then the first parameter, the slope of the power law, is varied. If **varyb** appears then the second parameter, the high-energy cutoff temperature in Kelvin, is varied. If **varyc** appears then the last parameter, the low-energy cutoff, is varied. Only one parameter may be varied at a time. The power law index is varied as a linear quantity since it is usually negative. If either of the cutoff energies is varied, the optimizer limits will be set such that the lower cutoff cannot move beyond the upper cutoff, or vice versa.

### 16.9.8 Save output

It is not possible to use some of the save output options while optimizing. Save output is designed to save predictions so that they can be analyzed after the calculation is complete. It makes little sense to do this during an optimization run with its hundreds of calculations. After the optimization is complete, rerun the optimal simulation with **save** commands included.

Most **save** options will work during optimization. Those that read a series of lines to determine what quantities to output will not work. This is because the command parser is not used in its usual mode when commands are read during an optimization run.

### 16.9.9 Radius

It is possible to specify the stopping radius or depth on the line but it is not possible to vary it. Only the starting radius is varied.

There could be a major source of confusion if the second parameter is entered and the two numbers are of the same order of magnitude. The logic used to interpret the second number is described on page [92](#) above. If the second number is greater than the first then it is interpreted as an outer radius; if less than, then the depth. As a result the interpretation of the second number can change while the first number is varied. It is safer to set an outer radius with the **stop thickness** or **stop radius** command rather than using the second number. If you vary the inner radius while keeping the outer radius fixed with the **stop radius** command, make sure that you use the **optimize range** command to keep the inner radius inside the outer radius. Failing to do so may result in premature termination of the optimization run.

### 16.9.10 Ratio alphox

The power law index is varied as a linear quantity since it is usually negative.

### 16.9.11 Stop thickness

Only one thickness can be specified. Additional parameters for the second and subsequent iterations will be ignored.

### 16.9.12 Stop radius

Only one radius can be specified. Additional parameters for the second and subsequent iterations will be ignored.

If you want to vary the outer radius while keeping the inner radius fixed, make sure that you use the **optimize range** command to keep the outer radius outside the inner radius. Failing to do so may result in premature termination of the optimization run when the optimizer takes the outer radius inside the inner radius. Alternatively, you can also use a combination of the **radius** and **stop thickness** commands.

If you want to vary the inner radius as well as the outer radius of a nebula, always use a combination of the **radius** and **stop thickness** commands. Varying the inner and outer radius simultaneously can lead to premature termination of the run if the optimizer takes the inner radius outside the outer radius, and is therefore not recommended.

### 16.9.13 Table star ...

The first parameter on the command line will always be varied, even if that is not the temperature. The minimum and maximum of the varied parameter depend on the chosen grid and are set in accordance.

## 16.10 Notes concerning the optimization process

### 16.10.1 Use physically motivated initial conditions

The algorithm will not be able to find a solution if one is not physically possible. For instance, an observed He II  $\lambda 4686/H\beta$  intensity ratio of 0.5 cannot be produced by a  $2e4$  K blackbody no matter how many other parameters are varied (it produces no  $He^+$ -ionizing radiation). It is probably necessary to start with parameters in the general area of the successful model. When far from the solution, it is also a good idea to use a large tolerance (using the **optimize tolerance** command) to stop it from over-optimizing a bad solution. Then do follow-up runs with a smaller tolerance once you have a better idea where the optimum solution is.

### 16.10.2 Change the increment size

The initial increment will often be the largest step ever taken during the optimization process. If the initial parameters are far from the solution then it may be wise to increase the increments. Depending on the optimization method used, it may not be possible to find solutions more than one or two increments away from the initial guess. If the increments are too big it may jump over valid solutions.

### 16.10.3 Set physically motivated limits to the variable quantities

The optimizer driver uses very simple methods and understands surprisingly little modern astrophysics. For instance, while trying to reproduce an observed He II  $\lambda 4686/H\beta$  intensity ratio of 0.5 by varying the temperature of a blackbody radiator, the algorithm may just as well examine the consequences of

Table 16.2: Optimizer results

Method	Iterations	Density	Temperature
Initial condition	—	5	4
Phymir	50	4.988	3.998
Subplex	64	5.001	3.997

photoionization by a 100 K radiation field. Physically, it is known that He II emission only occurs for stars hotter than  $\sim 5e4$  K (AGN3 section 2.5), so there is little purpose in examining temperatures lower than this. The process will converge more quickly if reasonable bounds to the range of the varied quantities are set using the **optimize range** command.

This advice is dangerous, of course, since you may limit yourself to solutions close to those you anticipate. Experiments should also be performed far from the anticipated solution.

#### 16.10.4 Don't give up!

My experience is that this process works about a quarter of the time. The problem is that the algorithm can easily home in on a local minimum which is actually a very bad global solution. When this occurs the best idea is to restart the optimization process with a different set of initial conditions. Better yet is to start the process with parameters that give answers known to be close to the solution, although there is some danger of limiting the outcome to be what you expect. Finally, don't be afraid to use CPU time.

### 16.11 Other optimization methods

Much of astrophysics involves solving the inverse problem—knowing an answer (the spectrum) and trying to deduce the question (the conditions that caused it). However, optimizing a multi-dimensional function is more an art than a science. We would be interested in learning about, and possibly adopting, other promising efficient optimization methods (especially if they can be parallelized). BSD-compatible license code is necessary.

### 16.12 The optimizer test cases

The suite of test cases that comes with the code includes scripts to drive each of the optimizers. These scripts are `optimize_*.in`. These were produced by first running the code at a hydrogen density of  $10^5 \text{ cm}^{-3}$  and a temperature of  $10^4$  K. The spectrum of [O II] and [O III] emission lines was taken from this calculation. Each optimizer starts at a density and temperature some distance away from this solution and tries to reproduce the spectrum. Table 16.12 shows the results of this test.



# Chapter 17

## THE GRID COMMAND

The **grid** command varies some of the input parameters to compute a grid of models. It is actually a form of the **optimize** command and uses much of the same code. It was added by Ryan Porter and its first use was described in [Porter et al. \(2006\)](#).

When the code is compiled with MPI support enabled (see Section 7.4 of HAZY 2), the **grid** command will run in parallel mode on any (distributed) MPI cluster.

If you want to calculate a grid of models, it is *mandatory* to use one of the following commands

```
// non-MPI runs
cloudy.exe -r gridrun
// alternative
cloudy.exe -p gridrun

// MPI runs
mpirun -np <n> /path/to/cloudy.exe -r gridrun
// alternative
mpirun -np <n> /path/to/cloudy.exe -p gridrun
```

This assumes that the input script is in the file `gridrun.in`. The normal input and output redirection shown elsewhere will not work in this case and CLOUDY will stop with an error message if you try to use it. The command line switches are described in Section 7.2 of HAZY 2. Using the **-r** or **-p** command line switches is necessary because the code needs to know the name of the input script in order to generate intermediate files with its name embedded. It is also necessary for the correct functioning of the code in MPI mode.

### 17.1 Grid start point, end point, increment [ linear ]

Parameters for those commands with the **vary** keyword (see Table 16.2 on page 200) can be varied within a grid. Each command with a **vary** option must be followed by a **grid** command. The value entered on the command with the **vary** option is ignored but must be given to satisfy the command parser.

The **grid** command line must have three numbers. The first and second are the start and end points of the range of variation. The last number is the value of the increment for each step. The increment can be either positive or negative. This behaves much the same way as a *do* loop in Fortran or a *for* loop in C. The **grid** command always changes variables from the start point to the end point. In other words, the start point must be less than the end point when the increment is positive, while, when the increment is negative, the start point must be larger than the end point. Note that the grid points are calculated in random order, so it no

longer matters if you use a positive or negative increment<sup>1</sup>. The following varies the blackbody temperature over a range of  $10^4$  to  $10^6$  K with three points.

```
C the blackbody command with vary option, the 1e5 K is needed to
c get past the command parser, but is otherwise ignored
blackbody 1e5 K vary
c this varies the blackbody temperature from 1e6 to 1e4 K with -1 dex
c steps, so that 1e6K, 1e5K, and 1e4K will be computed
grid, range from 6 to 4 with -1 dex increments
```

The following is a 2D grid in which both the ionization parameter and metallicity are varied. There will be five values of the ionization parameter and three values of the metallicity computed.

```
ionization parameter -2 vary
grid range from 0 to -4 with -1 dex steps
metals 0 vary
grid range from -1 to 1 with 1 dex steps
```

For nearly all commands, the quantity will be varied logarithmically (current exceptions are the **illuminate**, **ratio alphox**, **dlaw**, and **fudge** commands). If the quantity is varied logarithmically, the lower / upper limit and the step size also need to be given as logarithms, as shown above. If the keyword **linear** is included on the **grid** command, then these numbers will be interpreted as linear quantities. As an example, the following will produce a grid of models with a constant electron temperature of 5000, 10000, 15000, and 20000 K.

```
constant temperature 4 vary
grid range from 5000 to 20000 step 5000 linear
```

For some commands the unit of the quantity will be implicitly changed by the grid code. An example is the **radius** command. You can enter a radius in parsec using the **parsec** keyword. However, the grid code will always vary the radius in cm. In this case the lower / upper limit will also need to be the (logarithm of) a radius in cm. There is currently no way to overrule this. In general the lower / upper limit needs to have the exact same units as are used on the command line that is generated by the grid, *not* the command line as originally typed by the user.

## 17.2 Beware the grid command treatment of temperatures!!

The following will crash with an fpe

```
constant temperature 4 vary
grid range from 5000 to 20000 step 5000
```

This is because of the rule stated above that the **grid** command treats temperature ranges as logs unless the keyword **linear** occurs.

---

<sup>1</sup>In versions C10 and earlier of the code, the grid points were calculated in sequential order (at least for non-MPI runs) so it made a difference then. The option of choosing a negative increment is maintained for backward compatibility.

## 17.3 Grid output options

Several **save** output options were developed to retrieve information from **grid** runs. The **save FITS** command will generate FITS files for input into XSPEC (Porter et al., 2006). The **save grid** and **save line list** commands save the grid points and emission-line intensities.

When computing a grid, the default is for save files to not overwrite results of previous grid points (to not “clobber” themselves) and to append the results to the save file instead. Conversely, in optimizer runs the default is for save files to overwrite one another since you are usually not interested in output along the unpredictable convergence path. That way you only get the save output from the fully converged model.

When you include the **separate** keyword on a **save** command, the output of each grid point will be written to a separate file. See Section 15.34.10 for further details.

In the output from **save** commands the default behavior is to put separators consisting of hash marks in between the output from different iterations (unless the **no hash** option is used). In grid runs this behavior is slightly changed. There will be an additional separator at the very end of the output, which will also have the additional text “GRID\_DELIMIT” appended, as well as the number of the grid point in the format “grid000000000”. This makes it easy to find back the output from a specific grid point, as well as identify where there is output missing in case some of the grid points have serious problems.

## 17.4 Other grid options

The **no vary** command can be used to ignore all occurrences of the **grid** command and **vary** option in an input stream.

The **repeat** option on the **grid** command causes the expected number of grid steps to be computed but the initial value of the variable is not incremented. This is mainly a debugging aid.

## 17.5 Notes on various commands

### 17.5.1 Constant temperature

Section 17.2 describes the rules governing how the temperature can appear on the **constant temperature** command.



# Chapter 18

## MISCELLANEOUS COMMANDS

### 18.1 Overview

This Chapter describes commands that are used to disable physical processes, change the code's internal behavior, or to take care of housekeeping activities. These are not usually used.

### 18.2 Introduction to the compile commands

The following subsections describe how to set up and then compile some external data files that are needed by the code. The stellar atmosphere files must be compiled if you wish to use some of the **table star** emergent radiation fields. Most of the other files are included in the code's distribution and only need to be compiled if you change the code.

The files produced by the compilation process must be accessible to the code when it is executed from other directories. This is most easily done if you place the compiled files in the code's `data` directory.

The **compile** command will be executed after the command parser is finished examining the input deck. You must specify a complete model to get past the parser's validation of the input stream. The easiest way to do this is to also include the **test** command in addition to **compile** commands.

The code stops after executing the first **compile** command it comes across. It will not do more than one compilation in a single run.

### 18.3 Compile stars

Kevin Volk incorporated several large grids of stellar atmosphere continua into CLOUDY in the 1990's. Peter van Hoof has generalized the treatment and made several extensions. The **table star** commands use these atmospheres. The data files are very large and "direct access" is used to read these files quickly. The result is that the final files are not portable although the code used to read or write them is. The process of converting the stellar atmosphere files from their original format into a form that can be read by CLOUDY is referred to as compiling the stellar atmospheres.

The **table star** commands will only function if the atmosphere files are installed as described on the code's web site. This is only done once while installing CLOUDY although it will have to be done again if you ever change the continuum energy mesh. This step does not need to be done if you don't want to use these stellar atmospheres.

Full instructions on how to download and install the stellar continua are given at [trac.nublado.org/wiki/StellarAtmospheres](http://trac.nublado.org/wiki/StellarAtmospheres).

## 18.4 Compile opacities

*N.B.* This command does not now function and may be removed.

When the code is initialized it spends some time evaluating numerical fits to the needed opacities. This initialization time can be saved if the opacities are compiled and the resulting file placed on the path. To do this, execute the code and enter only the command **compile opacities**. The code will generate a binary file named **opacity.opc** containing the needed opacities and array indices. This file should be in the directory where the other data files are stored.

*N.B.* It is not really necessary to compile the opacities—the code will generate them when it starts up if the file does not exist. This may actually slow down the calculation if you are using a fast computer on a slow network.

## 18.5 Compile gaunt factors

The code normally reads in a table of free-free gaunt factors when it initializes. This command regenerates that file. It was introduced by Ryan Porter.

## 18.6 Compile recombination coefficients [H-like; He-like]

The code reads in a table of recombination coefficients for the hydrogen and helium isoelectronic sequences when it initializes. This command regenerates that file. It was introduced by Ryan Porter. One of the iso-electronic sequences must be specified with either keyword **H-like** or **He-like**.

## 18.7 Compile grains

This command prepares the grain opacity files that are used by the **grains** command. This does not need to be done if you only want to use the types of grains included in the data distribution. You can create other species, with their own size distribution and refractive indices, by compiling them with this command. It is also necessary to compile the grains if you change the code's continuum energy mesh.

This command uses a spherical Mie code originally developed by Peter G. Martin using code written by [Hansen and Travis \(1974\)](#), and implemented into CLOUDY by Peter van Hoof, to generate sets of grain opacities from a description of their size distribution and grain material optical properties ([van Hoof et al., 2004](#)). The set of grain opacities created by this **compile** command are then used to compute temperature, charge, drift velocity, and emitted spectrum, for each bin within the grain-size distribution. Section [A.2](#) describes how to create new grain opacity files.

A grain model is specified by the optical properties of the material and by a description of the distribution of grain sizes. The optical properties are given by a file, with a name ending in “.rfi”, giving the refractive indices as function of photon energy for the full energy range considered by the code. The grain-size distribution is specified in a separate data file with a name ending in “.szd”. Sample refractive index and size distribution files are included in the data directory or you can create your own. In all cases

Table 18.1: Grain keywords for size distribution (\*.szd files)

Keyword	Size distribution
0m010	0.01 $\mu\text{m}$
0m100	0.1 $\mu\text{m}$
1m000	1 $\mu\text{m}$
ab08	<a href="#">Abel et al., 2008</a>
c15	Small PAH, 15 C atoms
c120	Large PAH, 120 C atoms
ism	ISM distribution, <a href="#">Mathis et al., 1977</a>
orion	Orion distribution, <a href="#">Baldwin et al., 1991</a>

the **compile** command combines the refractive index data with the size distribution to produce an opacity file (with a name ending in “.opc”).

Section [A](#) includes far more information and should be consulted.

### 18.7.1 Compile grains

With no options this compiles the minimum number of grain types needed for the **grains** command to function. This command must be given from within the directory that contains the data files. Examine the output to check for problems.

### 18.7.2 Compile grain 10 bins, [filename, ism graphite]

This version of the command produces opacities of a single grain species and is used to create new types of grains. Both the optical properties and size distribution must be specified. This is done by giving keywords (to use one of the standard files located in the data distribution) or a filename between double quotes (to read properties for a new species).

The number on the command line specifies the number of grain size bins to compute. If no number appears then 10 is set by default.

**Keywords for standard data sets** One of a set of keywords may be used to specify refractive index files and grain size distributions. The keyword is usually the name of a file included in the CLOUDY distribution without the filename extension.

A grain-size distribution may be specified with one of the keywords given in Table [18.1](#). The first three are single-sized distribution functions that are mainly used for testing the code. For single-sized grains the supplied number of cells is ignored since one cell is always used. These files have names that end in “.szd”.

The keywords given in Table [18.2](#) may be used to specify a file containing refractive index information. These files have names that end in “.rfi”.

**Creating new data files** If none of the keywords listed in the tables occur then the name of the file must be given explicitly. This may be a user-generated file. A pair of double quotes must surround the filename, as in “name.rfi”. Names ending in “.rfi” are refractive index files while those ending in “.szd” are size distribution files. Filenames and keywords can be mixed on a single line as shown in the examples below.

Table 18.2: Grain keywords for refractive index data (\*.rfi files)

Keyword	Grain type	Reference
ac1-amcarb	amorphous carbon	<a href="#">Rouleau and Martin, 1991</a>
be1-amcarb	amorphous carbon	<a href="#">Rouleau and Martin, 1991</a>
graphite	graphite	<a href="#">Martin and Rouleau, 1991</a>
grey, gray	grey grain	
pah	PAH	original PAH model
silicate	astronomical silicate	<a href="#">Martin and Rouleau, 1991</a>

### 18.7.3 Some caveats

- You must compile the grains within the code's original data directory.
- The grains will need to be recompiled if the energy mesh of the radiation field is changed. The input script `compilegrains.in` in the data directory will do this.

### 18.7.4 Examples

```
// compile all grain types
compile grains

// only ism graphite
compile grains ism graphite

// use 20 bins for a silicate
// with Orion size distribution
compile grains 20 Orion silicate

// the grey.rfi file is the one read
// with the key grey, so the following
// is equivalent to grey ism
compile grains "grey.rfi" ism

// explicitly request the graphite.rfi
// (default with graphite) refractive index
// file, and the Orion size distribution
compile grains "graphite.rfi" "orion.szd"

// these refractive index files are also
// present in the standard distribution
compile grains "gdraine.rfi" ism // graphite, Draine web site, 2000 Nov 10
compile grains "sdraine.rfi" ism // silicate, Draine web site, 1993 Jun 2
compile grains "ph2n.rfi" ab08 // neutral PAH, Li and Draine (2001)
compile grains "ph2c.rfi" ab08 // charged PAH, Li and Draine (2001)
compile grains "ph3n.rfi" ab08 // neutral PAH, Draine and Li (2007)
compile grains "ph3c.rfi" ab08 // charged PAH, Draine and Li (2007)
```

## 18.8 Crash [keywords]

This command should cause the code to crash and is used to confirm that the machine environment is correctly set. One of the following keywords must appear.

The IEEE standard for floating point arithmetic says to not throw an exception when a floating-point exception occurs. Instead the result is set the result to **+/-inf** or **NaN** (not a number) and have the calculation continue. The code will only crash if this is explicitly requested by setting compiler options or enabling traps on the CPU. The source includes logic that will do this on most platforms. CLOUDY should crash on division by zero, overflow, or invalid operation. The **zero**, **overflow**, and **NaN** options on the **crash** command confirms this.

### 18.8.1 crash zero

causes the code to divide a positive number by zero. This causes a division by zero exception.

### 18.8.2 crash overflow

causes the code to divide a very large number by a very small number. The result will overflow.

### 18.8.3 crash long overflow

causes the code to convert a floating number that is larger than the largest long int into a long int. Some machines may throw an exception in this case (mine does not).

### 18.8.4 crash NaN

will divide zero by zero. This will cause an invalid operation exception.

### 18.8.5 crash setnan [float, double]

will test that routine *set\_NaN* sets variables to NaN. A variable is set to NaN with these routines and is then used in a multiplication.

### 18.8.6 crash isnan [float, double]

will test that routine *is\_nan* correctly determines whether a variable is NaN. A variable is set to NaN with *set\_nan* then is asserted not to be NaN. The monitor should fail.

### 18.8.7 crash monitor

causes the code to monitor that a positive number is less than zero. This should cause an exception when the code is compiled in debug mode, but will have no effect when the optimization is set to a high level or if the flag -DNDEBUG is included with the compiler options. If the code does indeed crash with a failed monitor then it may request that the output be posted on the web site. This is normal and only shows that the monitors are working properly.

### 18.8.8 crash bounds

will cause an array to be evaluated with an index that exceeds the array bounds. In some cases the code may crash when this occurs.

There are three types of arrays within the code and keywords say which one to test. Malloc'd arrays are created from pointers by calling *malloc* or *create*. Bounds errors for these types of arrays can be trapped with external tools such as *valgrind* (<http://valgrind.org>) or *Purify*. Declared arrays are explicitly given a size when the variable is declared in the source, as in

```
double c[5];
```

The Portland Group C++ compiler has options to check that limits are not exceeded on a declared array. Finally, the *multi\_arr* class was introduced when the code migrated to C++ and can check on array bounds if the macro **BOUNDS\_CHECK** is set when the code is compiled. This is done with the compiler option **-DBOUNDS\_CHECK** on most compilers.

A keyword specifying the type of array to test must appear. The keyword **heap** checks an array that is produced by a *malloc* off the heap. *valgrind* or *purify* should catch these bounds errors. The keyword **static** will use a static array. Either keyword **stack** or **auto** will use an array created off the stack. Code generated by a bounds-checking compiler such as the Portland Group compiler should catch these errors. The keyword **multi** will check an array created from the *multi\_arr* class. The two keywords **multi iter** will test an iterator in the *multi\_arr* class. These should crash if the macro **BOUNDS\_CHECK** is set. The **crash bounds multi iter** command does the same as the **crash bounds multi** command except that it tests access through iterators (which behave like pointers) rather than direct access to the array.

The **crash bounds** command has an optional offset to add to the array size **ARR\_SIZE**. If *n* is positive then the code will access **array[ARR\_SIZE+n]**. If it is negative then the code will access **array[n]**. The default is zero, that is, to access **array[ARR\_SIZE]**. If either of two keywords, **low** or **high**, occur with no number then the code will assume **n = 2** and check only the low or high bounds.

### 18.8.9 crash exception

will cause the code to throw an exception. The exception should be caught by the handler in the main program.

### 18.8.10 crash undefined

multiplies a valid constant by an undefined float. It has three possibilities. The keyword **static** will multiply by an undefined static variable. The keyword **stack** or **auto** will multiply by a variable created off the stack. If neither keyword occurs then the variable comes off the heap after a *malloc*. The ideal compiler would produce code that crashed when any of these occurs.

## 18.9 Drive fread, gaunts, pointers,...

The **drive** command enters a special debug mode in which the program requests information and responds with deduced quantities. The specific debug mode is selected with the optional keywords, as described next. Parameters for a valid model (density, continuum, and luminosity) must still be specified. The debug mode is entered *after* the last command is specified and the input stream ends.

### 18.9.1 Drive Case B

This option interpolates on [Storey and Hummer \(1995\)](#)'s calculations of Case B hydrogenic emissivity. The user enters the charge (1 for hydrogen, 2 for helium), temperature, density, and upper and lower quantum numbers, and the code returns the interpolated line emissivity. A null line exits the driver.

### 18.9.2 Drive cdLine

The code will loop over all lines entered in the emission-line stack and confirm that *cdLine* can find each one.

### 18.9.3 Drive E1

Values of  $\exp(-x)$ ,  $E1(x)$ , and  $E2(x)$  will be printed for a range of  $x$ .

### 18.9.4 Drive escape probabilities

This option examines calculations of escape probabilities. The user enters the log of an optical depth. The code queries three of the escape probability functions and reports the one-sided escape probabilities. The three are complete redistribution with damping wings, incomplete redistribution, and complete redistribution with only the Doppler core. A null line exits the driver.

### 18.9.5 Drive fread

The free-format scanner will request an input line and then prints the interpreted number until a line with the number zero is entered.

### 18.9.6 Drive gaunts

The program requests a temperature and photon energy, queries the free-free gaunt factor routine, and responds with the returned free-free gaunt factor. The original version of the gaunt factor routine was described in [Hummer \(1988\)](#) and Jason Ferguson extended it to include the full range of energy and temperature CLOUDY needs. Ryan Porter recoded and reorganized the routine for version 96.

### 18.9.7 Drive HyAs

The driver requests a pair of quantum numbers and responds with the hydrogenic Einstein transition probability. It queries the routine *EinstA* written by Jason Ferguson.

### 18.9.8 Drive pointers

This interrogates the photon-energy array. After the continuum is generated the driver will ask for a photon energy in Rydbergs (interpreted as a log if negative) and responds with the cell array index, frequency, cell width, boundaries, and the phase space factor  $2h\nu^3/c^2$ . Once complete, the calculation will continue as usual.

### 18.9.9 Drive pumping

This queries the routine *conpmp*, which evaluates the continuum-line pumping probability at various optical depths (Ferland, 1992).

### 18.9.10 Drive starburst

The code will ask for a metallicity and will return the abundances of the elements by interpolating on Fred Hamann's grid of starburst abundances (Hamann and Ferland, 1993).

### 18.9.11 Drive Voigt

The values of the Voigt function will be reported over a wide range of damping constant and Doppler displacement.

## 18.10 Eden -2

This adds free electrons to the gas. The argument is the log of the electron density [ $\text{cm}^{-3}$ ]. This command is mainly intended to test the behavior of CLOUDY in the limit of very low Compton temperatures. When the color temperature  $T_{\text{color}} \ll 10^4$  K the gas is almost entirely neutral and free electrons must be artificially added to test the Compton energy exchange problem in the strict TE limit. (Remember, charge conservation is a horrible thing to violate.)

Note: This command adds an extra component of electrons. The **set eden** commands, described on page 241, set the electron density. Both commands violate charge conservation.

## 18.11 Fudge factors 4.59678 [12.3 34.5 958 ...]

The numbers appearing on the line can be communicated to any part of the code by calling routine *fudge*. That routine has a single integer argument that is an index to the array of numbers entered on this command line. A call to *fudge*(0) would return the first number<sup>1</sup> and, in the example given above, a call to *fudge*(1) would return the value 12.3. Up to ten numbers can be entered on the command line.

This command is used to pass numbers to temporary or trial parts of the code. Routine *fudge* is a permanent part of CLOUDY and a warning is given at the end of the calculation if this function is evaluated. The code will stop if the index to the array of stored values exceeds the number of values entered. Extra numbers are simply ignored.

The code will abort if *fudge* is asked to return a parameter that was not defined. For instance if the command line reads

```
fudge 4.0
```

then *fudge*(1) does not exist and the code will terminate.

*fudge* will return the number of parameters entered on the command line if it is called with a negative argument. The following code fragment shows how to check on the number of parameters and then evaluate *fudge* if *fudge* factors were entered.

---

<sup>1</sup>In version 90 and before the array index was on the Fortran scale, so *fudge*(1) returned the first number. The code is now written in C++ and the array index is interpreted on the C scale. The first number is *fudge*[0].

```
factor = 1.;
if( fudge(-1) > 0 )
    factor = fudge(0);
```

### 18.11.1 Init [“c84.ini”, path]

This reads a set of commands from an initialization file. Frequently-used commands can be stored in this file and easily accessed.

There is no limit to the number of commands that can be in this initialization file other than the total limit of 4000 command lines that is intrinsic to the code. Only one **init** command can appear in a single input stream.

The default name for the initialization file is `cloudy.ini`. This will be used if no double quotes occur on the command line. Other file names are specified by including a file name within a pair of double quotes as in “`special.ini`”. The name can be any name allowed by the operating system in use.

The code will look for the initialization file in the local directory first and then in the data directory as set with the path. The code will check on the path first if the keyword **path** occurs on the **init** line.

The data directory includes the `ini` files that are used in the test suite. They were set up with particular applications in mind. They may or may not be appropriate for your purpose. Please review the contents of these files before using them.

## 18.12 No ...

It is possible to disable physical processes as a test of their importance. If a physical process is turned off then a flag is set to indicate that the treatment of a physical process has been disabled.

A warning will be printed at the end of the calculation as a reminder that the results of the calculation are not to be trusted. This warning will not be printed if the four-character keyword (**OK**) appears on the command line. The parenthesis is part of this keyword.

### 18.12.1 No advection [H-like, He-like, ...]

This turns off the effects of advection on the ionization, recombination and energy of the gas. Keywords make it possible to turn off these terms for only certain parts of the calculation. The **metals** option will turn off the effects of advection on the ionization of any species not treated as one of the iso-electronic sequences. **Cooling** will turn off thermal effects of advection.

### 18.12.2 No Auger effect

This turns off the Auger effect. Inner-shell ionizations will eject only one electron.

### 18.12.3 No buffering

Programs produce output by first writing into a buffer. Information is written to disk once the buffer is nearly full. If a C++ program crashes before this buffer is “flushed” the information within the buffer will be lost. This poses a problem if the printout generated just before the crash is needed for debugging. The **no buffering** command will redirect the standard output to `stderr` which is not buffered. **Save** commands also have a **no buffering** option to turn off file buffering for the files they create.

On most systems `stderr` can be directed to a file by redirection of 2 as in the following example

```
cloudy.exe < sim.in > sim.out 2> sim.err
```

or alternatively

```
cloudy.exe -r sim 2> sim.err
```

#### 18.12.4 No charge transfer

This turns off all charge transfer interactions.

#### 18.12.5 No collisional ionization

This turns off collisional ionization from ground states of all atoms and ions.

#### 18.12.6 No Compton effect

This command turns off Compton heating and cooling of free electrons and Compton recoil ionization of bound electrons. Electron scattering opacity is *not* turned off.

#### 18.12.7 No CTHeat

This turns off heating due to charge transfer. [Kingdon and Ferland \(1999\)](#) describe the process.

#### 18.12.8 No diffuse line pumping

The diffuse continuum produced by gas within the cloud is included as a general line-excitation mechanism. This turns it off and is useful as a check on the importance of the process. (This command is currently disabled. The code will issue a statement to that effect and exit if this command is entered. Pumping by local diffuse emission is not included. Pumping by diffuse emission from previous, downstream zones is always included.)

#### 18.12.9 No FeII pumping

This turns off H I  $L\alpha$  pumping of Fe II.

#### 18.12.10 No file opacity

The code can generate a file of stored opacities with the **compile opacity** command. This file will be used to generate the opacities in later calculations. The **no file opacity** command tells the code to ignore this opacity file even if it exists.

#### 18.12.11 No fine structure line optical depths

Fine structure lines, such as the  $^3P$  52, 88 $\mu$ m lines of [O III], can become optically thick under certain high-luminosity conditions (see, for example, [Rubin, 1983](#)). They can absorb the incident continuum and be a significant heating source for photodissociation regions ([Tielens and Hollenbach, 1985a](#)). Radiative transfer effects, including stimulated and maser emission, are fully treated for all lines. This turns off optical depths and line transfer for fine structure lines by setting the line opacity to zero.

*This command does not turn off line heating*—which will then be maximized since the lines will remain optically thin. The **no induced processes** command turns continuum pumping off for all lines and should be included to disable heating due to line absorption of the continuum.

The line transfer arrays are permanently injured by the **no fine structure** command. Subsequent runs with the same core load in a grid will still have the line optical depths disabled.

### 18.12.12 No fine opacities

The code uses a fine continuum and opacity grid to automatically account for line overlap. Figure 20 of [Shaw et al. \(2005\)](#) shows an example of this fine mesh. Multi-grid techniques are used to propagate this fine mesh back onto the coarse mesh that is used to evaluate photo rates. This fine grid can be turned off using this command.

### 18.12.13 No free free

Free-free heating, cooling, and emission are turned off with this command.

### 18.12.14 No grain [process]

This series of commands disables various processes involving grains.

**no grain electrons** This turns off the effects of grain charging, either negative or positive, on the overall charge balance in the gas. This violates charge conservation.

**no grain gas collisional energy exchange** Collisional energy exchange between grains and the gas is treated as in [van Hoof et al. \(2004\)](#) and [Abel et al. \(2005\)](#). This process acts to bring the grains and gas toward the same temperature. The two temperatures will be equal if collision energy exchange is fast. Often the gas is hotter than the grains in the  $H^+$  region and this process heats the grains and cools the gas. In fully molecular regions typically the reverse is true as the remaining continuum is very ineffective in heating the gas, but can still heat the grains. This command disables this physics.

**no grain molecules** Condensation of molecules onto cold grain surfaces was added by Nick Abel and is treated using the formalism outlined by [Hasegawa et al. \(1992\)](#) and [Hasegawa and Herbst \(1993\)](#). This turns off that process.

**no grain neutralization** Ions can become neutralized or ionized, by several stages of ionization, following a collision with a grain. [van Hoof](#) and [VAN HOOFF et al. \(2004\)](#) describe the treatment of these collisions. It is partially based on [Draine and Sutin \(1987\)](#)'s description of Coulomb interactions between the grains and gas. The effects of grain neutralization upon the ionization balance of the gas are turned off with this command although grain charging is still computed. This is not self consistent.

**no grain physics** This turns off all grain physics. The only remaining effect of grains is their continuous opacity. The resulting simulation will be much faster but incorrect. This is only intended to provide a method to do quick and dirty calculations. The spectrum emitted by the grains is not calculated so this command violates energy conservation.

**no grain qheat** This turns off quantum heating for all grain species.

**no grain x-ray treatment** This turns off the extensive treatment of inner shell X-ray processes within grains. This makes the X-ray physics more like [Weingartner and Draine \(2001a\)](#).

### 18.12.15 No induced processes

This turns off induced recombination and its cooling, stimulated two-photon emission and absorption ([Bottorff et al., 2006](#)), continuum fluorescent excitation, and stimulated emission of all lines.

### 18.12.16 No ionization reevaluation

This tells the code to not constantly reevaluate the ionization rates. This option can only be set when constant density is assumed.

### 18.12.17 No line transfer

This turns off line transfer for all lines except the  $L\alpha$  transitions of the species treated with the iso-sequences. This is the approximation made in most codes designed to consider classical nebulae and may be appropriate in some cases. This command also turns off line radiation pressure.

### 18.12.18 No Ly $\alpha$ 21cm pumping

Pumping of the H I 21 cm line by  $L\alpha$  is treated as in [Deguchi and Watson \(1985\)](#). This turns off the process. All three keywords must match.

### 18.12.19 No OTS [options]

**no Ly $\alpha$  OTS** This turns off H I  $L\alpha$  OTS rates.

**no HeII OTS** This turns off He II  $L\alpha$  and recombination continua OTS rates.

**no line OTS** This turns off all line OTS rates.

### 18.12.20 No level 2 lines

This turns off the large block of Opacity Project (“level 2”) lines. This should only be done in exploratory “quick look” calculations. The lines should be included for final results. These lines should not be disabled at higher densities since they may carry a large fraction of the cooling as the cloud approaches the black-body limit. They are important in UV photoexcitation of excited levels within split ground terms like O I\* or C II\*. Excited-state column densities will not be predicted if the level 2 lines are disabled.

### 18.12.21 No molecules[H2 CO]

CLOUDY does a molecule formation network that is close to today’s state of the art ([Abel et al., 2005](#); [Röllig et al., 2007](#)). The **no H2 molecules** or **no CO molecules** commands will turn off only the H<sub>2</sub> or CO parts of the network. There must be spaces to either side of the **H2** or **CO** keywords.

### 18.12.22 No on the spot

This turns on all ground-state recombination coefficients and turns off ionization by helium resonance lines. This last variable is then used to deduce the ionization efficiency of lines and continua.

### 18.12.23 No opacity reevaluation

Opacities are normally reevaluated every time the cooling function is reevaluated. When this is set opacities are only evaluated one time per zone.

### 18.12.24 No outward [options]

**no outward lines** This turns off the outward-only (Tarter, 1967) contribution by lines.

**no outward continuum** This turns off the outward-only contribution by continua.

### 18.12.25 No photoionization

This turns off photoionization of the ground states of all elements. It is designed to test the code in the collisional-ionization equilibrium limit.

This command can cause problems. Several iso-sequences are treated as full multi-level atoms. This includes all processes that affect internal excitations. The level-populations solver may have difficulty in finding a solution when photoionization is turned off with this command but the gas is very weakly collisionally ionized. Often internal continuum pumping of the Lyman lines will dominate excitations. When these radiative terms overwhelm the collisional-ionization term the ionization rates out of the ground state may underflow. In this case the solver will find negative level populations and the code will stop announcing a catastrophic failure. One solution is to turn off continuum pumping, with the **no induced processes** command. Only do this if the calculation fails.

### 18.12.26 No radiation pressure

This command turns radiation pressure completely off. Radiation pressure due to trapped lines will be counted in the total pressure when the constant pressure option is used. The default is for a constant-density model. Radiation pressure is not included if constant gas pressure is specified.

### 18.12.27 No recoil ionization

This command turns off Compton recoil ionization. Compton heating and cooling of free electrons is included, but this is the only remaining thermal effect of electron scattering. Bound-electron scattering opacity is still included when this command is issued.

### 18.12.28 No scattering opacity

See page 99 above.

### 18.12.29 No secondary ionizations

This command will turn off the effects of knock-on supra-thermal electrons. Normally these are treated as in Spitzer and Tomasko (1968), Bergeron and Souffrin (1971), Shull (1979), Shull and van Steenberg (1985), Xu and McCray (1991), and Dalgarno et al. (1999). This command will make X-rays 100% effective in generating heat and produce no secondary ionizations or  $L\alpha$  excitations.

### 18.12.30 No Stark broadening

Stark broadening (important for densities larger than  $\sim 10^{10}\text{cm}^{-3}$ ) is treated for hydrogen lines using the formalism described by [Puetter \(1981\)](#). This turns Stark broadening off.

### 18.12.31 No TePredictor

The code tries to predict the temperature of the next zone for constant density calculations. This stops the predictions from being used.

### 18.12.32 No static opacities

This forces all opacities to be reevaluated constantly within each zone. The default is to only evaluate minor opacities one time per zone.

### 18.12.33 No three body recombination

This turns off three-body recombination for the heavy elements that are treated as equivalent two-level systems. Three-body recombination for atoms and ions of the isoelectronic sequences is turned off by turning off collisional ionization (its time reversal) with the **atom [H-like or He-like] collisional ionization off** command.

### 18.12.34 No times

This stops the code from printing execution times. Turning this off will allow exact text comparisons of results between models run at different times or on different machines.

### 18.12.35 No UTA ionization

This turns off ionization by absorption of inner-shell lines. Details of how UTA transitions are handled can be changed with the **set UTA**, command described in [Section 18.14.52](#).

### 18.12.36 No vary

This command turns off the **vary** option set on various optimization commands.

## 18.13 Monitor commands

These tell the code a set of results that are expected. At the end of the calculation the expected and actual results are compared and an error condition is returned if the two disagree by more than an uncertainty. This set of commands is the foundation for automated testing of the code. In Lexington the full test suite is computed every night and a log is kept of all monitored results. An email warning is sent if any monitor fail. This insures the reliability of the code and guarantees that bugs are caught almost as soon as they are introduced.

If the characters “<” or “>” appear on the command line the expected result is taken as an upper or lower limit. The default is to check for equality.

The relative error is the second optional number on the line. If this is not specified then a relative error of 0.05 will be assumed.

### 18.13.1 Monitor set error 0.1

This provides a way to change the default relative error for all monitors of physics-based quantities that occur later in the input stream. The default error is normally the second optional number on each **monitor** command. The default is changed when this command is parsed so this should be the first **monitor** command in the input stream if you want to change the default error for all the monitors.

The majority of the monitors confirm quantities that are related to predictions. There are a special set of **monitor** commands which track the code's performance. The **monitor itrzn** command is an example. A default relative error of 0.2 is assumed for performance monitors. This default can be changed with the **Monitor set performance error xxx** command.

### 18.13.2 Monitor Case B [H-like, He-like] element error

The H and He recombination emission from lower density photoionized clouds that are optically thick in the Lyman continuum may be close to Case B values (AGN3). This command uses stored tables of Case B emission coefficients to compare the code's computed emission with Case B expectations. Assuming that the cloud conditions are set up properly, and that certain physical processes are disabled, this provides a way to check the accuracy of models of some atoms.

One of the iso-sequences, H-like or He-like, must be specified. The default relative error can be changed by specifying a number on the line. The code will compare Case B with computed values for all lines that are included in the emission-line output and a botched monitor will be declared if any of the code's predictions differ from Case B predictions by more than this error. A line will be printed that gives the mean error for the Case B comparisons.

**monitor Case B H-like [element error]** The H-like option will compare the code's predictions with the [Storey and Hummer \(1995\)](#) results. An element name, any between hydrogen and oxygen, must also appear.

**monitor Case B He-like error** This will compare the predictions with Case B predictions for He I emission given by [Porter et al. \(2005\)](#). The Case B values have the label "+Col" in the main emission-line printout. The element name must still appear but currently only helium itself can be tested.

**The range option** The keyword **range** tells the code to only check the monitored values over a restricted wavelength range. The wavelengths of the lines are stored in Angstroms so the range must be given in the same units. This was added as a way to exclude the intensities of unobservable MIR - FIR lines. These lines come from higher levels in the atom and generally have a larger error due to the finite size of the model.

### 18.13.3 Monitor column "species" 18.9

This checks the predicted column density for the molecular species included in quotes.

An alternative form with unquoted keywords **CO**, **H-**, **H2**, **H2+**, **H3+**, **H2g**, **H2\***, **HeH+**, **O2**, **SiO**, **C2**, **C3**, **OH**, **CN**, **CH+**, or **CH** is available at present but it is planned will be removed. To use this form, the labels must be surrounded by spaces. It is important that the log of the column density [ $\text{cm}^{-2}$ ] appear *after* the label because of the 2 in **H2** or **O2**, etc.

The command accepts a **log** option to interpret the error as a log. The column density itself is always interpreted as a log.

For  $H_2$  there is a **levels** option which tells the code to return the column density in a specific  $\nu, J$  level. This only works when the large  $H_2$  molecule is included. The numbers on the line must appear in the following order: first the 2 in **H2**, then  $\nu$ , and then  $J$ , and finally  $\log N(H_2)$ . The “wavelength” of the monitored quantity will be  $100\nu + J$ .

### 18.13.4 Monitor csupra –17.09

The secondary ionization rate is given by the variable *csupra*. This command checks the value of the secondary ionization rate. The number is the log of the secondary ionization rate [ $s^{-1}$ ].

### 18.13.5 Monitor Ctot -12.5

This checks that the local cooling rate [ $\text{erg cm}^{-3} \text{s}^{-1}$ ] of the last zone is equal to the expected value. The argument is the log of the cooling rate.

If the keyword **grid** appears, then a file name should be supplied between double quotes. This file should contain a series of cooling rates to be monitored. There must be one value for each grid point in a grid calculation (the **grid** command is described elsewhere). The file should not contain any other text, not even comments. The numbers should be separated by whitespace and/or newlines.

### 18.13.6 Monitor departure coefficients mean=1, error=0.04

This confirms that the departure coefficients predicted by one of the large model atoms are correct. The computed quantity is the mean departure coefficient for all levels in the model atom and is the first number on the line. The type of error represented by the second number depends on specifics. They are intended for situations close to LTE and so check that the predicted departure coefficient is within an error tolerance of unity.

One of the following keywords must appear.

**monitor departure coefficients, H-like helium, error=0.08** The keyword **H-like** tells the code that the departure coefficients predicted by an atom of the hydrogenic isoelectronic sequence should be checked. The name of one of the elements must also appear on the command line.

The error will be the largest single deviation from unity of any departure coefficient and is set with the second parameter on the command line. If the keyword **excited** appears then the ground state will not be included.

The keyword **ZeroOK** allows departure coefficients of exactly zero to pass the test. This is useful in large grids of calculations where the species being monitored actually has zero abundance at some points in the grid.

**monitor departure coefficients, He-like helium, error=0.08** This works like the H-like option, but for the helium-like isoelectronic sequence.

**monitor departure coefficients, FeII, error=0.08** The keyword **FeII** tells the code to confirm that departure coefficients predicted by the large Fe II atom are unity. The error is the standard deviation of the departure coefficients.

**monitor departure coefficient, hminus, error=0.08** The keyword **hminus** tells the code to confirm that the  $H^-$  departure coefficient is unity. The error is the deviation of the departure coefficient from unity.

**18.13.7 Monitor depth 13.2**

This checks that the cloud's thickness [cm] is equal to the expected value. The argument is always the log of the depth. The thickness is the length between the illuminated and shielded faces of the cloud.

**18.13.8 Monitor eden 9**

The number is the log of the electron density [ $\text{cm}^{-3}$ ] of the last zone.

**18.13.9 Monitor grain potential**

The grain bin number is the first number on the line. Next comes the grain potential. This is linear eV and can be positive or negative. The third number is the optional error.

**18.13.10 Monitor H2 grain rate -16.5**

The number is the total rate [ $\text{cm}^{-3} \text{s}^{-1}$ ] that  $\text{H}_2$  forms on grain surfaces for the last computed zone. The number is a log if it is negative.

**18.13.11 Monitor H2 ortho/para ratio 2.02**

This checks the ratio of the ortho to para  $\text{H}_2$  densities in the last computed zone. This is only meaningful if the large  $\text{H}_2$  molecule has been turned on.

**18.13.12 Monitor Htot -13.2**

This checks that the local heating rate [ $\text{erg cm}^{-3} \text{s}^{-1}$ ] of the last zone is equal to the expected value. The argument is the log of the heating rate.

**18.13.13 Monitor HHeicf -0.013**

This checks the helium—hydrogen ionization correction factor. The number is the linear difference between the atomic fractions of helium and hydrogen.

**18.13.14 Monitor ionization fraction oxygen 3 -3.45, error 0.1, weight = radius**

This checks the mean fractional ionization of an ionization stage of an element. An element name must appear somewhere on the line. The first number is the ionization stage, 1 for the atom, 2 for the first ion, etc. The second number is the expected ionization fraction. It is interpreted as a log if negative and as the linear ionization fraction if it is positive. The average can be with respect to radius or volume. The default is an average weighted with radius. If the keyword **volume** appears then the average will be weighted over volume.

If the keyword **grid** appears then a file name should be supplied between double quotes. This file should contain a series of ionization fractions to be monitored. There must be one value for each grid point in a grid calculation (the **grid** command is described below). The file should not contain any other text, not even comments. The numbers should be separated by whitespace and/or newlines.

An optional error may be supplied on the command line. The same error is assumed for each grid point.

### 18.13.15 Monitor molecular fraction H2 -3.45, error 0.1

This checks the mean molecular fraction. The label for a molecule, currently only H<sub>2</sub>, must appear somewhere on the line. The next number is the expected molecular fraction. If this number is  $\leq 0$  it is interpreted as a log and as the linear ionization fraction if it is positive. The average can be with respect to radius or volume. The default is an average weighted with radius but if the keyword **volume** appears then the average will be weighted over volume.

### 18.13.16 Monitor mpi

This checks that the code is running in MPI mode. The command is used in the `mpi` test suite. It has no additional parameters.

### 18.13.17 Monitor itrzn < 3.5

This performance monitor checks the convergence properties of a calculation. The quantity is the number of iterations required to converge each zone.

### 18.13.18 Monitor line “TOTL” 4861 < 1.01

This checks the relative intensity of a line. The string that gives the line label must appear between two double quotes and it must be four characters long. The line wavelength is the first number after the label. Both label and wavelength must appear exactly as they do in the output produced by the **save line labels** command or in the standard emission-line output.

The second number is the expected intensity relative to the normalization line. It is always the linear intensity relative to whatever normalization line is set for the model.

The sub-keyword is actually “**line\_**” to avoid confusion with the keyword “**linear**” that appears on some commands. The command will not be recognized if the trailing space is missing.

### 18.13.19 Monitor line [luminosity intensity] “Q(H)” 4861 38.91

This compares the predicted and expected luminosities [ $\text{erg s}^{-1}$ ] or intensities [ $\text{erg cm}^{-2} \text{s}^{-1}$ ] of any line. This command functions exactly as the **monitor line** command except that the quantity is the log of the luminosity or intensity of the transition and not the intensity relative to a normalization line.

### 18.13.20 Monitor niter < 4

This checks the number of iterations required in a calculation. This is usually an upper limit.

### 18.13.21 Monitor nothing 0

This will enter a clean monitor into the output. This is used for those simulations in the test suite which have nothing to monitor but are included for general testing.

### 18.13.22 Monitor nzone < 135

This checks how many zones were needed. This is usually an upper limit.

**18.13.23 Monitor pressure error < 0.01**

The number is the ratio of the standard deviation of the pressure to its mean value. It is interpreted as a log if it is negative.

**18.13.24 Monitor PRadMax 0.34**

The monitored quantity is the maximum ratio of radiation to gas pressure.

**18.13.25 Monitor temperature hydrogen 2, 4.02 volume, error 0.01**

This checks the mean temperature of any species. The name of one of the elements or the keywords **grains** and **H2** are recognized. When the name of an element appears then the code will compare the computed mean temperature for that stage of ionization with the monitored value. The first number on the line is the stage of ionization, with 1 the atom, 2 the first ion, etc. The second number is the temperature, interpreted as a log if it is  $\leq 10$ . It will be linear if the keyword **linear** appears. The last number is the relative error.

The code computes means weighted over radius and over volume. If the keyword **volume** appears then the temperature will be compared with the volume-weighted mean. The default is weighting over radius.

If the keyword **grid** appears, then a file name should be supplied between double quotes. This file should contain a series of temperatures to be monitored. There must be one value for each grid point in a grid calculation (the **grid** command is described elsewhere). The file should not contain any other text, not even comments. The numbers should be separated by whitespace and/or newlines.

An optional error may be supplied on the command line. The same error is assumed for each grid point.

**18.13.26 Monitor grain temperature index 2, temperature 234**

If no element name appears but the keyword **grains** does then the code will compare the computed and monitored grain temperatures. The first number on the line is an index giving the grain type. This index is from the order in which the grains were specified in the input stream and is given in the output. The first grain that occurs in the input stream is number 1. The second number is the temperature and is interpreted as a log if  $\leq 10$ . The **linear** keyword forces smaller numbers to be interpreted as linear quantities. The optional error is the third number on the line. The temperature is always averaged over radius.

**18.13.27 Monitor temperature at face 11400K**

This checks the temperature at the illuminated face of the cloud.

**18.13.28 Monitor radius 18.2**

This checks that the outer radius [cm] of the computed model is equal to the expected value. The radius is the distance from the center of the central object to the shielded face of the cloud.

**18.13.29 Monitor thickness 13.2**

This checks the thickness [cm] of the computed structure. The argument is always the log of the thickness. The thickness is the length between the illuminated and shielded faces.

### 18.13.30 Monitor velocity 7.6 km/s

This checks the final velocity of a wind model. The quantity is the expected final velocity in  $\text{km s}^{-1}$ .

### 18.13.31 Table lines “LineList\_PDR.dat”

This provides a way to check that the emission-line labels in any of the standard “LineList\*.dat” files in the data directory are valid. This is actually a form of the **monitor** command since it will announce a botched monitor if it cannot find any of the lines.

## 18.14 Set commands

These commands change internal variables used by CLOUDY. These are mainly intended for testing and are not normally used.

### 18.14.1 Set 12C13C -3.2

This sets the  $^{12}\text{C}/^{13}\text{C}$  abundance ratio. The default is 30. If the number is negative or the keyword **log** appears then the number is interpreted as the log of the  $^{12}\text{C}/^{13}\text{C}$  ratio. It is the linear ratio otherwise. The code currently predicts the  $^{13}\text{CO}$  rotation spectrum and the intensity of  $^{13}\text{C III } \lambda 1910\text{\AA}$  (Clegg et al., 1997) using this ratio. The code does not now solve for  $^{12}\text{C}$  and  $^{13}\text{CO}$  abundances and ionic fractions but rather assumes that the ratio  $^{12}\text{CO}/^{13}\text{CO}$  and the  $^{12}\text{C}^{+2}/^{13}\text{C}^{+2}$  ionization fractions are equal to  $^{12}\text{C}/^{13}\text{C}$ . This ignores chemical fractionation. A full treatment of this physics is high on the list of priorities.

The  $^{12}\text{C}/^{13}\text{C}$  ratio depends on both location in the galaxy and age. It is  $\approx 90$  in the solar system (Anders and Grevesse, 1989) and reflects the galactic value when the sun formed. The value toward the Galactic center is about 20 increasing to  $\approx 77$  at the solar radius (Wilson and Rood, 1994). The default value of 30 is a compromise.

### 18.14.2 Set assert abort

If the code is compiled with C language asserts enabled then internal sanity checks will be performed. They are not done when the code is highly optimized. This command will cause the code to abort when an assert is thrown. This can be caught if the user chooses to write code to do so.

### 18.14.3 Set atomic data [options ...]

This allows certain choices of atomic data sets to be specified in the input script. One of the keywords **ion** or **molecule** must appear. If **ion** appears then the name of an element and an integer giving the ionization stage, with 1 for the atom, 2 for the first ion, etc, must be given. If **molecule** appears then the name of a molecule must appear.

One of the keywords **CS**, **DR**, or **AS** must appear. These indicate whether collision strengths, dielectronic recombination rates, or transition probabilities are to be set.

The remaining options depend on the particular application. The following describe the choices currently implemented.

**set atomic data molecule cs H2 H collisions** - sets collision rates for  $\text{H}_2 - \text{H}^0$  collisions. There are two data sets. The default is **2007** and uses the rates given by Wrathmall et al. (2007). The **1999** option uses the rates given by Le Bourlot et al. (1999).

**set atomic data molecule cs H2 He collisions** - sets collision rates for  $\text{H}_2$  -  $\text{He}^0$  collisions. There are two data sets. The default is **ORNL** and uses the rates given by [Lee et al. \(2006\)](#). The **Le Bourlot** option uses the rates given by [Le Bourlot et al. \(1999\)](#).

### 18.14.4 Set charge transfer -11.5

This command establishes the coefficient in the statistical hydrogen charge transfer rate coefficients used for species more than four times ionized ([Ferland et al., 1997](#)). If the number is negative then it is assumed to be the log of the coefficient, if zero then this estimate is turned off, and if positive the number is the coefficient itself. It is stored as the variable *HCTMin* and has the default of  $1.92(10^{-9} \text{ cm}^3 \text{ s}^{-1})$ . This is used to set a rate coefficient of *HCTMin %q* where *q* is the excess charge of the heavy element.

### 18.14.5 Set chemistry

This changes some aspects of the chemistry network.

**set chemistry Federman [ON , OFF ]** This determines whether the rate coefficients derived by [Zsargó and Federman \(2003\)](#) are used. Their chemical network consists of a small subset of reactions important to the formation of  $\text{CH}$ ,  $\text{CO}$ ,  $\text{HCO}^+$ ,  $\text{CH}_2^+$ , and  $\text{CH}_3^+$  in regions with large amounts of  $\text{CH}^+$ . The default is “**ON**”, that is, to use these rates instead of UMIST in the reaction network. If **OFF** is specified then UMIST rates are used.

**set chemistry non equilibrium** This uses the chemical model of [Federman et al. \(1996\)](#) to examine the effects of nonthermal chemistry on diffuse cloud chemistry. This command uses an effective kinetic temperature for a chemical reaction that is caused by ion / molecule slip when turbulence is present. The effective temperature is given by

$$T_{eff} = \frac{3}{2}kT + \frac{1}{2}\mu\Delta u_{turb}^2 \quad (18.1)$$

where  $k$  is Boltzmann’s constant,  $T$  is the gas kinetic temperature,  $\mu$  is the reduced mass of the two reactants, and  $\Delta u_{turb}$  is the turbulent velocity. [Zsargó and Federman \(2003\)](#) summarize the physical mechanism of non-thermal chemistry as:

“The origin of the nonthermal motion is assumed to be the result of the propagation of Alfvén waves, constantly entering the cloud from the intercloud medium. The dissipation of these waves is concentrated primarily in a diffuse cloud boundary layer, the transition zone between the cloud and the intercloud medium.”

The effect of  $T_{eff}$  is to increase the rates of those reactions which have a strong  $\exp(-c/T)$  temperature barrier. This command primarily effects the formation of  $\text{CH}^+$  (the abundance of which cannot be explained by equilibrium chemistry models) by eliminating the temperature barrier for the  $\text{C}^+ + \text{H}_2 \rightarrow \text{CH}^+ + \text{H}$  formation channel, allowing  $\text{CH}^+$  to form. The formation of  $\text{CH}^+$  has trickle down effects on the predicted abundances of other molecules, such as  $\text{CH}$ ,  $\text{C}_2$ ,  $\text{CN}$ , and  $\text{OH}$  (see equations 7 & 8 of [Zsargó and Federman, 2003](#)). This option was added by Nick Abel. The keyword can be **non equilibrium** or **non-equilibrium**.

**set chemistry non equilibrium neutrals [ON , OFF ]** If the option **neutrals off** is also included then  $T_{eff}$  will equal  $T$  for all neutral-neutral reactions, so non-equilibrium chemistry is not included for these species. The physical assumption is that neutrals are not coupled to the magnetic field and therefore

do not experience the effects of nonthermal chemistry. This was used by [Federman et al. \(1996\)](#) to explain low OH abundances in regions with high  $\text{CH}^+$ , such as  $\xi$  Per. By default, neutral-neutral reactions are included in the non-equilibrium chemistry.

**set chemistry proton elimination [ON , OFF ]** In “proton elimination” reactions, an atom-molecule non-charge transfer reaction leads to the formation of either H or  $\text{H}^+$ . An example is  $\text{C}^+ + \text{OH}$  which leads to either  $\text{CO} + \text{H}^+$  or  $\text{CO}^+ + \text{H}$ . [Huntress \(1977\)](#) states that the energetics of the reaction makes the  $\text{H}^+$  formation channel highly unlikely. This command sets the rates of these reactions leading to  $\text{H}^+$  (which currently only includes the example) to zero. By default, proton elimination is included.

### 18.14.6 Set check energy every zone

The code checks that it has not used more energy than is available in the incident radiation field when the calculation ends. This command will cause that check to occur for every zone. This does slow down the calculation somewhat, so it a debugging tool to use when energy conservation problems occur.

### 18.14.7 Set collisional ionization [Dima, Hybrid]

The collisional ionization rates of [Voronov \(1997\)](#), as implemented by Dima Verner soon after publication of that paper, were used through version C10. These are complete over the range of temperatures considered by CLOUDY. [Dere \(2007\)](#) presents updated rates but these do not cover the temperature range we need. The [Voronov \(1997\)](#) and [Dere \(2007\)](#) data are generally in excellent agreement. We scale the [Voronov \(1997\)](#) rates by the ratio of the [Dere \(2007\)](#) to [Voronov \(1997\)](#) to obtain updated rates over the full temperature range. We refer to this as the hybrid scheme. The scaling factor for each species is the Dere coefficient from the center of the temperature range given in [Dere \(2007\)](#) divided by the [Voronov \(1997\)](#) coefficient at that same temperature. The **set collisional ionization Dima** uses the [Voronov \(1997\)](#) rates while **set collisional ionization Hybrid**, the default, uses this scaling.

### 18.14.8 Set collision strength averaging on

This controls whether the *l*-mixing collision strengths used for hydrogenic levels are evaluated at  $kT$  (the default) or are an average over the thermal Maxwellian. If the keyword **on** appears then averaging will be done—this is very slow due to the large number of levels and evaluations involved. Tests show that the default, the evaluation at a single energy of  $kT$ , is significantly faster and produces very similar predictions.

### 18.14.9 Set continuum options

**set continuum resolution 0.1** This changes the resolution of the coarse continuum energy mesh by a constant scale factor. The resolution of the continuum mesh as a function of energy is defined by the data file `continuum_mesh.ini`, which is located in the data directory. Permanent changes to the continuum resolution should be made there. This command allows the continuum mesh to be changed by a temporary scale factor. The number on the command line multiplies the resolution used by the code. Factors less than unity make the cells smaller, for higher resolving power, while factors greater than unity make the resolution coarser. For instance, an entry of 0.1 would make the resolution ten times finer or the resolving power ten times greater. If the number is less than zero it is interpreted as the log of the resolution scale factor.

This was originally added so that the entire continuum resolution could be improved by large factors when running some of the fundamental tests of hydrogenic and helium-like emission. The code’s

execution speed is affected by the number of coarse continuum cells due to the frequent reevaluations of the opacity and photo-interaction rates. For factors near unity the execution time will scale roughly inversely linearly.

The code can be sped up by making the factor larger than unity. But there is a limit, roughly 5, where the continuum cells become so coarse that the code will no longer pass its internal sanity checks. A factor near 2 will cut the execution time by about 40%. This will affect the predictions and should only be done in exploratory calculations.

**set continuum shielding** This changes the treatment of shielding of the incident continuum by line optical depths. There are several options. **Pesc** uses the inward-looking escape probability. **Federman** is the default and uses the function given in the appendix of [Federman et al. \(1979\)](#). **Ferland** uses the function given by [Ferland \(1992\)](#). **None** turns off self-shielding.

**set FeII continuum** This changes the lower and upper bounds, and the resolution, of the Fe II pseudo-continuum predicted with the **save FeII continuum** command. Three numbers, the short and long wavelength limits (both in Å) and the number of cells to divide this into, must be specified. All three numbers must be specified. The default are lower and upper wavelength limits of 1000 Å and 7000 Å broken 1000 into bins.

**set fine continuum** This changes the logic used to determine the resolution of the fine continuum mesh. The command has two arguments. The name of an element must appear on the line—the atomic weight of this element will be used to determine the narrowest lines that must be resolved. The number of resolution bins over a HWHM must also appear on the line.

A **range** option can be used with the **set fine continuum** command. The first number is interpreted as the lower limit (in Rydbergs) of the fine continuum. An optional second number modifies the default upper limit. For both parameters, negative numbers are interpreted as logs. This command is experimental and can appreciably change results in conditions where line overlap is important.

### 18.14.10 Set convergence ...

The error in the heating-cooling balance is set with the **set temperature convergence** command. The error in the electron density is set with the **set eden convergence** command. The error in the local pressure is set with the **set pressure convergence** command. In cases where the code is having trouble converging the **set presioniz** command will limit the number of ionization evaluations before declaring a failure.

### 18.14.11 Set coverage [fast]

This limits the number of zones and iterations that will be done so that the code runs more quickly. It allows quick runs of the test suite with tools such as *Purify* and *valgrind*. If the **fast** option appears then only one and one iteration will be performed. Otherwise up to ten zones and two iterations will be done. This limit is imposed on top of whatever other limits may exist in the input stream.

### 18.14.12 Set csupra = -12.34

This sets the  $H^0$  secondary ionization rate due to supra-thermal electrons to the number on the line. The number is the log of the rate [ $s^{-1}$ ]. The excitation rate of  $L\alpha$  is assumed to be the same. This option is used

to test the code in secondary-ionization dominated cases. Normally the secondary ionization rate is determined self-consistently from the high-energy radiation field or the cosmic ray density.

### 18.14.13 Set D/H -3.2

This sets the D/H abundance ratio. The default is the primordial abundance of  $1.65 \times 10^{-5}$  as measured by [Pettini and Bowen \(2001\)](#). The number is interpreted as the log of the D/H ratio if it is negative or the keyword **log** appears, and as the linear ratio otherwise. This mainly affects HD cooling. Currently the molecular abundance ratio HD/H<sub>2</sub> is assumed to be equal to the D/H ratio.

### 18.14.14 Set didz 0.05

The thickness of the first zone is chosen so that the largest continuous optical depth through it is one percent of the entered value. Thereafter the zone thickness is continuously adjusted by checking that the optical depth at the maximum continuum-gas interaction energy is set to this value. The default is 0.15. If the value is less than or equal to zero, then it is interpreted as the log of the quantity, and linear if greater than zero.

### 18.14.15 Set dr 11.2

This forces the zone thickness to a prescribed value. A space is required after the “**dr**”. The argument is the log of the thickness in cm. The number is interpreted as the linear thickness if the keyword **linear** appears. If the keyword **relative** is present the number will be interpreted as a relative fraction of the current radius. In that case the value needs to be between 0 and 1. The default is that this command is not in effect and the adaptive stepsize algorithm will set the zone thickness in accordance with the local physical conditions.

Use this command with great caution! Forcing the code to take steps that are too large can lead to inaccurate results, or even destabilize the code.

### 18.14.16 Set drmax 11.2

This sets the largest allowed zone thickness [cm]. The zone thickness will not become larger than this. The number is the log of the thickness if it is less than 38 or if the keyword **log** appears. It is linear if the keyword **linear** appears. If the keyword **relative** is present the number will be interpreted as a relative fraction of the current radius. In that case the value needs to be between 0 and 1. The default for the maximum zone thickness is  $10^{30}$  cm.

### 18.14.17 Set drmin 11.2

This sets the minimum zone thickness [cm]. The zone thickness will not become smaller than this, except possibly in the last zone to avoid overshooting the outer radius. The number is the log of the thickness if it is less than 38 or if the keyword **log** appears. It is linear if the keyword **linear** appears. If the keyword **relative** is present the number will be interpreted as a relative fraction of the current radius. In that case the value needs to be between 0 and 1.

The keyword **depth** works similarly to the keyword **relative** but sets the minimum zone thickness relative to the depth into the cloud. There is a default value of  $10^{-5}$ . This minimum is not active if a **set dr** command is used.

The default for the minimum zone thickness is the greater of approximately  $1.2 \times 10^{-36}$  cm and the default relative to depth.

Use this command with great caution! Forcing the code to take steps that are too large can lead to inaccurate results, or even destabilize the code.

### 18.14.18 Set dynamics commands

These commands change aspects of dynamical or time-dependent calculations. They are described in [13 DYNAMICAL & TIME-DEPENDENT CALCULATIONS](#)

### 18.14.19 Set eden [options ....]

These commands provide several ways to set the electron density or change its convergence criterion.

**set eden 2.3** If no other keywords are recognized then this command sets the electron density. The number is the log of the density [ $\text{cm}^{-3}$ ].

**set eden convergence 0.01** This sets the convergence criterion for the electron density. The number is the largest relative error in the electron density. It is interpreted as the log of the relative error if it is negative. The default value is 0.01. The old form of the command, **set eden error**, is also recognized.

**set eden fraction 1e-3** This sets the electron fraction,  $n_e/n(\text{H})$ , where  $n(\text{H})$  is the density of hydrogen in all forms. The number is the electron fraction and is interpreted as a log if it is  $\leq 0$ .

Note: The **eden** command, described on page [224](#), add an extra source of electrons. These **set eden** commands set the electron density itself. These commands violate charge conservation.

### 18.14.20 Set flxfnt -20

The highest photon energy that must be considered is lower for relatively soft continua such as a star than for X-ray sources such as AGNs. The criterion used to choose the highest energy to be considered  $\nu_{\text{high}}$  is that  $\nu f_{\nu}(\nu_{\text{high}})/\nu f_{\nu}(\nu_{\text{peak}}) < \text{flxfnt}$ , where  $\nu_{\text{peak}}$  is the frequency where the continuum reaches its maximum  $\nu f_{\nu}$ . **FluxFaint** is normally  $10^{-10}$ . This command changes the value of **FluxFaint**. The argument is the log of the value.

### 18.14.21 Set gbar off

By default the g-bar approximation is used for transitions in the Chianti and Stout databases which have no collision strengths. G-bar values are taken from [Mewe \(1972\)](#) for both allowed and forbidden transitions. For simplicity, transitions with gf values greater than or equal to  $10^{-8}$  are considered to be allowed.

This command says not to use g-bar for any database transition. If there is no collision data and gbar is turned off, then 0.01 is used for the collision strength.

### 18.14.22 Set grain heating factor 2.

This command allows you to enter a fudge factor to alter the amount of photoelectric heating from the grains (also when the **set PAH Bakes** command is in effect). The number you enter is a multiplicative factor and is always interpreted as a linear number. This command violates energy conservation and is intended for testing only.

### 18.14.23 Set H2 ...

This command changes some aspects of the H<sub>2</sub> molecule. Other aspects of this molecule are changed with the **atom H2** command.

**set H2 fraction** This sets the ratio  $n(\text{H}_2)/n(\text{H})$ . The number is interpreted as the log of the ratio if it is less than or equal to zero and as the linear ratio otherwise. An upper limit of 0.5 will be silently imposed. This command turns off the normal H<sub>2</sub> molecular network and forces the H<sub>2</sub> density to the hydrogen density multiplied by this fraction. This is totally unphysical and is only intended to provide an easy way to test the H<sub>2</sub> molecule.

**set H2 formation scale** This scales the H<sub>2</sub> formation rate (via three-body recombination). The number is interpreted as the log of the scaling factor if it is less than or equal to zero and as the linear factor otherwise. In the fully molecular or fully ionized limits, this command should be used rather than the **set H2 fraction** command because it allows the same functionality without breaking numerous consistency checks.

**set H2 Jura [TH85; CT02; SN99 ]** This changes the “Jura rate”, the rate H<sub>2</sub> forms on grains (Jura, 1975). The default is the Cazaux and Tielens (2002) rate, which depends on grain temperature and abundance, and this can also be specified with the **CT02** option. The option **TH85** will use rates from Tielens and Hollenbach (1985a), and **SN99** will use rates for Sternberg and Neufeld (1999).

**set H2 Jura scale** The number is a linear scale factor that multiplies the formation rate obtained by one of the above methods. If the scale factor is negative or the keyword **log** appears then the number is interpreted as the log of the scale factor. Habart et al. (2004) suggest that the rate can vary across the galaxy by large factors.

**set H2 Jura rate** The number is the log of the H<sub>2</sub> grain formation rate  $k$  [cm<sup>3</sup> s<sup>-1</sup>]. This is used to give a simple grain formation rate  $R = kn(\text{H}_{\text{tot}})n(\text{H}^0)$  [cm<sup>-3</sup> s<sup>-1</sup>]. If no number appears on the line then the Jura (1975) rate of  $3 \times 10^{-17}$  will be assumed.

**set H2 Solomon [BD96; TH85; ELWERT ]** This changes how the Solomon process is treated when the small H<sub>2</sub> molecule is used. The fits to the dissociation rate derived by Elwert et al. (2005) are the default and will be used if the keyword **ELWERT** appears. The keyword **BD96** will use Bertoldi and Draine (1996) and the keyword **TH85** will use the Tielens and Hollenbach (1985a) rate. These rates differ by  $\geq 1$  dex for some H<sub>2</sub> column densities. When the large H<sub>2</sub> molecule is used, as set with the **atom H2** command, the Solomon process is treated in a self-consistent manner. Abel et al. (2004) show that H<sub>2</sub> column densities are quite sensitive to the correct treatment of this physics for translucent clouds.

**set H2 continuum dissociation [Stancil; AD69 ]** This command changes how direct photodissociation of H<sub>2</sub> is treated. By default, CLOUDY computes the photodissociation rate by integrating the cross-section for photodissociation over the energy range for dissociation. The cross sections used for this process come from Stancil et al. (in preparation) and are specified by the keyword **Stancil**. The other option is to use a constant H<sub>2</sub> cross section for this process, which comes from the work of Allison and Dalgarno (1969) and is used when **AD69** appears on the command line. This process, while not the dominant destruction process for H<sub>2</sub> in a PDR, may be important in some environments.

**set H2 grain formation pumping** This changes the distribution function for populations of  $v$ ,  $J$  levels of H<sub>2</sub>. There are three possible distributions: Takahashi (2001, **Taka**, this is the default); Draine and Bertoldi (1996, **DB96**); and thermal (**thermal**).

**set H2 Tad 420** This changes the binding energy,  $T_{ad}$ , in the formalism described by [Le Bourlot \(2000\)](#) to account for deexcitation of  $H_2$  while on a grain surface. The number is the binding energy expressed as a temperature. The default value of 800 K maximizes the rates of  $H_2$  collisional deexcitation and ortho-para conversion. If the number is  $\leq 10$  it is interpreted as a log of the temperature unless the keyword **linear** appears.

### 18.14.24 Set HCORR

The density used in electronic collisions is actually  $n_e + 1.7 \times 10^4 n(H^0) f$ . The second term is an approximate correction for collisions by neutral hydrogen. This is only a guess based on [Drawin \(1969\)](#), (see also [Weisheit, 1974](#), [Steenbock and Holweger, 1984](#), [Lambert, 1993](#), and [Kiselman, 2001](#)). The number on this command adjusts the scale factor  $f$ . You can turn off the process by setting the number to zero.

### 18.14.25 Set HO charge transfer [chemistry; ionization]

This command is no longer supported.

### 18.14.26 Set ind2 [on, off]

This provides a way to turn off the affects of induced two-photon emission or absorption. One of the keywords **on** or **off** must appear to turn induced two-photon processes on or off. It is on by default.

### 18.14.27 Set ionization tolerance 0.01

Sets the allowed error tolerance on ionization solver solutions.

### 18.14.28 Set isotopes [ALL]

This command enables singly-substituted isotopologues of all molecules. Densities are simply scaling by fractionations of constituent elements.

At present, **all** is the only option. Deuterium is not presently enabled by this command. Isotopes of all other elements are enabled.

### 18.14.29 Set kshell energy 1e6

This changes the energy of the highest continuum point considered for photoelectric opacity. The default is 1 MeV, sufficiently high that Compton recoil and pair production are the dominant opacity sources and K-shell opacity may safely be ignored. Setting this limit to smaller values will save some compute time since the evaluation of the photoionization rate integrals will not extend to as high an energy. The argument is the energy in Rydbergs and it must be greater than 194 Ryd. If zero is entered then the high-energy limit of the continuum will be used.

### 18.14.30 Set Leiden hack

This replaces certain physical processes with the simple prescriptions that were specified for the 2004 Leiden PDR workshop ([Röllig et al., 2007](#)). These are only intended for testing and would not be used in a

real calculation. If any **set Leiden hack** commands are entered the code will complain that a physical process has been disabled.

This enables all hacks. Individual hacks can be turned on with additional keywords. They are:

**set Leiden hack H2\* off** The chemistry network used in the workshop did not include  $\text{H}_2^*$  (see [Tielens and Hollenbach, 1985a](#) for a definition). This turns off reactions between that species and the CO network (although it is still present in the H- $\text{H}_2$  network).

**set Leiden hack CR off** This turns off cosmic-ray excitation for the large  $\text{H}_2$  molecule. This is normally treated as in [Dalgarno et al. \(1999\)](#).

**set Leiden hack UMIST** This forces the code to use parts of the UMIST database that (we feel) we do better with other methods.

### 18.14.31 Set line precision [4, 5, or 6]

This changes how the emission lines are printed in the final pages of output. Emission-line wavelengths are normally printed with four digits, as in “4861”. This command can increase the number of digits to 5 or 6. The lines are printed in four columns when four digits are chosen. With five or six digits the lines will no longer fit across the page so the number of columns is automatically reduced to three.

### 18.14.32 set monitor scientific notation

**monitors** are commands that tell the code what value for a predicted quantity to expect. These are part of the test suite and allow automatic testing of the code’s results. This command causes the printed monitored values to be printed in scientific notation rather than a float format. The **monitor** command is described on page [230](#) above.

### 18.14.33 Set nchrg 3

The grain physics uses an  $n$ -charge state model where, for each bin, the charge distribution is resolved in exactly  $n$  charge states, independent of grain size. This is discussed in [van Hoof et al. \(2004\)](#). The default value of  $n$  is 2 but can be reset with this command to any value between 2 and 5. Higher values of  $n$  will give more accurate results at the expense of greater compute time.

### 18.14.34 Set negopc

Negative opacities may occur during a calculation if a level happens to maser ([Ferland, 1993](#)). The code will generate a comment at the end if this happens. This command tells the code to save the optical depth array when negative opacities occur. The output will go to the file `negopc.txt`.

### 18.14.35 Set nend 500

This sets the default limit to the number of zones that will be computed. The preset default limiting number of zones is 1400 but more zones may be needed in large column density clouds or ones exposed to very intense radiation fields.

The limit to the number of zones that will be computed can be set with either this command or with the **stop zone** command. The only difference is in the level of warning that will be generated if the code stops

after reaching the limiting number of zones. If the code stops because it reached the number of zones set by the **stop zone** command then it thinks that this was the intended stopping criterion and no comment is generated. However the code generates a *warning* if it stops because it reaches the default limit to the number of zones since this probably *was not* intended. By using this command the limit can be increased while still retaining the checking and warnings that are generated if the code stops for an unintended reason.

The code allocates memory to store a great deal of information for each zone. Increasing the number of zones will also increase the memory needed to run the code.

### 18.14.36 Set nFnu [options]

When the **print continuum** command is issued, CLOUDY will print the continuum flux at certain wavelengths as a series of entries in the standard emission line array. See Section 15.14 for a full description. The **set nFnu** command changes which parts of the radiation field are included in the entry with the *nFnu* label. There are four possible radiation fields, the transmitted and reflected incident radiation field, and the transmitted and reflected diffuse emission produced by the nebula. Any or all of these may be entered on the command line, but at least one must occur. Any component left off the command will not be included.

The four keywords, and the component that is included, are the following:

**incident reflected** or **incident\_reflected** includes the incident reflected continuum.

**incident transmitted** or **incident\_transmitted** includes the incident transmitted continuum.

**diffuse inward** or **diffuse\_inward** includes the diffuse inward continuum.

**diffuse outward** or **diffuse\_outward** includes the diffuse outward continuum.

All desired components must be specified on a single **set nFnu** command. The following shows how to only include the outward incident and outward diffuse emission in the *nFnu* entry in the printout:

```
set nFnu diffuse outward, incident transmitted
```

If this command is entered then **print continuum** does not also need to be given—the continuum points will automatically be included in the printout.

This command does *not* change the quantities printed with the *nInu* label—these are always the sum of the reflected plus transmitted incident continuum.

### 18.14.37 Set nFnu add 300 micron

You can also add custom wavelengths or frequencies at which the *nFnu* and *nInu* entries in the emission-line printout are evaluated. You can do that by adding one **set nFnu add** command for each point. You can enter as many as you like. Each line must contain a number and a unit to identify the wavelength or frequency. Adding the unit is mandatory. The following keywords are supported: **eV**, **keV**, **MeV**, **Hz**, **kHz**, **MHz**, **GHz**, **Angstrom**, **nm**, **micron**, **mm**, **cm** or **centimeter**, **wavenumbers**, **erg**, **ryd**, **K** or **Kelvin**. If this command is entered then **print continuum** does not also need to be given—the continuum points will automatically be included in the printout. Some examples are:

```
set nFnu add 22 GHz
set nFnu add 350 micron
set nFnu add 4200 angstrom
```

### 18.14.38 Set nmaps 50

This controls the number of steps in the heating-cooling map that results from either the **map** or **save map** commands. Normally about 20 steps are taken between the lowest and highest temperatures.

### 18.14.39 Set numerical derivatives

This tells the code to use numerical rather than analytic derivatives of the heating and cooling functions. The default is to use the analytic derivatives.

### 18.14.40 Set PAH option

**set PAH constant or “H”** This changes the function that describes how PAH abundances depend on physical conditions. The default, which can also be specified with the string "H", is for the PAH abundance to scale as  $n(\text{H}^0) / n(\text{H}_{\text{tot}})$ . You can also specify the PAH abundance to scale as the total abundance of neutral atomic and molecular hydrogen with the string "H, H2". The abundance will be constant if the keyword **constant** appears.

**set PAH Bakes** will replace our self-consistent treatment of photoelectric heating by all grains with the PAH photoelectric heating equation given by [Bakes and Tielens \(1994\)](#). This command no longer guarantees energy conservation and is only intended for testing.

### 18.14.41 Set phfit [1995, 1996]

The key **1995** tells the code to use photoionization cross sections from [Verner and Yakovlev \(1995\)](#). The key **1996** is the default and uses [Verner et al. \(1996\)](#), which is partially based on Opacity Project cross sections.

### 18.14.42 Set presioniz 50

This sets a limit to the number of times the bottom ionization solver will be called from the top pressure solver within a zone. This is a debugging aid as well as a means to limit the time it takes the code to declare convergence failure. The limit has a default value of 3000. This is approximately 500 more calls than is ever needed in any test suite simulations. The vast majority ( $\sim 99\%$ ) of zones are converged in less than 100 calls. Users should exercise caution in increasing the limit. Encountering the default limit is a strong indication that something is wrong with the simulation. It is unlikely the simulation will converge if more calls are allowed.

### 18.14.43 Set pressure convergence 0.01

This sets the convergence criterion for the total pressure. The number is the largest relative error in the pressure. The number is interpreted as the linear error if it is positive and the log of this error if negative. The default value is 0.01.

### 18.14.44 Set save commands

Save output is the primary output mechanism for the code. This command sets various details about how this output is generated.

**set save hash “newstring”** When more than one iteration is saved into a file each ends with a series of hash marks that makes it easy to locate with an editor. This sets the hash string to something else. A new string must appear within the pair of double quotes.

The special string “**return**” is replaced with a single carriage return which translates into the pair of carriage returns that *gnuplot* uses to separate plots. The special string “**time**” will give the elapsed

time since the start of time-dependent calculations. In both cases the keyword must appear within the pair of double quotes.

The hash can be completely turned off with the **no hash** option on the **save** command.

**set save prefix “test”** This adds a prefix to all filenames and so provides an easy way to change all file names at one time. The prefix is any string that appears between the pair of double quotes on the command line.

**set save line width / resolution, suppress** The observed contrast between emission lines and the continuum depends on the intrinsic line width and, for an unresolved line, the resolution of the spectrometer. Lines are included in the radiation field produced by the **save continuum** commands. The default behavior is to do this in such a way that the energy is conserved in the resulting output.<sup>2</sup> This command allows you to adjust the contrast between the lines and continuum by, in effect, changing the velocity resolution of the spectrometer which views the unresolved lines.

Lines and continua are stored separately throughout the code. They are combined only when the output from the **save continuum** command is produced using the expression

$$vF_v(\text{total}) = vF_v(\text{continuum}) + RI(\text{line}) \quad (18.2)$$

where  $R \equiv \lambda / \Delta\lambda$  is the resolution of the spectrum. The default behavior is to match  $R$  to the resolution of the coarse continuum mesh of CLOUDY at the frequency of the line. This assures energy conservation. If you want to boost weak lines in a plot, you can artificially change the resolution of the spectrum by using this command.

When you use the **set save line width** command, you should supply a velocity width  $\Delta v$  in  $\text{km s}^{-1}$ . This will set  $R = c / \Delta v$ , where  $c$  is the speed of light. If you use the alternative **set save resolution** command, you can specify  $R$  directly. Supplying a smaller value of  $\Delta v$  or a higher value of  $R$  will increase the line-to-continuum ratio and thereby make lines appear stronger.

```
// set velocity resolution to 100 km/s => R = 3000 (approximately)
set save line width 100
// alternatively set spectral resolution directly
set save resolution 3000
```

Note that this command will *only* adjust the height of the line, not the width. The latter will always be the width of one cell in the coarse continuum mesh (even if the line is broader than that cell). This implies that the line flux in the continuum array is artificially changed by this command. Changing the spectral resolution can be useful to emphasize weak lines in a plot, but should never be used when energy conservation is important, e.g. when you want to fold the saved continuum with a photometric passband.

If the keyword **absorption** occurs then the effects of absorption lines on the transmission of the incident continuum will be modified by the factor given in equation 18.3. The transmitted radiation field is changed as

$$vf_v = vf_v^0 \max \left[ 1 - (1 - trans) R \frac{\Delta v}{v}, 0 \right] \quad (18.3)$$

<sup>2</sup>In C90.00 the standard was to use a line width equal to the speed of light. In C90.04 the standard was changed to using a line width of  $1000 \text{ km s}^{-1}$ . Finally, in version C10 the standard was changed again to using energy conservation. Versions prior to C90.00 did not include emission lines in the saved spectral energy distribution.

where *trans* is the correct transmission factor as propagated from the fine to coarse mesh, and  $v/\Delta v$  is the resolution of the coarse continuum mesh. The keyword **absorption** makes the effects of absorption appear larger than they actually are, but gives an impression their appearance would have if the spectrum were viewed at a higher resolution. This approach uses the opacities stored in the much higher resolution fine continuum. As is the case for emission lines, using this option will violate energy conservation.

If you include the keyword **suppress** on the command line, then emission lines will not be included in the saved spectral energy distribution. If you combine the keywords **suppress** and **absorption**, then the effects of absorption lines will also be suppressed and only a pure continuum will be saved.

The only effect of this command is to change the line-to-continuum contrast in output from all **save** commands except for that produced by the **save transmitted continuum** command.

### 18.14.45 Set recombination keywords

The keyword **dielectronic** must appear. This changes the treatment of various details of the ionic recombination physics.

**set dielectronic recombination mean [options ]** At present rate coefficients for dielectronic recombination through low-lying autoionizing states have not been computed for lower stages of ionization of most elements on the third row and higher. The **mean** option modifies the treatment of the estimates of the missing dielectronic recombination coefficients.

The default is to use means of all existing DR rates for each ion stage to replace missing data for that stage. For instance,  $\text{Fe}^+ \Rightarrow \text{Fe}^0$  does not have reliable DR rates. Its rate will be the mean DR rate for all first ions of all elements with published rates.

**set dielectronic recombination mean off** will turn off guesses for DR rates. These guesses are normally used for those ions that have no rate coefficients because no better can be done at present.

**set dielectronic recombination mean scale** will multiply the DR guesses by scale factors. One or more scale factors may appear on the line, and each will multiply the mean rate for successive ions. If there are fewer scale factors than ions then the last scale factor entered will be used for all higher ions. The scale factors must be greater than or equal to zero.

**set dielectronic recombination mean noise [dispersion ]** will introduce Gaussian noise with the indicated dispersion. This provides a way to quantify the uncertainty caused by the need to use mean rates. This adds a component of Gaussian random noise to the means of the dielectronic recombination rate coefficients. The number on the line is the dispersion. The resulting random number will multiply the rate coefficient. The seed for the random number generator is set when this command is parsed. As a result the same DR rates will be used throughout any single calculation but the noise multiplying the rate will change from run to run.

### 18.14.46 Set species gbar 0.01

This sets a default collision strength for database transitions that have no collision or radiative data. You can turn this feature off by setting the value to zero.

### 18.14.47 Set temperature [floor, convergence]

These commands change some details of the thermal solution.

**set temperature floor** This sets a lowest kinetic temperature to allow in a calculation. When the temperature falls below this floor the code goes over to a constant temperature solution at the floor temperature. This provides a way to mimic having a minimum temperature that is set by some external and unspecified source of heat. The temperature will be interpreted as a log if it is less than or equal to 10 or the keyword **log** is present, and as linear if the keyword **linear** is present.

**set temperature convergence** The gas kinetic temperature is set by the balance between the heating and cooling. This command sets the relative error allowed in the heating-cooling match. The number is the largest fractional error allowed. It is interpreted as the error itself if it is positive and the log of the error if it is less than or equal to zero. The default is 0.005. This will be the error allowed in each zone. The total error or energy conservation mismatch integrated over a cloud will be much smaller, usually of order ten times smaller than the tolerance specified.

### 18.14.48 Set test

This sets the logical variable *lgTestCodeEnabled* to true. It provides the facility to conditionally run test code somewhere in the main body of CLOUDY.

### 18.14.49 Set trimming -9 [upper lower, off]

The code saves execution time by not computing the population of stages of ionization with trivial abundances. The thresholds for excluding an ionization stage are chosen with photoionization equilibrium in mind. These may not be appropriate for some other conditions or if your definition of trivial is different from mine.

This command changes the limit for the smallest fractional abundance,  $n(A^{+x})/n(A)$ , to consider. The smallest relative abundance to be considered for a stage of ionization higher than the ionization peak is changed with the **upper** keyword. The command **set trimming upper off** will turn off trimming of the highest stage of ionization. The smallest relative abundance of ions below the peak is changed with the **lower** keyword. The default relative ionization fractions are  $10^{-6}$  and  $10^{-10}$  respectively. If no keyword appears then both are changed to the number entered. The argument is the log of the lowest or highest ionization fraction to consider.

Generally, line excitation energies for atoms with stages of ionization higher than the peak ionization will strongly exceed the ambient temperature so these ions will have little influence on the calculated temperature or spectrum. This is not true for lines formed by ions below the peak distribution. The keyword **off** sets the smallest abundance to just above the machine's floating precision limit.

### 18.14.50 Set tsqden 8

The code performs an analysis of the predicted emission-line spectrum at the end of the calculation. This analysis will find the structural  $t^2$  as well as a  $t^2$  deduced from the [O III] and H I spectrum (Kingdon and Ferland, 1995 discuss this at length). Such an analysis only makes sense for densities below the critical density of the [O III] atom, which is  $\sim 10^5 \text{ cm}^{-3}$ . The results of this analysis will not be printed if the density is higher than the value of *tsqden*, currently  $10^7 \text{ cm}^{-3}$ . The number on the line is the log of the highest hydrogen density for which this analysis will be performed.

### 18.14.51 set update couplings every ion

This updates the couplings between the ionization networks fully after every ion balance solution, rather than only when all ions and the chemical network have been calculated. This may be necessary to allow the solution to converge in cases where the coupling sources dominate collisional and radiative processes, but will increase run times in general.

### 18.14.52 Set UTA

This changes which UTA line data are used. Three sets of UTA data are available for some stages of ionization of iron. These include Behar et al. (2001), Gu et al. (2006) (these papers consider  $\text{Fe}^0$  through  $\text{Fe}^{+15}$ ) and Kisielius et al. (2003, this includes  $\text{Fe}^{+13}$  though  $\text{Fe}^{+15}$  but has many more lines), as described in Ferland et al. (2012 in preparation). Additional inner shell data are given by Behar and Netzer (2002). The Gu et al. (2006) and Kisielius et al. (2003) results are used by default.

**set UTA Gu06** [on off -] this will enable or disable the Gu et al. (2006) rates. They are used by default.

**set UTA Kisielius** [on off -] this will enable or disable the Kisielius et al. (2003) rates. They are disabled by default. The Behar or Gu data are replaced with the Kisielius et al. (2003) results for the three stages of ionization considered in that paper when this is enabled.

The **no UTA** command (Section 18.12.35) turns off UTA ionization.

### 18.14.53 Set WeakHeatCool 0.02

This command sets the threshold for the weakest cooling or heating source included in output from the **save heating** or **save cooling** commands. The default is 0.05. The number entered is interpreted as a log if it is negative.

## 18.15 Table lines “name.dat”

When the code is used as a subprogram for other, larger, codes, it is possible to read in a series of lines whose intensity will later be extracted by first calling *cdGetLineList*, then by calling *cdLine*. The procedure is described in Part 2 of this document. A set of lines that occur within any of several data files is then read. This method is used in most of the large grid programs I use.

This command provides a quick way to confirm that the list of lines in the line data files have valid names. The command takes the name of a file as its argument and checks that all lines can be found. See the discussion of *cdGetLineList* in Part 2 for further information.

## 18.16 Test

This command does a “smoke test” and provides an easy way to do a quick sanity check on the code. It issues a series of commands to run a two-zone constant-temperature model. The **table agn** command is used with the density and temperature constant at  $10^4$  K. The ionization parameter is  $U = 10^{-2}$  and the calculation stops after two zones and one iteration. Many **monitor** commands are used to verify predictions. The commands that set up the model will be printed if the keyword **print** occurs on the line.

### 18.16.1 Test FeII

When the **FeII** keyword appears the large Fe II atom will be computed and checked as well.

### 18.16.2 Test large

When the **large** keyword appears the model hydrogen atom will be set to a large number of levels.

### 18.16.3 Test H2

This tests the large H<sub>2</sub> molecule.

### 18.16.4 Test molecular

This does a simulation that is cold and nearly fully molecular. The can be combined with the **H2** keyword to test the H<sub>2</sub> molecule in the fully molecular limit.

## 18.17 Performance speedups

It is possible to speed up the calculation at the loss of some physical fidelity or stability. This section outlines the commands that make this possible. Each command is described in greater detail in sections earlier in this document.

Many of these options are included in the `fast.ini` initialization file. Using this `ini` file will decrease the execution time by roughly an order of magnitude. This is meant as a way to explore vast ranges of parameters or as a debugging aid.

*N.B.!!* The fidelity of the simulation is compromised! These turn off significant physical processes.

### 18.17.1 Turn off minor elements

The ionization distribution and the effects of an element on the gas cooling and opacity are all determined self-consistently. This includes the first 30 elements and many of these have trivial abundances. The calculation can be sped up with no loss of physical fidelity elements with very small abundances are turned off. This is done with the **element off** command. The `ini` files `c84.ini`, `fast.ini`, and `ism.ini`, among others, include a set of **element off** commands to do this. The **element limit** command provides a way to turn off all elements which have an abundance smaller than a specified limit.

Turning off an element will affect results if the opacity, heating, or cooling due to the element is significant. Minor elements can have major effects in very dense, optically thick, gas, where all coolants are close to the black body limit.

### 18.17.2 Turn off the chemistry

The chemical network requires a fair amount of time due to the size of the matrix that must be solved. The chemical state is determined even in ionized regions to ensure continuity in the transition between the H<sup>+</sup> - H<sup>0</sup> - H<sub>2</sub> regions. The chemistry can be safely ignored if only ionized regions are present. This is done with the **no molecules** command.

### 18.17.3 Turn off grain physics

The treatment of grain physics is today's state of the art (van Hoof et al., 2004) and can be CPU-intensive. Grains have several major effects. Elements locked up in solids are missing from the gas phase and so their cooling is also missing. Grains provide the dominant opacity across much of the optical, near IR, and UV spectrum. This absorbs the incident continuum, affects the radiative acceleration of the gas, and the transfer of optically thick lines. Radiative and collisional interactions between grains and the gas affect the gas temperature. In PDR and molecular regions, grains have an important effect on the charge balance of the gas. This affects both the ionization and chemistry (Abel et al., 2005). Grain surface reactions and molecular freeze-out change the chemistry and charge balance of the gas.

The first effect can be included at no expense by setting the gas-phase abundance of an element to a depleted value. Gas-phase abundances can be decreased by typical ISM depletion factors using the **metals deplete** command. This does not turn on grains and applying a depletion factor has no impact on the execution time.

**Turn off quantum heating.** Quantum heating is the process where a grain's temperature spikes after absorbing a single photon. This temperature spiking has an effect on the Wien tail of the grain's emitted spectral energy distribution but no other effect. Quantum heating can be disabled with the **no qheat** option on the **grain** command if the thermal continuum is not something you need to predict. Quantum heating only affects the emitted spectrum so turning it off will not affect results if the emitted IR continuum does not affect the gas. The IR continuum will affect the gas if it is absorbed by the gas or dust, which can occur with some line, or if the source is optically thick in the near IR continuum.

**Use single rather than distributed grains.** If the **single** keyword appears on the **grain** command then a single mean grain size will take be used instead of the size-resolved grain distribution. This affects the entire simulation, including the gas temperature and emission line spectrum, because the grain - gas interactions depend on the grain size.

**Turning off all grain physics.** All grain-gas interactions, except for their opacity, are turned off with the **no grain physics** command. Diffuse emission of the grains is no longer included so energy is not conserved. The dynamical and opacity effects of the grains will still be included.

**Grains no reevaluate.** The **no reevaluate** option on the **grains** command will speed up a calculation by not reevaluating grain quantities all the time. Roughly a 30% speedup can be achieved. This is potentially dangerous and can destabilize a solution and/or lead to wrong results. It should be used under certain experimental circumstances, and not in a true simulation of a cloud.

### 18.17.4 Turn off line transfer

Many lines are optically thick. If the density is high then photons are thermalized after multiple scatterings. When dust opacities are present lines can also be absorbed by continuous absorption. In this case they act as an ionization and heating agent. The **no line transfer** command turns off line transfer for all lines except the H and He  $L\alpha$  transitions. These assumptions are common in codes designed to treat classical nebulae but are not appropriate for dense gas.

### 18.17.5 Turn off level 2 lines

This is done with the **no level2 lines** command. The level 2 lines are a large set of transitions that came from the Opacity Project. They are important in dense or very high ionization gas. The Level 2 lines are important for pumping excited levels of many heavy elements. These include species such as C I\*, C II\*, etc.

### 18.17.6 Don't reevaluate the ionization or opacities

The **no ionization reevaluate** command tells the code not to constantly reevaluate the level of ionization during the thermal solution. This may affect the code's stability for dense or dust-free gas but should not affect results.

The **no opacity reevaluation** command tells the code not to reevaluate the opacities as it searches for a thermal solution. This may affect the code's stability for dense or dust-free gas but should not affect results.

These commands are safe when grains are present since their opacity strongly diminishes the diffuse radiation field. When grains are not present the diffuse radiation fields within the Balmer continuum or  $L\alpha$  can be quite intense and dominate the photoionization of some third row atoms. In this case constant reevaluation of the opacity and ionization is needed for a stable solution.

### 18.17.7 Turn off fine opacities.

The code uses a multi-grid approach to handle continuum interactions quickly, but also resolve lines so that line overlap can be treated in an automatic manner. There is a coarse continuum mesh, with a relatively low resolution and a high-resolution or fine mesh to resolve all lines. This second mesh is computationally expensive and is turned off with the **no fine opacities** command.

Turning off the fine mesh also turns off the treatment of line overlap and will affect results when overlap is important. There are many situations, like classical nebulae, where line overlap is not important.

### 18.17.8 Degrade the continuum resolution

The resolution of the coarse continuum mesh affects the execution time since photoionization rates and opacities involve repeated sums over it. The resolution is changed with the **set continuum resolution** command. This is not included in the `fast.ini` file since it is not possible to use the grains that are part of the code distribution. It would be necessary to recompile the grains at the lower resolution (with the **compile grains** command) to use grains.

### 18.17.9 Make the iso-sequence model atoms as small as possible

The code treats several iso-sequences with a unified model atom. The execution time increases when the number of levels within the model atoms is increased. Less time will be used if the smallest possible number of levels is used. The number of levels is adjusted with the **levels** option on the **atoms** command. The **atom levels** commands for the H-like and He-like atoms accepts the keywords **very small** to make the atom as compact as possible. The line spectrum predicted by these atoms is likely to be highly inaccurate, and Case B intensities are far better when a compact model is used.



# Appendix A

## USING THE GRAIN CODE IN CLOUDY

### A.1 Introduction

This release of Cloudy contains a grain model that constitutes a significant upgrade from the original model that was described in [Baldwin et al. \(1991\)](#). The code has been written by Peter van Hoof, except where indicated differently. These are the main features:

- The code resolves the size distribution of the grains in an arbitrary number of size bins (chosen by the user), and calculates all grain parameters such as temperature, charge distribution, emitted flux, etc., separately for each bin. Since grain opacities depend strongly on the grain radius, they need to be calculated separately for each bin as well.
- For this purpose Cloudy contains a Mie code for spherical grains (written by P.G. Martin, based on a code by [Hansen and Travis \(1974\)](#)). This code allows the user to calculate grain opacities using either a pre-defined or a user-supplied set of optical constants or opacities, an arbitrary size distribution, and an arbitrary number of grain size bins. The code can handle any number of grain bins, only limited by the memory on your machine.
- The code fully treats quantum heating of grains using a robust and efficient algorithm (which is a comprehensively upgraded version of a code originally written by K. Volk), implementing an improved version of the procedure described in [Guhathakurta and Draine \(1989\)](#). Combined with resolved size distributions, this will lead to a much more realistic modeling of the grain emission under all circumstances. Quantum heating is turned on automatically for all resolved size distributions<sup>1</sup> and single-sized grains (including PAH's, but excluding grey grains for which quantum heating is never used). The user can change the default behavior of the code by including the keyword **qheat** (to enable quantum heating) or **no qheat** (to disable quantum heating) with the **grains** command. If the relative grain abundance  $A_{\text{rel}}(r)$  in a particular zone (variable *gv.bin[nd]->dstAbund*) drops below a preset threshold value (variable *gv.dstAbundThreshold*, default value  $10^{-5}$ ), quantum heating will be disabled for that zone only. Note that quantum heating usually only influences the energy distribution of the emitted spectrum, nothing else<sup>2</sup>. So switching off

---

<sup>1</sup>The actual criterion is that the ratio of the volumes of the largest and smallest grain in each bin is smaller than 100 for quantum heating to be the default. Note that this criterion is very generous and that a much smaller ratio (i.e., a higher number of size bins) will usually be necessary to achieve proper convergence of the emitted spectrum.

<sup>2</sup>Quantum heating can influence the emission line spectrum as well if continuum pumping of the lines by the short wavelength end of the dust spectrum is important. Typically these will be molecular lines.

quantum heating can be a good idea to speed up the modeling, provided the correct shape of the emitted spectrum has no influence on the results the user is interested in.

- The treatment of the grain physics has been completely overhauled, following the discussion in [Weingartner and Draine \(2001a\)](#), [van Hoof et al. \(2004\)](#), and [Weingartner et al. \(2006\)](#). The grain model has a detailed treatment of the photo-electric effect and collisional processes, and includes thermionic emissions. The code uses the  $n$ -charge state model where for each bin the charge distribution is resolved in exactly  $n$  discrete charge states, independent of the grain size. The default value for  $n$  is 2, but the user can choose any number between 2 and  $NCHS/3 = 10$  using the **set nchrg** <n> command (note that there is no “a” in **nchrg**!). Choosing a higher value will usually give more accurate results at the expense of computing time. Using the default  $n = 2$  should give sufficient accuracy for most astronomical applications. The maximum value of  $n$  can be increased by altering the definition of  $NCHS$  in `grainvar.h` and recompiling the code. It is however extremely unlikely that a value of  $n > 10$  would ever be needed. A detailed description of the  $n$ -charge state model can be found in [van Hoof et al. \(2004\)](#).

Extensive comparisons in collaboration with Joe Weingartner done in 2001 show that the photo-electric heating rates and collisional cooling rates predicted by Cloudy agree very well with the results from the [Weingartner and Draine \(2001a\)](#) model for a wide range of grain sizes (between 5 Å and 0.1 μm), and using various choices for the incident radiation field. A detailed discussion of this comparison can be found in [van Hoof et al. \(2001\)](#).

## A.2 Using the grain model

In order to use the grain model, two steps need to be taken. In the first step, the grain opacities are calculated using the **compile grain** command. In the second step these opacities can be used with the **grains** command to create the actual photo-ionization model. The Cloudy distribution comes with a number of pre-compiled opacity files which cover a number of standard combinations of grain materials and size distributions. If these are sufficient for your needs, you can skip the first step, and use these opacities directly in the **grains** command. If you wish to use different grain materials and/or size distributions, you will have to compile the grain opacities first with the **compile grain** command described on page 218. In order to do this, you start up Cloudy in the data directory containing all the refractive index, mixed medium and size distribution files (files with names ending in “.rfi”, “.mix”, or “.szd”, resp.). You then type in a single command line, e.g.:

```
compile grain "silicate.rfi" "ism.szd" 10
```

followed by an extra carriage return. This will instruct the Mie code to calculate opacities using optical constants for astronomical silicate and a [Mathis et al. \(1977\)](#) standard ISM size distribution. The size distribution will be resolved in 10 bins. This will produce a file `silicate_ism_10.opc` which contains all the opacities. This opacity file is in human readable form and contains many comments to clarify its contents. It also contains a table of the size distribution function  $a^4 n(a)$  as a function of the grain radius  $a$  for reference. The format of the table is such that it could be used directly to define a size distribution table (see section A.5.7). Note that only a single **compile grain** command can be given in a single Cloudy run. Note furthermore that the opacity file produced in the example above is already included in the Cloudy distribution!

In the previous example a refractive index file was used to define the optical properties of a pure grain material (e.g., astronomical silicate or graphite). A second example could be:

```
compile grain "fluffy-sil.mix" "ism.szd" 10
```

(note that the mixed medium file `fluffy-sil.mix` is not included in the Cloudy distribution, the text is shown in Table A.9). Here the mixed medium file is used instead of a refractive index file to define a mixture of two or more grain materials (possibly including vacuum for defining fluffy grains). In this case the optical properties of the constituting materials are combined with a mixing law (also called effective medium theory or EMT) to create a set of optical constants that represents the mixture and can be fed into the Mie theory. Hence the refractive index and mixed medium files play similar roles in that both define a set of optical constants to be used by the Mie code. They differ in the fact that refractive index files are used to define pure materials, while mixed medium files define impure materials. As a consequence the internal format of both files is very different and will be described in more detail in Sections A.3 and A.4. The opacities generated from both types of input files are fully compatible though and can be used in exactly the same way, as shown below.

In the second step, you can use these opacities in a subsequent run of Cloudy with the **grains** command described in Hazy. An example could be:

```
set nchrg <n> // optional
grains "silicate_ism_10.opc" +0.100 log // quantum heating on
grains "fluffy-sil_ism_10.opc" no qheat // quantum heating off
```

Several **grains** commands may be used simultaneously to define mixtures of grains. One can freely mix **set nchrg** and **grains** commands, and different grain types may be calculated using a different number of charge states. The **set nchrg** command will only affect **grains** commands that come later in the input file. For ease of use, the filenames of certain refractive index, size distribution, and opacity files in the standard Cloudy distribution may be replaced by keywords, as described in Hazy.

The refractive index, mixed medium, and size distribution files may be replaced by user-defined versions, giving the user considerably more freedom to define grain properties compared to the old grain model in Cloudy. The format for each of those files will be defined in Sections A.3, A.4, and A.5.

## A.3 Description of the refractive index files<sup>3</sup>

In order for the Mie code in Cloudy to work, it needs to know the optical properties of the grains under consideration. If the grain consists of a single, pure material, these have to be defined in a separate file with a name that must end in `".rfi"`. In this section we will describe the format of this file. It is helpful to compare with e.g. the `graphite.rfi` or `silicate.rfi` file in the standard distribution while reading this section. This document pertains to refractive index files with magic number *1030103*. Mixtures of grain materials can also be defined using mixed medium files which are described in Section A.4.

As is the case with all files connected with the Mie code in Cloudy, the user has the freedom to add comments to the file provided they start with a sharp sign (`#`). These comments may either occupy an entire line (in which case the sharp sign has to be in the first column), or be appended to some input value. Comments have been liberally added to the refractive index files that come with the standard Cloudy distribution in an effort to make them self-explanatory. All refractive index files start with a magic number for version control. This number should simply be copied from the files in the standard distribution. Next comes the chemical formula of the grain material, for graphite this would simply be `"C"`; for a certain type of silicate this could be `"Mg0.6Fe0.4SiO3"` indicating  $\text{Mg}_{0.6}\text{Fe}_{0.4}\text{SiO}_3$ . Note that the formula is case

<sup>3</sup>Note that the term "refractive index file" is used rather loosely here. It also pertains to materials for which no refractive index data in the strict sense exist, such as grey grains and PAH's.

Table A.1: The definition of each of the material types hardwired into Cloudy. The code in column 1 needs to be entered in the refractive index file. Each of the entries in columns 3 and higher will be explained in the table indicated in the header of that column.

code	mnemonic	Table A.2	Table A.3	Table A.4	Table A.5	Table A.6	Table A.7	Table A.8
1	<i>MAT_CAR</i>	<i>ENTH_CAR</i>	<i>ZMIN_CAR</i>	<i>POT_CAR</i>	<i>IAL_CAR</i>	<i>PE_CAR</i>	<i>STRG_CAR</i>	<i>H2_CAR</i>
2	<i>MAT_SIL</i>	<i>ENTH_SIL</i>	<i>ZMIN_SIL</i>	<i>POT_SIL</i>	<i>IAL_SIL</i>	<i>PE_SIL</i>	<i>STRG_SIL</i>	<i>H2_SIL</i>
3	<i>MAT_PAH</i>	<i>ENTH_PAH</i>	<i>ZMIN_CAR</i>	<i>POT_CAR</i>	<i>IAL_CAR</i>	<i>PE_CAR</i>	<i>STRG_CAR</i>	<i>H2_CAR</i>
4	<i>MAT_CAR2</i>	<i>ENTH_CAR2</i>	<i>ZMIN_CAR</i>	<i>POT_CAR</i>	<i>IAL_CAR</i>	<i>PE_CAR</i>	<i>STRG_CAR</i>	<i>H2_CAR</i>
5	<i>MAT_SIL2</i>	<i>ENTH_SIL2</i>	<i>ZMIN_SIL</i>	<i>POT_SIL</i>	<i>IAL_SIL</i>	<i>PE_SIL</i>	<i>STRG_SIL</i>	<i>H2_SIL</i>
6	<i>MAT_PAH2</i>	<i>ENTH_PAH2</i>	<i>ZMIN_CAR</i>	<i>POT_CAR</i>	<i>IAL_CAR</i>	<i>PE_CAR</i>	<i>STRG_CAR</i>	<i>H2_CAR</i>

sensitive. For simplicity I will call this elementary building block the grain molecule, even though this term is not always appropriate. The molecular weight will be calculated by Cloudy using the chemical formula. The next two lines in the refractive index file define the default abundance of the grain molecule. The first number gives the maximum number density  $A_{\max}$  of the grain molecule (relative to hydrogen = 1) that can be formed, assuming it completely depletes at least one of the constituting atoms from the gas phase. Let us assume that the initial abundances in the gas phase (i.e., abundances *before* grains were formed) were  $A(X)$ . Then, for the silicate example above,  $A_{\max}$  should be  $\min(A(\text{Mg})/0.6, A(\text{Fe})/0.4, A(\text{Si}), A(\text{O})/3)$ . The second number gives the fraction  $A_{\text{eff}}$  of the maximum amount that is actually formed (i.e., the efficiency of the process), and should be a number between 0 and 1. The default abundance of the grain molecule is then given by the product of these two numbers:  $A_{\text{eff}}A_{\max}$ . The actual grain abundance used in the Cloudy modeling can be set with the **grains** and the **metals** command (see Hazy for details). This essentially defines an additional multiplier  $A_{\text{rel}}$  which may be either smaller or larger than 1, and may depend on position  $r$ . The actual grain molecule abundance used in the Cloudy model is then given by  $A_{\text{rel}}(r)A_{\text{eff}}A_{\max}$ . For the silicate example above, the number density of iron locked up in these grains would be given by  $0.4A_{\text{rel}}(r)A_{\text{eff}}A_{\max}$  (relative to hydrogen = 1), or  $0.4A_{\text{rel}}(r)A_{\text{eff}}A_{\max}n_{\text{H}}(r)$  (in atoms/cm<sup>3</sup>,  $n_{\text{H}}$  is the hydrogen number density as defined by the **hden** command). The next line in the refractive index file gives the specific density of the grain material in g/cm<sup>3</sup>. The grain code needs to know the material type in order to determine certain grain properties that are currently hardwired into the code. Examples would be the grain enthalpy as a function of temperature and the ro-vibrational distribution of H<sub>2</sub> formed on the grain surface. The next line indicates which material type to use. Currently six choices are available. They are outlined in Table A.1. The next two lines give the work function and the bandgap between the valence and conduction band in Rydberg respectively. For conductors the bandgap should be set to zero, for insulators such as silicates, a non-zero value should be used. The next line gives the efficiency of thermionic emissions. This parameter is usually unknown for materials of astrophysical interest, and using 0.5 should be a reasonably safe guess. Next comes the sublimation temperature in Kelvin. Then comes a line with a keyword which identifies what type of refractive index file is being read. It determines what the remainder of the file will look like. Allowed values are *rfl\_tbl*, *opc\_tbl*, *grey*, *pah1*, *ph2n*, *ph2c*, *ph3n*, and *ph3c*. In the *grey*, *pah1*, *ph2n*, *ph2c*, *ph3n*, and *ph3c* cases, no further data is needed and the refractive index file ends there (i.e., the information needed to calculate the opacities is hardwired in the code).

### A.3.1 rfl\_tbl

This format is used to define the refractive index as a function of wavelength, which will then be used by the Mie code to generate the opacities when combined with a size distribution file.

The remaining lines in the refractive index file define the optical constants. First the user has to enter a

Table A.2: The various choices for the enthalpy function hardwired in Cloudy.

mnemonic	type	reference
<i>ENTH_CAR</i>	graphite	<a href="#">Guhathakurta and Draine (1989)</a> , Eq. 3.3
<i>ENTH_SIL</i>	silicate	<a href="#">Guhathakurta and Draine (1989)</a> , Eq. 3.4
<i>ENTH_PAH</i>	PAH	<a href="#">Dwek et al. (1997)</a> , Eq. A4
<i>ENTH_CAR2</i>	graphite	<a href="#">Draine and Li (2001)</a> , Eq. 9
<i>ENTH_SIL2</i>	silicate	<a href="#">Draine and Li (2001)</a> , Eq. 11
<i>ENTH_PAH2</i>	PAH	<a href="#">Draine and Li (2001)</a> , Eq. 33

Table A.3: The various choices for the minimum charge hardwired in Cloudy.

mnemonic	type	reference
<i>ZMIN_CAR</i>	graphite	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 23a+24
<i>ZMIN_SIL</i>	silicate	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 23b+24

Table A.4: The various expressions for the electron affinity hardwired in Cloudy.

mnemonic	type	reference
<i>POT_CAR</i>	graphite	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 4
<i>POT_SIL</i>	silicate	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 5

Table A.5: The various choices for the inverse attenuation length. Note that these choices will *only* be used if no refractive index data is contained in the refractive index file.

mnemonic	type	description
<i>IAL_CAR</i>	graphite	use <code>graphite.rfi</code> to calculate the inverse attenuation length
<i>IAL_SIL</i>	silicate	use <code>silicate.rfi</code> to calculate the inverse attenuation length

Table A.6: The various expressions for the photoelectric yield hardwired in Cloudy.

mnemonic	type	reference
<i>PE_CAR</i>	graphite	<a href="#">Weingartner et al. (2006)</a> , Sect. 4 – 6
	graphite	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 16 (with <b>no grain x-ray treatment</b> )
<i>PE_SIL</i>	silicate	<a href="#">Weingartner et al. (2006)</a> , Sect. 4 – 6
	silicate	<a href="#">Weingartner and Draine (2001a)</a> , Eq. 17 (with <b>no grain x-ray treatment</b> )

Table A.7: The various choices for splitting up the grain emissions.

mnemonic	type	description
<i>STRG_CAR</i>	graphite	store emitted spectrum as graphitic emission.
<i>STRG_SIL</i>	silicate	store emitted spectrum as silicate emission.

Table A.8: The expressions for the ro-vibrational distribution of H<sub>2</sub> formed on various grain surfaces.

mnemonic	type	reference
<i>H2_ICE</i>	ice mantle	<a href="#">Takahashi and Uehara (2001)</a> , Table 2
<i>H2_CAR</i>	graphite	<a href="#">Takahashi and Uehara (2001)</a> , Table 2
<i>H2_SIL</i>	silicate	<a href="#">Takahashi and Uehara (2001)</a> , Table 2

code to define how the complex refractive index  $n$  is written up; the following choices are supported:

1. – supply  $\text{Re}(n^2)$ ,  $\text{Im}(n^2)$  (the dielectric function),
2. – supply  $\text{Re}(n - 1)$ ,  $\text{Im}(n)$ ,
3. – supply  $\text{Re}(n)$ ,  $\text{Im}(n)$ .

The next line gives the number of principal axes  $N_a$  for the grain crystal and should be a number between 1 and 3. For amorphous materials one should always choose 1 axis. For crystalline materials the number may be 2 or 3. Next comes a line with  $N_a$  numbers giving the relative weights for each of the axes. These numbers will be used to average the opacities over each of the axes in crystalline materials. For materials with only one axis, this number is obviously redundant, and a single 1 should be entered. For graphite it is appropriate to enter “1 2” indicating that the first axis will have relative weight 1/3 and the second 2/3 (i.e., the relative weights are 1:2). Next come  $N_a$  chunks of data defining the optical constants for each axis. Each chunk starts with a line giving the number of data points  $N_d$  for that axis, followed by  $N_d$  lines containing 3 numbers: the wavelength in  $\mu\text{m}$ , and the real and imaginary part of the complex number defined above. Note that the wavelengths may be either monotonically increasing or decreasing, and that the number of data points or the wavelength grid may be different for each axis. The grid of wavelengths need not coincide with the Cloudy grid, nor does it need to cover the entire range of energies used in Cloudy. Logarithmic interpolation or extrapolation will be performed where needed. *It is the users responsibility to ensure that each wavelength grid contains sufficient points to make this process meaningful; only minimal checks will be performed by Cloudy.* Note that if your refractive index data do not have sufficient wavelength coverage (as will usually be the case if they come from laboratory experiments) you cannot simply merge data from another refractive index file to extend the range. This is because the refractive index data need to obey the Kramers-Kronig relations. If you take data from two different sources, this will not be the case. In most cases you need to extend your data into the EUV and X-ray regime. The proper procedure in this case is to calculate the absorption opacity by adding the photoionization opacities (including inner-shell ionizations) for each of the atoms that make up the grain using data for neutral atoms. You then need to combine these data with the Kramers-Kronig relations to reverse engineer the refractive index data. This is the procedure that was used to create the refractive index files that are included in the Cloudy distribution.

### A.3.2 `opc_tbl`

This format can be used to directly define the opacities as a function of photon energy. It is mainly useful to define alternative prescriptions for PAH's. Note that the refractive index file created this way still needs to be combined with a size distribution file in the usual way with the **compile grain** command. This step will not alter the opacities themselves, but is necessary to compute certain quantities that are related to the size distribution which are not defined in the refractive index file itself. It is not allowed to resolve the size distribution when using an opacity table. If you want to define a resolved size distribution, you will have to supply an opacity table and corresponding size distribution file for each size bin separately.

The remaining lines in the refractive index file define the opacities. The first line contains the number of data values  $N_v$  supplied on each line in the table. Allowed values are:

1. – supply  $\sigma_{\text{abs}}$  only (in  $\text{cm}^2/\text{H}$ ),
2. – supply  $\sigma_{\text{abs}}$ ,  $\sigma_{\text{sct}} \times (1 - g)$  (in  $\text{cm}^2/\text{H}$ ),
3. – supply  $\sigma_{\text{abs}}$ ,  $\sigma_{\text{sct}}$  (in  $\text{cm}^2/\text{H}$ ), and  $(1 - g)$  separately.
4. – supply  $\sigma_{\text{abs}}$ ,  $\sigma_{\text{sct}}$  (in  $\text{cm}^2/\text{H}$ ),  $(1 - g)$ , and the inverse attenuation length (in  $\text{cm}^{-1}$ ).

Table A.9: Example of a mixed medium file for fluffy silicate (`fluffy-sil.mix`).

```
# simplistic toy model of fluffy silicate; for test purposes only!
4030103 # magic number for version control
0.61    # default depletion
2       # number of separate materials in grain
#
  50    "vacuum.rfi"
  50    "silicate.rfi"
#
fa00    # which EMT should be used
```

Here  $\sigma_{\text{abs}}$  and  $\sigma_{\text{sct}}$  are the absorption and scattering cross sections, and  $g$  is called the asymmetry factor or phase function. The latter is needed since the radiative transfer in Cloudy assumes that photons that are scattered in a forward direction (at an angle of less than  $90^\circ$ ) are not lost from the beam (i.e., they still make it out of the cloud). The asymmetry factor  $g$  gives the average value of the cosine of the scattering angle, so that  $(1 - g)$  is an approximate correction factor for the anisotropy of the scattering by grains. If no scattering cross sections are supplied,  $\sigma_{\text{sct}} \times (1 - g)$  will default to 10% of the absorption cross section. If no asymmetry factor is supplied,  $g$  will default to zero. If no inverse attenuation lengths are supplied, they will be derived from the material type supplied previously in the file. On the next line is a keyword with two allowed values: **log** or **linear**, defining whether the opacity table will contain logarithmic or linear data values. The next line gives the number of data points  $N_d$ , followed by  $N_d$  lines of actual data. Each line of the table should contain  $N_v + 1$  numbers, starting with the photon energy in Rydberg, followed by the absorption cross section, the scattering cross section, the factor  $(1 - g)$ , and the inverse attenuation length (the last three values may be omitted, depending on the value of  $N_v$ ). The photon energies must either be strictly monotonically increasing or decreasing. The grid of photon energies need not coincide with the Cloudy grid, nor does it need to cover the entire range of energies. Logarithmic interpolation or extrapolation will be performed where needed. *It is the users responsibility to ensure that the frequency grid contains sufficient points to make this process meaningful; only minimal checks will be performed by Cloudy.*

## A.4 Description of the mixed medium files

In order to define the optical properties of a grain consisting of a mixture of materials<sup>4</sup>, a separate file with a name that must end in “`.mix`” has to be used. In this section we will describe the format of this file. An example of a mixed medium file is shown in Table A.9. This document pertains to mixed medium files with magic number 4030103.

As is the case with all files connected with the Mie code in Cloudy, the user has the freedom to add comments to the file provided they start with a sharp sign (#). These comments may either occupy an entire line (in which case the sharp sign has to be in the first column), or be appended to some input value. All mixed medium files start with a magic number for version control, as shown in Table A.9. The chemical formula and the abundance at maximum depletion of the mixed material will be derived by Cloudy using the information supplied in the refractive index files of the constituting materials. However, the default depletion cannot be calculated and needs to be supplied by the user on the next line. This number is defined

<sup>4</sup>In this section the term material can also mean vacuum so that the user can define fluffy grains by mixing one or more materials with vacuum.

Table A.10: Allowed choices for the mixing law.

mnemonic	reference
<i>BR35</i>	<a href="#">Bruggeman (1935)</a>
<i>FA00</i>	<a href="#">Voshchinnikov and Mathis (1999)</a> <a href="#">Farafonov (2000)</a>
<i>ST95</i>	<a href="#">Stognienko et al. (1995)</a>

as a fraction of the maximum depletion, and should be a number between 0 and 1 (see also the discussion in Section A.3). When the opacities are calculated, the code will print the chemical formula and the abundances (both at maximum and default depletion), so that the user can check whether the default abundance is correct. The next line gives the number  $n$  of separate materials in the grain ( $n$  should be at least 2; it is allowed to specify the same material several times), followed by  $n$  lines giving information about the materials. Each of these lines should give the relative fraction of the volume occupied by that particular material, followed by the name of the refractive index file between double quotes. Note that the refractive index files have to be of type *rfl.tbl* since mixing laws need optical constants as input and cannot work with opacities. The normalization of the relative volumes can be on an arbitrary scale. The last line in the file should be a keyword identifying which mixing law is to be used. Allowed values are listed in Table A.10. In the case of [Farafonov \(2000\)](#), the mixing law assumes that the grain consists of concentric layers of material. It is assumed that the first material supplied in the mixed medium file identifies the innermost layer, and the following lines identify the subsequent layers towards the outer edge of the grain. The outermost layer will determine the material type as defined in Table A.1. In the case of [Bruggeman \(1935\)](#) and [Stognienko et al. \(1995\)](#), the grain is assumed to be a random (possibly fractal) mixture of materials and the sequence in the mixed medium file is irrelevant, except that the material type of the mixture is still defined by the last entry in the list of materials. For this reason it is not allowed to have vacuum as the last entry. In the case of a layered grain it would also not make sense to have vacuum as the outermost layer of course.

## A.5 Description of the size distribution files

In order for the Mie code in Cloudy to work, it needs to know the size distribution of the grains under consideration. This distribution has to be defined in a separate file with a name that must end in “.szd”. In this section I will describe the format of this file. This document pertains to size distribution files with magic number 2010403.

If we denote the number of grains  $n_g da$  with radii between  $a$  and  $a + da$  as  $n_g da = n(a) da$ , the purpose of the size distribution file is to define  $n(a)$ , or alternatively  $a^4 n(a)$  which is more commonly used.

As is the case with all files connected with the Mie code in Cloudy, the user has the freedom to add comments to the file provided they start with a sharp sign (#). These comments may either occupy an entire line (in which case the sharp sign has to be in the first column), or be appended to some input value. Comments have been liberally added to the size distribution files that come with the standard Cloudy distribution in an effort to make them self-explanatory. All size distribution files start with a magic number for version control. This number should simply be copied from the files in the standard distribution. The next line should contain a keyword indicating which type of size distribution will be entered. The following choices are currently supported: *ssize* - a single sized grain, *ncarb* - a PAH molecule with a specified number of carbon atoms, *power* - a simple power law, *exp1*, *exp2*, *exp3* - power laws with an exponential cutoff, *normal*, *lognormal* - a Gaussian distribution in  $a$  or  $\ln(a)$ , *table* - an arbitrary size distribution

supplied as a table. This keyword is case insensitive. The rest of the file contains the parameters needed to fully define each of those choices. I will now describe these choices in more detail. It should be noted that at this stage the absolute normalization of the size distribution is irrelevant; that will be defined in the refractive index file by the default grain abundance. Each parameter mentioned below should be entered on a separate line, unless indicated otherwise. All size parameters should be entered in  $\mu\text{m}$ .

### A.5.1 ssize

In this case the size distribution is given by a simple delta function:

$$n(a) \propto \delta(a - a_0)$$

The only parameter that needs to be supplied is the radius of the grain  $a_0$ .

### A.5.2 ncarb

This case also describes a single-sized grain, but this time the number of carbon atoms is the only parameter that is supplied. This is convenient for defining a PAH molecule of a specific size. This size distribution is obviously only meaningful when combined with carbonaceous material.

### A.5.3 power

In this case the size distribution is given by a simple power law:

$$n(a) \propto a^\alpha \quad a_0 \leq a \leq a_1$$

Hence this distribution needs three parameters, which need to be supplied in the order  $a_0, a_1, \alpha$ .

### A.5.4 exp1, exp2, exp3

In this case the size distribution is given by a power law with a first-, second-, or third-order exponential cutoff:

$$n(a) \propto a^\alpha F(a; \beta) C_l(a; a_l, \sigma_l) C_u(a; a_u, \sigma_u) \quad a_0 \leq a \leq a_1.$$

The function  $F$  is included to give extra curvature in the power-law region, the functions  $C_l$  and  $C_u$  define the cutoff of the distribution below  $a_l$  and above  $a_u$ . These functions are defined as follows:

$$F(a; \beta) = \begin{cases} (1 - \beta a)^{-1} & \text{if } \beta < 0 \\ 1 & \text{if } \beta = 0 \\ (1 + \beta a) & \text{if } \beta > 0 \end{cases}$$

$$C_l(a; a_l, \sigma_l) = \begin{cases} \exp \left[ - \left( \frac{a_l - a}{\sigma_l} \right)^n \right] & \text{if } a < a_l \\ 1 & \text{if } a \geq a_l \end{cases}$$

$$C_u(a; a_u, \sigma_u) = \begin{cases} 1 & \text{if } a \leq a_u \\ \exp \left[ - \left( \frac{a - a_u}{\sigma_u} \right)^n \right] & \text{if } a > a_u \end{cases}$$

The values of  $\sigma_l$  or  $\sigma_u$  may be set to zero, in which case a straight cutoff in the size distribution will be used. Note that when  $\beta$ ,  $\sigma_l$ , and  $\sigma_u$  are all set to zero, this size distribution degenerates to the simple power law discussed above. The parameters need to be supplied in the following order:  $a_l, a_u, \alpha, \beta, \sigma_l, \sigma_u, a_0, a_1$ .

The value of  $n$  is determined by the keyword used:  $n = 1$  for *expI*, etc. The parameter  $\beta$  should be entered in  $\mu\text{m}^{-1}$ . Note that this size distribution extends infinitely beyond  $a_l$  and  $a_u$ , so additional cutoffs at  $a_0$  and  $a_1$  are needed. Either of these values may be set to zero, in which case Cloudy will calculate a safe default value such that only a negligible amount of mass is contained in the tail beyond that limit.

### A.5.5 normal

In this case the size distribution is given by a Gaussian distribution in  $a$ :

$$n(a) \propto \frac{1}{a} \exp \left( -\frac{1}{2} \left[ \frac{a - a_c}{\sigma} \right]^2 \right) \quad a_0 \leq a \leq a_1$$

The parameters for this distribution need to be supplied in the order:  $a_c, \sigma, a_0, a_1$ . As was discussed in the previous section, the values of  $a_0$  or  $a_1$  may be set to zero in which case Cloudy will calculate a safe default.

### A.5.6 lognormal

This case is completely analogous to the *normal* case discussed above, except that the distribution is now given by:

$$n(a) \propto \frac{1}{a} \exp \left( -\frac{1}{2} \left[ \frac{\ln\{a/a_c\}}{\sigma} \right]^2 \right) \quad a_0 \leq a \leq a_1$$

### A.5.7 table

This option allows the user to define an arbitrary size distribution in the form of a table of  $a^4 n(a)$  as a function of  $a$ . First values for the lower and upper size limit  $a_0$  and  $a_1$  should be supplied. These values need not coincide with the lower and upper size limit of the table, although the range of the table should be at least that large (no extrapolation will be performed). Next the number of data pairs  $n$  in the table should be supplied, followed by  $n$  lines each containing two numbers:  $a$  (in  $\mu\text{m}$ ) and  $a^4 n(a)$  (in arbitrary units). Note that the values for  $a$  in the table must be strictly monotonically increasing.

# Appendix B

## INCLUDING USER-DEFINED ATMOSPHERE GRIDS IN CLOUDY

### B.1 Introduction

Cloudy now features the possibility of including user-defined stellar atmosphere grids with an arbitrary number of dimensions (this is the number of parameters that are varied in the grid). Using such a grid requires two steps. The first is to create an ascii file with all the necessary information. The format of this file will be described in Sect. B.2. The second step is to compile this file into a binary atmosphere file, just like any other atmosphere grid used by Cloudy. This is described in Sect. B.3. The runtime behavior of the code is described in Sect. B.4.

### B.2 The ascii file

Each stellar atmosphere grid needs to be defined in a single ascii file containing all the necessary information. The format is illustrated in Table B.1. The aim of this format is to keep the data in the ascii file as close as possible to the original calculations. The file starts with some general information, followed by a block of model parameters, the frequency/wavelength grid, and finally each of the spectral energy distributions (SEDs). No comments of any sort are allowed in the file. It is implicitly assumed that each SED has been rebinned onto the same frequency/wavelength grid. This grid does not need to coincide with the Cloudy grid. The grid will be automatically rebinned onto the Cloudy grid during the compilation stage described in Sect. B.3. The supplied frequency/wavelength grid doesn't need to cover the entire Cloudy grid. Extrapolation will be used to fill in the missing data. It is allowed for flux points in the Wien tail to have zero flux. It is however the users responsibility to assure that sufficient data are supplied to enable a safe extrapolation of the spectra to the entire Cloudy grid.

I will now describe each of the items in the ascii file in more detail. The first line contains the magic number that identifies the syntax version. This number is the same in all ascii files that are used by Cloudy. It is checked when Cloudy compiles the ascii file. This document describes version 20060612. The second line contains the number of parameters *ndim* that are varied in the grid. Typically this number is 2, but it may be any number  $\geq 1$  and  $\leq MDIM$  (the latter parameter is defined in `stars.h`). The default value for *MDIM* is 4, which should be sufficient for all current grids. The parameter can however be increased if the user wishes so. The code, as well as the binary atmosphere files, will then have to be recompiled. The third line contains the number of parameters *npar* that are supplied for each atmosphere model. This number may be larger than *ndim*, but not smaller. The additional parameters are printed in the output, so using *npar*

> *ndim* can be a useful way of supplying additional information about the models. The number of parameters is limited by the parameter *MDIM* defined in `stars.h`. Next follow *npar* lines, each giving a label for that parameter. This is used in the Cloudy output. The labels are completely free. However, if the first label matches the string *Teff*, and the second label matches *log(g)* (case sensitive), then special rules apply. We will refer to this as a *Teff-log(g)* grid. See Sections B.3 and B.4 for further details. The next line gives the number of atmosphere models *nmod* in the grid, followed on the next line by the number of frequency/wavelength points *nfreq* in each of those models. In order to keep the format of the ascii file as close as possible to the original models, it is allowed to use either a frequency or wavelength grid in arbitrary units. The same holds for the dependent variable, which may either be a flux per frequency or wavelength unit. Both the dependent and independent variable should be entered as linear quantities, so logarithmic units like magnitudes are not supported. With this amount of freedom, the code needs to know how to convert these variables to Cloudy's internal units. This is defines on the next 4 lines. The next line should contain either *nu* to state that the file contains a frequency grid, or *lambda* to state that it contains a wavelength grid. The next line contains a conversion factor to convert the numbers in the ascii file to a frequency in Hz (case *nu*) or a wavelength in Å (case *lambda*). The conversion factor is multiplied with the numbers in the ascii file. So, if the ascii file would contain a wavelength grid in nanometer, then the conversion factor would have to be 10 to convert it into a grid in Å. The next line defines the data type of the dependent variable. Legal values are *F\_nu*, *H\_nu* for fluxes per frequency unit, or *F\_lambda*, *H\_lambda* for fluxes per wavelength unit. The next line contains the conversion factor to convert the numbers in the ascii file to a flux in  $\text{erg cm}^{-2} \text{s}^{-1} \text{Hz}^{-1}$  (case *F\_nu*, *H\_nu*) or  $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1}$  (case *F\_lambda*, *H\_lambda*). Again the conversion factors are multiplied with the numbers in the ascii file. In the cases *H\_nu* and *H\_lambda* no implicit factor  $4\pi$  will be used! So if the ascii file contains Eddington fluxes *H\_nu* in  $\text{erg cm}^{-2} \text{s}^{-1} \text{Å}^{-1} \text{sr}^{-1}$ , then the conversion factor should be 12.56637... All fluxes are eventually renormalized in Cloudy, but nevertheless it is important to get this conversion correct. The effective temperature of interpolated models is internally checked by evaluating the integral:

$$\int_0^\infty F_\nu d\nu = \sigma T_{\text{eff}}^4.$$

If the result deviates too much from the expected value an error will be printed. When compiling the grid, each model in the grid will be tested in the same manner. A warning will be printed for each model that deviates from the expected value. If all models generate such a warning, you should check your normalization.

This concludes the general setup of the grid. The remainder of the file contains the actual parameters and the data of the atmosphere models. These numbers can be formatted in any way you like, as long as it complies with C formatting rules. More in particular, you can supply more than 1 number per line, as long as they are separated by whitespace. Several forms of Fortran number formatting are not recognized in C! First, using “D-format” numbers (e.g. 1.0d+20) is not allowed as C does not recognize this notation. Second, Fortran may omit the “e” in numbers with large exponents (e.g. 1.0-102). This notation is not recognized either by C. The “e” in the exponential notation may be either lowercase or uppercase. In the ascii file, first the model parameters must be supplied. This means that  $nmod \times npar$  numbers must be entered, first all parameters for model #1, then the parameters for model #2, etc. Next follows a block of *nfreq* numbers defining the frequency/wavelength grid. Finally, *nmod* blocks, each containing *nfreq* numbers, must be entered which give the fluxes for each of the atmosphere models. This then concludes the ascii file.

Table B.1: Example of an ascii file, derived from the kwerner.ascii file. **Comments are not allowed in the file and are only shown here for clarity.**

```

20060612      # magic number
2             # ndim
2             # npar
Teff          # label par 1
log(g)        # label par 2
20           # nmod
513          # nfreq
nu            # type of independent variable (nu or lambda)
3.28984196e+15 # conversion factor for independent variable
F_nu         # type of dependent variable (F_nu/H_nu or F_lambda/H_lambda)
1.00000000e+00 # conversion factor for dependent variable
# nmod sets of npar model parameters
  80000. 5.0 80000. 6.0 80000. 7.0 80000. 8.0
 100000. 5.0 100000. 6.0 100000. 7.0 100000. 8.0
 120000. 6.0 120000. 7.0 120000. 8.0 140000. 6.0
 140000. 7.0 140000. 8.0 160000. 7.0 160000. 8.0
 180000. 7.0 180000. 8.0 200000. 7.0 200000. 8.0
# the frequency/wavelength grid, nfreq points
1.0100000e-05 3.0396596e-04 6.0762797e-04 9.1129000e-04 9.8728144e-04
... <505 more frequency points>
1.7655824e+02 1.7940598e+02 1.8225368e+02
# the SED for model 1, nfreq flux points
6.2701018e-11 5.5260639e-08 2.1959737e-07 4.9197354e-07 5.7711065e-07
... <505 more flux points>
9.0885815e-37 2.7039771e-37 7.9828291e-38
... <the SED's for models 2 ... 19>
# the SED for model 20, nfreq flux points
1.4960523e-10 1.3383193e-07 5.3344235e-07 1.1975753e-06 1.4049202e-06
... <505 more flux points>
2.1177483e-13 1.3848120e-13 9.0415034e-14

```

### B.3 Compiling the grid

Ascii files containing the stellar atmosphere grid can have arbitrary names as long as the filename extension is “.ascii”. In the remainder we will assume the file has been named `usergrid.ascii`. In order for the grid to be used by Cloudy, it must be compiled into a binary format. This format is platform dependent, so the binary file needs to be recreated for every machine architecture that you wish to use it on. In order to compile the file, go to the directory that contains the ascii file (this does not need to be the Cloudy data directory), start up Cloudy and type the following command:

```
compile stars "usergrid.ascii"
```

followed by two carriage returns. Cloudy will now create a file `usergrid.mod`. If you did the above outside the normal Cloudy directory, you now need to move the `usergrid.mod` file to the Cloudy data directory. You can now use the grid by including the following in your input file:

```
table star "usergrid.mod" 2.4e4 4.3
```

In the case of a Teff-log(g) grid (see Section B.2 for a definition) you can supply only Teff, and log(g) will default to the highest value in the grid. In all other cases you need to supply exactly *ndim* parameters. See Section 6.12 for further details.

### B.4 Runtime behavior

When Cloudy encounters the following command in its input:

```
table star "usergrid.mod" 24300 4.3
```

it will try to interpolate the requested model using as few models as possible. This means that if an exact match could be found in the grid, only that model will be used. If an exact match could be found for one parameter, but not another, then only interpolation in the latter parameter will be performed. In general no extrapolation will be performed. The only exception is the log(g) parameter in Teff-log(g) grids for which more relaxed rules are used. More on that later. First we will return to the example above. Let's assume that the `usergrid` contains models for  $\text{Teff} = \{\dots 24000, 25000 \dots\}$  and  $\log(g) = \{\dots 4.0, 4.5 \dots\}$ . Then Cloudy will perform interpolation using the following 4 models:  $(\text{Teff}, \log(g)) = (24000, 4.0)$ ,  $(24000, 4.5)$ ,  $(25000, 4.0)$ , and  $(25000, 4.5)$ . It will perform linear interpolation on those models using the log of the flux. If any of the models it needs for the interpolation is not present in the grid, the interpolation will fail and Cloudy will stop. However, more relaxed rules exist for log(g) in Teff-log(g) grids (see Section B.2 for a definition). If it cannot find a model with a given log(g), it will substitute the model with the nearest log(g) instead. The reasoning behind this is that in general the spectral energy distribution is not very sensitive to the value of log(g).

# Appendix C

## LATEX STYLE AND MACROS

### C.1 Cross references

See Section [8.6.2 \*cdColm—the computed column densities\*](#) in Hazy 2.

See  
Section `\ref{Hazy3-sec:SubroutineCdColm}`  
`\cdSectionTitle{\refname{Hazy2-sec:SubroutineCdColm}}`  
in Hazy 2.

For this to work across all volumes of Hazy we must include the package *xr* and we must list the filenames of all chapters of all three volumes in `head.info.tex` using the `externaldocument` markup.

### C.2 Blocks of verbatim text

```
3198CellPeak1.00E+00   Lo 9.99e-09=912.21cm   Hi-Con:1.20E+02 Ryd   E(hi):7.35E+06Ryd   E(hi):   100.01 MeV
```

Table [C.1](#) gives naming convention for labels.


### C.3 Macros

Table [C.2](#) lists some of the macros defined in `macros.tex`.

Table C.1: Naming convention for labels

Tables	tab:TableLabel
Equations	eqn:EquationLabel
Figures	fig:FigureLabel
Section	sec:SectionLabel

Table C.2: Macros defined in `macros.tex`

<code>\Cloudy</code>	CLOUDY	the name of the code
<code>\Hazy</code>	HAZY	the name of this document
<code>\cdCommand{command}</code>	<b>command</b>	a command
<code>\cdFilename{file name}</code>	file name	a file name
<code>\cdTerm{jargon}</code>	<b><i>jargon</i></b>	a defined term
<code>\experimental</code>		indicates experimental code
<code>\cdVariable{variable name}</code>	<i>variable name</i>	name of variable
<code>\cdRoutine{routine name}</code>	<i>routine name</i>	routine name
<code>\cdSectionTitle{Section of Hazy}</code>	<i>Section of Hazy</i>	title of a section of Hazy
<code>\cdMono{typewriter text}</code>	typewriter text	text in monospaced format

# REFERENCES

- N. P. Abel, C. L. Brogan, G. J. Ferland, C. R. O'Dell, G. Shaw, and T. H. Troland. Physical Conditions in Orion's Veil. *ApJ*, 609:247–260, July 2004. doi: 10.1086/421009.
- N. P. Abel, G. J. Ferland, G. Shaw, and P. A. M. van Hoof. The H II Region/PDR Connection: Self-consistent Calculations of Physical Conditions in Star-forming Regions. *ApJS*, 161:65–95, November 2005. doi: 10.1086/432913.
- N. P. Abel, P. A. M. v. Hoof, G. Shaw, G. J. Ferland, and T. Elwert. Sensitivity of PDR Calculations to Microphysical Details. *ApJ*, 686:1125–1136, October 2008. doi: 10.1086/591505.
- T. F. Adams. The Escape of Resonance-Line Radiation from Extremely Opaque Media. *ApJ*, 174:439, June 1972. doi: 10.1086/151503.
- C. W. Allen. *Astrophysical Quantities*. London: Athlone (3rd edition), 1976.
- C. Allende Prieto, D. L. Lambert, and M. Asplund. The Forbidden Abundance of Oxygen in the Sun. *ApJ*, 556:L63–L66, July 2001. doi: 10.1086/322874.
- C. Allende Prieto, D. L. Lambert, and M. Asplund. A Reappraisal of the Solar Photospheric C/O Ratio. *ApJ*, 573:L137–L140, July 2002. doi: 10.1086/342095.
- L. H. Aller and S. J. Czyzak. Chemical compositions of planetary nebulae. *ApJS*, 51:211–247, February 1983. doi: 10.1086/190846.
- A. C. Allison and A. Dalgarno. Photodissociation of Vibrationally Excited H<sub>2</sub>, HD, and D<sub>2</sub> by Absorption into the Continua of the Lyman and Werner Systems. *Atomic Data*, 1:91, 1969. doi: 10.1016/S0092-640X(69)80021-5.
- E. Anders and N. Grevesse. Abundances of the elements - Meteoritic and solar. *Geochim. Cosmochim. Acta*, 53:197–214, January 1989. doi: 10.1016/0016-7037(89)90286-X.
- N. Arimoto and Y. Yoshii. Chemical and photometric properties of a galactic wind model for elliptical galaxies. *A&A*, 173:23–38, February 1987.
- K. A. Arnaud. XSPEC: The First Ten Years. In G. H. Jacoby and J. Barnes, editors, *Astronomical Data Analysis Software and Systems V*, volume 101 of *Astronomical Society of the Pacific Conference Series*, page 17, 1996.
- Y. Ascasibar and A. I. Díaz. Photoionized gas in hydrostatic equilibrium: the role of gravity. *MNRAS*, 404: 275–282, May 2010. doi: 10.1111/j.1365-2966.2010.16270.x.
- A. M. Atoyan and F. A. Aharonian. On the mechanisms of gamma radiation in the Crab Nebula. *MNRAS*, 278:525–541, January 1996.
- Y. Avni and H. Tananbaum. X-ray properties of optically selected QSOs. *ApJ*, 305:83–99, June 1986. doi: 10.1086/164230.
- Y. Avni, D. M. Worrall, and W. A. Morgan, Jr. The Underlying Distribution of Optical to X-Ray Spectral Index for Quasars in the Presence of Detection Thresholds. *ApJ*, 454:673, December 1995. doi: 10.1086/176520.

- S. Bajtlik, R. C. Duncan, and J. P. Ostriker. Quasar ionization of Lyman-alpha clouds - The proximity effect, a probe of the ultraviolet background at high redshift. *ApJ*, 327:570–583, April 1988. doi: 10.1086/166217.
- E. L. O. Bakes and A. G. G. M. Tielens. The photoelectric heating mechanism for very small graphitic grains and polycyclic aromatic hydrocarbons. *ApJ*, 427:822–838, June 1994. doi: 10.1086/174188.
- S. A. Balbus and C. F. McKee. The evaporation of spherical clouds in a hot gas. III - Suprathermal evaporation. *ApJ*, 252:529–552, January 1982. doi: 10.1086/159581.
- J. A. Baldwin, G. J. Ferland, P. G. Martin, M. R. Corbin, S. A. Cota, B. M. Peterson, and A. Slettebak. Physical conditions in the Orion Nebula and an assessment of its helium abundance. *ApJ*, 374: 580–609, June 1991. doi: 10.1086/170146.
- J. A. Baldwin, G. J. Ferland, K. T. Korista, F. Hamann, and A. LaCluyzé. The Origin of Fe II Emission in Active Galactic Nuclei. *ApJ*, 615:610–624, November 2004. doi: 10.1086/424683.
- R. P. Bauman, R. L. Porter, G. J. Ferland, and K. B. MacAdam. J-Resolved He I Emission Predictions in the Low-Density Limit. *ApJ*, 628:541–554, July 2005. doi: 10.1086/430665.
- M. A. Bautista and T. R. Kallman. Recombination Spectra of Helium-like Ions. *ApJ*, 544:581–591, November 2000. doi: 10.1086/317206.
- J. Bechtold, R. J. Weymann, Z. Lin, and M. A. Malkan. The integrated ultraviolet radiation field from QSOs. *ApJ*, 315:180–197, April 1987. doi: 10.1086/165123.
- E. Behar and H. Netzer. Inner-Shell 1s-2p Soft X-Ray Absorption Lines. *ApJ*, 570:165–170, May 2002. doi: 10.1086/339581.
- E. Behar, M. Sako, and S. M. Kahn. Soft X-Ray Absorption by  $\text{Fe}^{0+}$  to  $\text{Fe}^{15+}$  in Active Galactic Nuclei. *ApJ*, 563:497–504, December 2001. doi: 10.1086/323966.
- J. Bergeron and S. Souffrin. Optical line spectrum of a gas heated by hard UV radiation or energetic particles. *A&A*, 14:167–188, September 1971.
- E. A. Bergin, W. D. Langer, and P. F. Goldsmith. Gas-phase chemistry in dense interstellar clouds including grain surface molecular depletion and desorption. *ApJ*, 441:222–243, March 1995. doi: 10.1086/175351.
- F. Bertoldi and B. T. Draine. Nonequilibrium Photodissociation Regions: Ionization-Dissociation Fronts. *ApJ*, 458:222, February 1996. doi: 10.1086/176805.
- E. Bica. Population synthesis in galactic nuclei using a library of star clusters. *A&A*, 195:76–92, April 1988.
- L. Binette, A. Prieto, E. Szusiewicz, and W. Zheng. Relation between the ionizing continuum and the emission lines in Fairall 9. *ApJ*, 343:135–141, August 1989. doi: 10.1086/167691.
- J. H. Black. Heating and cooling of the interstellar gas. In D. J. Hollenbach and H. A. Thronson, Jr., editors, *Interstellar Processes*, volume 134 of *Astrophysics and Space Science Library*, pages 731–744, 1987.
- K. J. Borkowski and J. P. Harrington. A grain-heated, dusty planetary nebula in M22. *ApJ*, 379:168–176, September 1991. doi: 10.1086/170493.
- M. Bottorff and G. Ferland. Dissipative Heating and Quasar Emission Lines. *ApJ*, 568:581–591, April 2002. doi: 10.1086/339058.
- M. Bottorff, J. Lamothe, E. Momjian, E. Verner, D. Vinković, and G. Ferland. Luminosity Indicators in Dusty Photoionized Environments. *PASP*, 110:1040–1045, September 1998.
- M. C. Bottorff, J. A. Baldwin, G. J. Ferland, J. W. Ferguson, and K. T. Korista. He II Reverberation in Active Galactic Nucleus Spectra. *ApJ*, 581:932–947, December 2002. doi: 10.1086/344408.
- M. C. Bottorff, G. J. Ferland, and J. P. Straley. Two-Photon Transitions and Continuous Emission from Hydrogenic Species. *PASP*, 118:1176–1179, August 2006. doi: 10.1086/506974.

- J. D. Bregman, L. J. Allamandola, F. C. Witteborn, A. G. G. M. Tielens, and T. R. Geballe. The infrared emission bands. II - A spatial and spectral study of the Orion bar. *ApJ*, 344:791–798, September 1989. doi: 10.1086/167844.
- D. A. G. Bruggeman. Berechnung verschiedener physikalischer Konstanten von heterogenen Substanzen. I. Dielektrizitätskonstanten und Leitfähigkeiten der Mischkörper aus isotropen Substanzen. *Annalen der Physik*, 416:636–664, 1935. doi: 10.1002/andp.19354160705.
- M. G. Burton, D. J. Hollenbach, and A. G. G. M. Tielens. Line emission from clumpy photodissociation regions. *ApJ*, 365:620–639, December 1990. doi: 10.1086/169516.
- A. G. W. Cameron. Elemental and Nuclidic Abundances in the Solar System. In *Essays in Nuclear Astrophysics*, page 23, 1982.
- J. A. Cardelli. The Abundance of Heavy Elements in Interstellar Gas. *Science*, 265:209, July 1994. doi: 10.1126/science.265.5169.209.
- J. A. Cardelli, B. D. Savage, F. C. Bruhweiler, A. M. Smith, D. C. Ebbets, K. R. Sembach, and U. J. Sofia. First results from the Goddard High-Resolution Spectrograph - Elemental abundances in the diffuse clouds toward XI Persei. *ApJ*, 377:L57–L60, August 1991. doi: 10.1086/186116.
- S. Cazaux and A. G. G. M. Tielens. Molecular Hydrogen Formation in the Interstellar Medium. *ApJ*, 575:L29–L32, August 2002. doi: 10.1086/342607.
- F. H. Chaffee, Jr. and R. E. White. A survey of interstellar neutral potassium. I - Abundances and physical conditions in clouds toward 188 early-type stars. *ApJS*, 50:169–198, November 1982. doi: 10.1086/190824.
- J. Clavel and M. Santos-Lleo. The turn-over of the 'big bump' in Fairall 9 and HS 1700 + 6416 - A genuine difference between Seyfert galaxies and quasars? *A&A*, 230:3–10, April 1990.
- R. E. S. Clegg and J. P. Harrington. The photo-ionization of He I (2 3S) in nebulae. *MNRAS*, 239:869–883, August 1989.
- R. E. S. Clegg, P. J. Storey, J. R. Walsh, and L. Neale. Measurement of the  $^{12}\text{C}/^{13}\text{C}$  ratio in planetary nebulae. *MNRAS*, 284:348–358, January 1997.
- L. L. Cowie and A. Songaila. High-resolution optical and ultraviolet absorption-line studies of interstellar gas. *ARA&A*, 24:499–535, 1986. doi: 10.1146/annurev.aa.24.090186.002435.
- G. Crinklaw, S. R. Federman, and C. L. Joseph. The depletion of calcium in the interstellar medium. *ApJ*, 424:748–753, April 1994. doi: 10.1086/173927.
- R. Cruddace, F. Paresce, S. Bowyer, and M. Lampton. On the opacity of the interstellar medium to ultrasoft X-rays and extreme-ultraviolet radiation. *ApJ*, 187:497–504, February 1974. doi: 10.1086/152659.
- A. Dalgarno, M. Yan, and W. Liu. Electron Energy Deposition in a Gas Mixture of Atomic and Molecular Hydrogen and Helium. *ApJS*, 125:237–256, November 1999. doi: 10.1086/313267.
- K. Davidson. On photoionization analyses of emission spectra of quasars. *ApJ*, 218:20–32, November 1977. doi: 10.1086/155653.
- K. Davidson and R. A. Fesen. Recent developments concerning the Crab Nebula. *ARA&A*, 23:119–146, 1985. doi: 10.1146/annurev.aa.23.090185.001003.
- S. Deguchi and W. D. Watson. Excitation of the hyperfine transitions of atomic hydrogen, deuterium, and ionized helium 3 by Lyman-alpha radiation. *ApJ*, 290:578–586, March 1985. doi: 10.1086/163014.
- K. P. Dere. Ionization rate coefficients for the elements hydrogen through zinc. *A&A*, 466:771–792, May 2007.
- K. P. Dere, E. Landi, H. E. Mason, B. C. Monsignori Fossi, and P. R. Young. CHIANTI - an atomic database for emission lines. *A&AS*, 125:149–173, October 1997.

- F.-X. Desert, F. Boulanger, and J. L. Puget. Interstellar dust models for extinction and emission. *A&A*, 237:215–236, October 1990.
- B. T. Draine and F. Bertoldi. Structure of Stationary Photodissociation Fronts. *ApJ*, 468:269, September 1996. doi: 10.1086/177689.
- B. T. Draine and A. Li. Infrared Emission from Interstellar Dust. I. Stochastic Heating of Small Grains. *ApJ*, 551:807–824, April 2001. doi: 10.1086/320227.
- B. T. Draine and B. Sutin. Collisional charging of interstellar grains. *ApJ*, 320:803–817, September 1987. doi: 10.1086/165596.
- H. W. Drawin. Influence of atom-atom collisions on the collisional-radiative ionization and recombination coefficients of hydrogen plasmas. *Zeitschrift fur Physik*, 225:483–493, October 1969. doi: 10.1007/BF01392775.
- E. Dwek, R. G. Arendt, D. J. Fixsen, T. J. Sodroski, N. Odegard, J. L. Weiland, W. T. Reach, M. G. Hauser, T. Kelsall, S. H. Moseley, R. F. Silverberg, R. A. Shafer, J. Ballester, D. Bazell, and R. Isaacman. Detection and Characterization of Cold Interstellar Dust and Polycyclic Aromatic Hydrocarbon Emission, from COBE Observations. *ApJ*, 475:565, February 1997. doi: 10.1086/303568.
- J. E. Dyson and D. A. Williams. *The physics of the interstellar medium, 2nd ed.* The graduate series in astronomy. Bristol: Institute of Physics Publishing, 1997. ISBN 0750303069.
- M. Elitzur and G. J. Ferland. Radiation pressure and emission clouds around active galactic nuclei. *ApJ*, 305:35–44, June 1986. doi: 10.1086/164226.
- M. Elvis, B. J. Wilkes, J. C. McDowell, R. F. Green, J. Bechtold, S. P. Willner, M. S. Oey, E. Polonski, and R. Cutri. Atlas of quasar energy distributions. *ApJS*, 95:1–68, November 1994. doi: 10.1086/192093.
- T. Elwert, G. J. Ferland, W. J. Henney, and R. J. R. Williams. Modeling dissociation of molecular hydrogen. In *IAU Symposium*, volume 235 of *IAU Symposium*, page 132P, 2005.
- V. G. Farafonov. Light Scattering by Multilayer Ellipsoids in the Rayleigh Approximation. *Optics and Spectroscopy*, 88:441–443, March 2000. doi: 10.1134/1.626814.
- S. R. Federman, A. E. Glassgold, and J. Kwan. Atomic to molecular hydrogen transition in interstellar clouds. *ApJ*, 227:466–473, January 1979. doi: 10.1086/156753.
- S. R. Federman, Y. Sheffer, D. L. Lambert, and R. L. Gilliland. Detection of boron, cobalt, and other weak interstellar lines toward Zeta Ophiuchi. *ApJ*, 413:L51–L54, August 1993. doi: 10.1086/186957.
- S. R. Federman, J. M. C. Rawlings, S. D. Taylor, and D. A. Williams. Synthesis of interstellar  $\text{CH}^+$  without OH. *MNRAS*, 279:L41–L46, April 1996.
- J. W. Ferguson and G. J. Ferland. Accurate Hydrogen Spectral Simulations with a Compact Model Atom. *ApJ*, 479:363, April 1997. doi: 10.1086/303880.
- J. W. Ferguson, K. T. Korista, D. A. Verner, and G. J. Ferland. Spectral Simulations from a Model Hydrogenic Atom. In G. Ferland and D. W. Savin, editors, *Spectroscopic Challenges of Photoionized Plasmas*, volume 247 of *Astronomical Society of the Pacific Conference Series*, page 287, 2001.
- G. Ferland. The Spectrum of a Single Photoionized Cloud. In G. Ferland and J. Baldwin, editors, *Quasars and Cosmology*, volume 162 of *Astronomical Society of the Pacific Conference Series*, page 147, 1999a.
- G. Ferland. Quasars and Starbursts in Young Giant Elliptical Galaxies. In E. Perez, R. M. Gonzalez Delgado, and G. Tenorio-Tagle, editors, *Star Formation Through Time*, volume 297 of *Astronomical Society of the Pacific Conference Series*, page 69, 2003.
- G. J. Ferland. N III line emission in planetary nebulae - Continuum fluorescence. *ApJ*, 389:L63–L65, April 1992. doi: 10.1086/186349.

- G. J. Ferland. A masing forbidden Fe XI line. *ApJS*, 88:49–52, September 1993. doi: 10.1086/191814.
- G. J. Ferland. Hydrogen Emission from Low Column Density Gas: Case C. *PASP*, 111:1524–1528, December 1999b. doi: 10.1086/316466.
- G. J. Ferland and M. Elitzur. Radiation pressure and the stability of broad-line region clouds. *ApJ*, 285: L11–L14, October 1984. doi: 10.1086/184354.
- G. J. Ferland and R. F. Mushotzky. Broad line region clouds and the absorbing material in NGC 4151. *ApJ*, 262:564–577, November 1982. doi: 10.1086/160448.
- G. J. Ferland and R. F. Mushotzky. Cosmic rays and the emission-line regions of active galactic nuclei. *ApJ*, 286:42–52, November 1984. doi: 10.1086/162574.
- G. J. Ferland and S. E. Persson. Implications of Ca II emission for physical conditions in the broad-line region of active galactic nuclei. *ApJ*, 347:656–673, December 1989. doi: 10.1086/168156.
- G. J. Ferland and G. A. Shields. Heavy element abundances of Nova Cygni 1975. *ApJ*, 226:172–185, November 1978. doi: 10.1086/156597.
- G. J. Ferland, G. A. Shields, and H. Netzer. Asymmetries of the emission lines of QSOs, Seyfert galaxies, and novae. *ApJ*, 232:382–388, September 1979. doi: 10.1086/157297.
- G. J. Ferland, D. L. Lambert, M. L. McCall, G. A. Shields, and M. H. Slovak. Physical conditions in the accretion disk of V603 Aquilae. *ApJ*, 260:794–806, September 1982. doi: 10.1086/160298.
- G. J. Ferland, B. M. Peterson, K. Horne, W. F. Welsh, and S. N. Nahar. Anisotropic line emission and the geometry of the broad-line region in active galactic nuclei. *ApJ*, 387:95–108, March 1992. doi: 10.1086/171063.
- G. J. Ferland, A. C. Fabian, and R. M. Johnstone. The Physical Conditions Within Dense Cold Clouds in Cooling Flows. *MNRAS*, 266:399, January 1994.
- G. J. Ferland, K. T. Korista, D. A. Verner, and A. Dalgarno. Charge Transfer between Neutral Atoms and Highly Ionized Species: Implications for ISO Observations. *ApJ*, 481:L115+, June 1997. doi: 10.1086/310655.
- G. J. Ferland, A. C. Fabian, and R. M. Johnstone. The physical conditions within dense cold clouds in cooling flows - II. *MNRAS*, 333:876–884, July 2002. doi: 10.1046/j.1365-8711.2002.05470.x.
- G. J. Ferland, A. C. Fabian, N. A. Hatch, R. M. Johnstone, R. L. Porter, P. A. M. van Hoof, and R. J. R. Williams. Collisional heating as the origin of filament emission in galaxy clusters. *MNRAS*, 392: 1475–1502, February 2009a. doi: 10.1111/j.1365-2966.2008.14153.x.
- G. J. Ferland, C. Hu, J.-M. Wang, J. A. Baldwin, R. L. Porter, P. A. M. van Hoof, and R. J. R. Williams. Implications of Infalling Fe II-Emitting Clouds in Active Galactic Nuclei: Anisotropic Properties. *ApJ*, 707:L82–L86, December 2009b. doi: 10.1088/0004-637X/707/1/L82.
- G. J. Ferland, R. L. Porter, P. A. M. van Hoof, R. J. R. Williams, N. P. Abel, M. L. Lykins, G. Shaw, W. J. Henney, and P. C. Stancil. The 2013 Release of Cloudy. *ArXiv e-prints*, February 2013.
- G. B. Field, D. W. Goldsmith, and H. J. Habing. Cosmic-Ray Heating of the Interstellar Gas. *ApJ*, 155: L149+, March 1969. doi: 10.1086/180324.
- P. J. Francis. The continuum slopes and evolution of active galactic nuclei. *ApJ*, 407:519–524, April 1993. doi: 10.1086/172533.
- A. E. Glassgold and W. D. Langer. Model calculations for diffuse molecular clouds. *ApJ*, 193:73–91, October 1974.
- O. Gnat and A. Sternberg. Time-dependent Ionization in Radiatively Cooling Gas. *ApJS*, 168:213–230, February 2007. doi: 10.1086/509786.
- N. Grevesse and E. Anders. Solar-system abundances of the elements - A new table. In C. J. Waddington, editor, *Cosmic Abundances of Matter*, volume 183 of *American Institute of Physics Conference*

- Series*, pages 1–8, 1989. doi: 10.1063/1.38013.
- N. Grevesse and A. Noels. Cosmic abundances of the elements. In S. Kubono and T. Kajino, editors, *Origin and Evolution of the Elements*, pages 15–25, January 1993.
- N. Grevesse and A. J. Sauval. Standard Solar Composition. *Space Science Reviews*, 85:161–174, May 1998. doi: 10.1023/A:1005161325181.
- N. Grevesse, M. Asplund, A. J. Sauval, and P. Scott. The chemical composition of the Sun. *Ap&SS*, 328: 179–183, July 2010. doi: 10.1007/s10509-010-0288-z.
- M. F. Gu, T. Holczer, E. Behar, and S. M. Kahn. Inner-Shell Absorption Lines of Fe VI-Fe XVI: A Many-Body Perturbation Theory Approach. *ApJ*, 641:1227–1232, April 2006. doi: 10.1086/500640.
- P. Guhathakurta and B. T. Draine. Temperature fluctuations in interstellar grains. I - Computational method and sublimation of small grains. *ApJ*, 345:230–244, October 1989. doi: 10.1086/167899.
- F. Haardt and P. Madau. Radiative Transfer in a Clumpy Universe. II. The Ultraviolet Extragalactic Background. *ApJ*, 461:20, April 1996. doi: 10.1086/177035.
- E. Habart, F. Boulanger, L. Verstraete, C. M. Walmsley, and G. Pineau des Forêts. Some empirical estimates of the H<sub>2</sub> formation rate in photon-dominated regions. *A&A*, 414:531–544, February 2004. doi: 10.1051/0004-6361:20031659.
- H. J. Habing. The interstellar radiation density between 912 Å and 2400 Å. *Bull. Astron. Inst. Netherlands*, 19:421, January 1968.
- F. Hamann and G. Ferland. The Chemical Evolution of QSOs and the Implications for Cosmology and Galaxy Formation. *ApJ*, 418:11, November 1993. doi: 10.1086/173366.
- R. J. Hanisch, A. Farris, E. W. Greisen, W. D. Pence, B. M. Schlesinger, P. J. Teuben, R. W. Thompson, and A. Warnock, III. Definition of the Flexible Image Transport System (FITS). *A&A*, 376:359–380, September 2001. doi: 10.1051/0004-6361:20010923.
- J. E. Hansen and L. D. Travis. Light scattering in planetary atmospheres. *Space Science Reviews*, 16: 527–610, October 1974. doi: 10.1007/BF00168069.
- J. P. Harrington. The scattering of resonance-line radiation in the limit of large optical depth. *MNRAS*, 162:43, 1973.
- T. I. Hasegawa and E. Herbst. New gas-grain chemical models of quiescent dense interstellar clouds - The effects of H<sub>2</sub> tunnelling reactions and cosmic ray induced desorption. *MNRAS*, 261:83–102, March 1993.
- T. I. Hasegawa, E. Herbst, and C. M. Leung. Models of gas-grain chemistry in dense interstellar clouds with complex organic molecules. *ApJS*, 82:167–195, September 1992. doi: 10.1086/191713.
- C. Heiles and R. Crutcher. Magnetic Fields in Diffuse HI and Molecular Clouds. In R. Wielebinski and R. Beck, editors, *Cosmic Magnetic Fields*, volume 664 of *Lecture Notes in Physics*, Berlin Springer Verlag, page 137, 2005. doi: 10.1007/11369875\_7.
- C. Heiles and T. H. Troland. The Millennium Arecibo 21 Centimeter Absorption-Line Survey. IV. Statistics of Magnetic Field, Column Density, and Turbulence. *ApJ*, 624:773–793, May 2005. doi: 10.1086/428896.
- W. J. Henney, S. J. Arthur, R. J. R. Williams, and G. J. Ferland. Self-Consistent Dynamic Models of Steady Ionization Fronts. I. Weak-D and Weak-R Fronts. *ApJ*, 621:328–347, March 2005. doi: 10.1086/427491.
- W. J. Henney, R. J. R. Williams, G. J. Ferland, G. Shaw, and C. R. O’Dell. Merged Ionization/Dissociation Fronts in Planetary Nebulae. *ApJ*, 671:L137–L140, December 2007. doi: 10.1086/525023.
- J. J. Hester. The Crab Nebula: An Astrophysical Chimera. *ARA&A*, 46:127–155, September 2008.

- D. J. Hollenbach, T. Takahashi, and A. G. G. M. Tielens. Low-density photodissociation regions. *ApJ*, 377: 192–209, August 1991. doi: 10.1086/170347.
- H. Holweger. Photospheric Abundances: Problems, Updates, Implications. In R. F. Wimmer-Schweingruber, editor, *Joint SOHO/ACE workshop "Solar and Galactic Composition"*, volume 598 of *American Institute of Physics Conference Series*, page 23, 2001. doi: 10.1063/1.1433974.
- E. N. Hubbard and R. C. Puetter. Theoretical quasar emission-line ratios. VII - Energy-balance models for finite hydrogen slabs. *ApJ*, 290:394–410, March 1985. doi: 10.1086/162997.
- D. G. Hummer. Non-coherent scattering-III. The effect of continuous absorption on the formation of spectral lines. *MNRAS*, 138:73, 1968.
- D. G. Hummer. A fast and accurate method for evaluating the nonrelativistic free-free Gaunt factor for hydrogenic ions. *ApJ*, 327:477–484, April 1988. doi: 10.1086/166210.
- W. T. Huntress, Jr. Laboratory studies of bimolecular reactions of positive ions in interstellar clouds, in comets, and in planetary atmospheres of reducing composition. *ApJS*, 33:495–514, April 1977. doi: 10.1086/190439.
- S. Ikeuchi and J. P. Ostriker. Evolution of the intergalactic medium - What happened during the epoch  $Z = 3-10$ ? *ApJ*, 301:522–543, February 1986. doi: 10.1086/163921.
- N. Indriolo, T. R. Geballe, T. Oka, and B. J. McCall.  $H_3^+$  in Diffuse Interstellar Clouds: A Tracer for the Cosmic-Ray Ionization Rate. *ApJ*, 671:1736–1747, December 2007. doi: 10.1086/523036.
- E. B. Jenkins. Element abundances in the interstellar atomic material. In D. J. Hollenbach and H. A. Thronson, Jr., editors, *Interstellar Processes*, volume 134 of *Astrophysics and Space Science Library*, pages 533–559, 1987.
- R. M. Johnstone, A. C. Fabian, A. C. Edge, and P. A. Thomas. The spectral signature of the cooling flow in Abell 478. *MNRAS*, 255:431–440, April 1992.
- M. Jura. Interstellar clouds containing optically thin  $H_2$ . *ApJ*, 197:575–580, May 1975. doi: 10.1086/153545.
- J. B. Kaler and G. H. Jacoby. Central star temperatures of low-excitation planetary nebulae. *ApJ*, 372: 215–224, May 1991. doi: 10.1086/169967.
- Kalkofen, W., editor. *Numerical radiative transfer*. Cambridge: University Press, 1987.
- T. Kato. Radiation from a hot, thin plasma from 1 to 250 Å. *ApJS*, 30:397–449, April 1976. doi: 10.1086/190367.
- G. S. Khromov. Planetary nebulae. *Space Science Reviews*, 51:339–423, December 1989. doi: 10.1007/BF00172024.
- J. Kingdon, G. J. Ferland, and W. A. Feibelman. Grains in ionized nebulae: Spectral line diagnostics. *ApJ*, 439:793–799, February 1995. doi: 10.1086/175217.
- J. B. Kingdon and G. J. Ferland. Temperature Fluctuations in Photoionized Nebulae. *ApJ*, 450:691, September 1995. doi: 10.1086/176175.
- J. B. Kingdon and G. J. Ferland. The Effects of Charge Transfer on the Thermal Equilibrium of Photoionized Nebulae. *ApJ*, 516:L107–L109, May 1999. doi: 10.1086/312008.
- D. Kiselman. NLTE effects on oxygen lines. *New Astronomy Review*, 45:559–563, July 2001. doi: 10.1016/S1387-6473(01)00127-0.
- R. Kisieliuss, A. Hibbert, G. J. Ferland, M. E. Foord, S. J. Rose, P. A. M. van Hoof, and F. P. Keenan. Inner-shell photoexcitation of FeXV and FeXVI. *MNRAS*, 344:696–706, September 2003. doi: 10.1046/j.1365-8711.2003.06801.x.

- K. Korista, J. Baldwin, G. Ferland, and D. Verner. An Atlas of Computed Equivalent Widths of Quasar Broad Emission Lines. *ApJS*, 108:401, February 1997a. doi: 10.1086/312966.
- K. Korista, G. Ferland, and J. Baldwin. Do the Broad Emission Line Clouds See the Same Continuum That We See? *ApJ*, 487:555, October 1997b. doi: 10.1086/304659.
- J. H. Krolik, C. F. McKee, and C. B. Tarter. Two-phase models of quasar emission line regions. *ApJ*, 249: 422–442, October 1981. doi: 10.1086/159303.
- R. L. Kurucz. Model atmospheres for G, F, A, B, and O stars. *ApJS*, 40:1–340, May 1979. doi: 10.1086/190589.
- R. L. Kurucz. New Lines, New Models, New Colors. In A. G. D. Philip, A. R. Upgren, and K. A. Janes, editors, *Precision Photometry: Astrophysics of the Galaxy*, page 27, 1991.
- F. La Franca, A. Franceschini, S. Cristiani, and R. Vio. On the relationship between the optical and X-ray luminosities of quasars. *A&A*, 299:19, July 1995.
- D. L. Lambert. Quantitative stellar spectroscopy with large optical telescopes. *Physica Scripta Volume T*, 47:186–198, 1993.
- E. Landi, G. Del Zanna, P. R. Young, K. P. Dere, and H. E. Mason. CHIANTI - An Atomic Database for Emission Lines. XII. Version 7 of the Database. *ApJ*, 744:99, January 2012. doi: 10.1088/0004-637X/744/2/99.
- J. Le Bourlot. Ortho to para conversion of  $H_2$  on interstellar grains. *A&A*, 360:656–662, August 2000.
- J. Le Bourlot, G. Pineau des Forêts, and D. R. Flower. The cooling of astrophysical media by  $H_2$ . *MNRAS*, 305:802–810, May 1999. doi: 10.1046/j.1365-8711.1999.02497.x.
- T.-G. Lee, N. Balakrishnan, R. C. Forrey, P. C. Stancil, D. R. Schultz, and G. J. Ferland. State-to-state rotational transitions in  $H_2+H_2$  collisions at low temperatures. *J. Chem. Phys.*, 125(11):114302, September 2006. doi: 10.1063/1.2338319.
- T.-G. Lee, N. Balakrishnan, R. C. Forrey, P. C. Stancil, G. Shaw, D. R. Schultz, and G. J. Ferland. Rotational Quenching Rate Coefficients for  $H_2$  in Collisions with  $H_2$  from 2 to 10,000 K. *ApJ*, 689: 1105–1111, December 2008. doi: 10.1086/592560.
- C. Leitherer, D. Schaerer, J. D. Goldader, R. M. G. Delgado, C. Robert, D. F. Kune, D. F. de Mello, D. Devost, and T. M. Heckman. Starburst99: Synthesis Models for Galaxies with Active Star Formation. *ApJS*, 123:3–40, July 1999. doi: 10.1086/313233.
- V. Luridiana, S. Simón-Díaz, M. Cerviño, R. M. G. Delgado, R. L. Porter, and G. J. Ferland. Fluorescent Excitation of Balmer Lines in Gaseous Nebulae: Case D. *ApJ*, 691:1712–1728, February 2009. doi: 10.1088/0004-637X/691/2/1712.
- D. C. V. Mallik and M. Peimbert. Filling factor determinations and their effects on planetary nebula studies. *Revista Mexicana de Astronomía y Astrofísica*, 16:111–121, December 1988.
- P. R. Maloney, D. J. Hollenbach, and A. G. G. M. Tielens. X-Ray-irradiated Molecular Gas. I. Physical Processes and General Results. *ApJ*, 466:561, July 1996. doi: 10.1086/177532.
- P. G. Martin. *Cosmic dust. Its impact on astronomy*. Oxford Studies in Physics. Oxford: Clarendon Press, 1978.
- P. G. Martin and F. Rouleau. Extreme Ultraviolet Opacity with Interstellar Dust. In R. F. Malina and S. Bowyer, editors, *Extreme Ultraviolet Astronomy*, page 341, 1991.
- J. C. Mather, D. J. Fixsen, R. A. Shafer, C. Mosier, and D. T. Wilkinson. Calibrator Design for the COBE Far-Infrared Absolute Spectrophotometer (FIRAS). *ApJ*, 512:511–520, February 1999. doi: 10.1086/306805.
- W. G. Mathews and G. J. Ferland. What heats the hot phase in active nuclei? *ApJ*, 323:456–467, December 1987. doi: 10.1086/165843.

- J. S. Mathis. Abundances of N, S, and He, and relative stellar temperatures, in low-excitation nebulae. *ApJ*, 261:195–199, October 1982. doi: 10.1086/160330.
- J. S. Mathis, W. Rumpl, and K. H. Nordsieck. The size distribution of interstellar grains. *ApJ*, 217: 425–433, October 1977. doi: 10.1086/155591.
- F. Matteucci and L. Greggio. Relative roles of type I and II supernovae in the chemical enrichment of the interstellar gas. *A&A*, 154:279–287, January 1986.
- F. Matteucci and A. Tornambe. Chemical evolution of elliptical galaxies. *A&A*, 185:51–60, October 1987.
- B. J. McCall, A. J. Huneycutt, R. J. Saykally, T. R. Geballe, N. Djuric, G. H. Dunn, J. Semaniak, O. Novotny, A. Al-Khalili, A. Ehlerding, F. Hellberg, S. Kalhori, A. Neau, R. Thomas, F. Österdahl, and M. Larsson. An enhanced cosmic-ray flux towards  $\zeta$  Persei inferred from a laboratory study of the  $\text{H}_3^+ - \text{e}^-$  recombination rate. *Nature*, 422:500–502, April 2003. doi: 10.1038/nature01498.
- C. F. McKee. The Dynamical Structure and Evolution of Giant Molecular Clouds. In C. J. Lada and N. D. Kylafis, editors, *NATO ASIC Proc. 540: The Origin of Stars and Planetary Systems*, page 29, 1999.
- R. Mewe. Interpolation Formulae for the Electron Impact Excitation of Ions in the H-, He-, Li-, and Ne-Sequences. *A&A*, 20:215, August 1972.
- D. M. Meyer, M. Jura, and J. A. Cardelli. The Definitive Abundance of Interstellar Oxygen. *ApJ*, 493:222, January 1998. doi: 10.1086/305128.
- D. Mihalas. *Non-LTE model atmospheres for B and O stars*, volume NCAR/STR-76 of *Colorado, Tech. Notes*. Boulder, Colorado: Natl. Cent. Atmos. Res., 1972. 7+114 p.
- D. Mihalas. *Stellar atmospheres /2nd edition/*. San Francisco, W. H. Freeman and Co., 1978. 650 p.
- J. S. Mihalzski and G. J. Ferland. Density inhomogeneities and the deduced chemical composition of planetary nebulae. *PASP*, 95:284–288, May 1983. doi: 10.1086/131159.
- K. Mitsuda, H. Inoue, K. Koyama, K. Makishima, M. Matsuoka, Y. Ogawara, K. Suzuki, Y. Tanaka, N. Shibasaki, and T. Hirano. Energy spectra of low-mass binary X-ray sources observed from TENMA. *PASJ*, 36:741–759, 1984.
- M. Moraes and M. Diaz. HR Del Remnant Anatomy Using Two-Dimensional Spectral Data and Three-Dimensional Photoionization Shell Models. *AJ*, 138:1541–1556, December 2009. doi: 10.1088/0004-6256/138/6/1541.
- C. Morisset. Cloudy\_3D, a new pseudo-3D photoionization code. In M. J. Barlow & R. H. Méndez, editor, *Planetary Nebulae in our Galaxy and Beyond*, volume 234 of *IAU Symposium*, pages 467–468, 2006. doi: 10.1017/S1743921306003772.
- C. Morisset and G. Stasinska. An atlas of synthetic line profiles of Planetary Nebulae. *Revista Mexicana de Astronomia y Astrofisica*, 44:171–180, April 2008.
- R. Morrison and D. McCammon. Interstellar photoelectric absorption cross sections, 0.03–10 keV. *ApJ*, 270:119–122, July 1983. doi: 10.1086/161102.
- K. L. Mullman, J. E. Lawler, J. Zsargo, and S. R. Federman. Absolute Vacuum Ultraviolet Oscillator Strengths in CO II and the Interstellar Cobalt Abundance. *ApJ*, 500:1064, June 1998. doi: 10.1086/305780.
- J. F. Navarro, C. S. Frenk, and S. D. M. White. The Structure of Cold Dark Matter Halos. *ApJ*, 462:563, May 1996. doi: 10.1086/177173.
- E. Novotny. *Introduction to stellar atmospheres and interiors*. New York: Oxford University Press, 1973.
- H. Nussbaumer and P. J. Storey. Dielectronic recombination at low temperatures. II Recombination coefficients for lines of C, N, O. *A&AS*, 56:293–312, June 1984.
- D. Osterbrock and E. Flather. Electron Densities in the Orion NEBULA.II. *ApJ*, 129:26, January 1959. doi: 10.1086/146592.

- D. E. Osterbrock and G. J. Ferland. *Astrophysics of gaseous nebulae and active galactic nuclei*, 2nd. ed. Sausalito, CA: University Science Books, 2006.
- D. E. Osterbrock, H. D. Tran, and S. Veilleux. Faint emission lines in the spectrum of the Orion Nebula and the abundances of some of the rarer elements. *ApJ*, 389:305–324, April 1992. doi: 10.1086/171206.
- J. P. Ostriker and S. Ikeuchi. Physical properties of the intergalactic medium and the Lyman-alpha absorbing clouds. *ApJ*, 268:L63–L68, May 1983. doi: 10.1086/184030.
- P. J. E. Peebles. *Physical cosmology*. Princeton Series in Physics. Princeton, N.J.: Princeton University Press, 1971.
- E. W. Pellegrini, J. A. Baldwin, C. L. Brogan, M. M. Hanson, N. P. Abel, G. J. Ferland, H. B. Nemala, G. Shaw, and T. H. Troland. A Magnetically Supported Photodissociation Region in M17. *ApJ*, 658: 1119–1135, April 2007. doi: 10.1086/511258.
- R. M. Pengelly and M. J. Seaton. Recombination spectra, II. *MNRAS*, 127:165, 1964.
- D. Pequignot and M. Dennefeld. The Crab Nebula. *A&A*, 120:249–262, April 1983.
- D. Pequignot, P. Petitjean, and C. Boisson. Total and effective radiative recombination coefficients. *A&A*, 251:680–688, November 1991.
- M. Pettini and D. V. Bowen. A New Measurement of the Primordial Abundance of Deuterium: Toward Convergence with the Baryon Density from the Cosmic Microwave Background? *ApJ*, 560:41–48, October 2001. doi: 10.1086/322510.
- R. L. Porter and G. J. Ferland. Revisiting He-like X-Ray Emission-Line Plasma Diagnostics. *ApJ*, 664: 586–595, July 2007. doi: 10.1086/518882.
- R. L. Porter, R. P. Bauman, G. J. Ferland, and K. B. MacAdam. Theoretical He I Emissivities in the Case B Approximation. *ApJ*, 622:L73–L75, March 2005. doi: 10.1086/429370.
- R. L. Porter, G. J. Ferland, S. B. Kraemer, B. K. Armentrout, K. A. Arnaud, and T. J. Turner. A Cloudy/XSPEC Interface. *PASP*, 118:920–923, June 2006. doi: 10.1086/506333.
- R. L. Porter, G. J. Ferland, P. J. Storey, and M. J. Detisch. Improved He I emissivities in the case B approximation. *MNRAS*, 425:L28–L31, September 2012.
- R. C. Puetter. Theoretical quasar emission line ratios. IV - General asymptotic escape probabilities and the effects of linear Stark broadening. *ApJ*, 251:446–450, December 1981. doi: 10.1086/159482.
- T. Rauch. Implication of light metals (Li-Ca) on NLTE model atmospheres of compact hot stars. *A&A*, 320:237–248, April 1997.
- T. Rauch. A grid of synthetic ionizing spectra for very hot compact stars from NLTE model atmospheres. *A&A*, 403:709–714, May 2003. doi: 10.1051/0004-6361:20030412.
- C. T. Richardson, J. A. Baldwin, G. J. Ferland, E. D. Loh, C. A. Kuehn, A. C. Fabian, and P. Salomé. The Nature of the H<sub>2</sub>-Emitting Gas in the Crab Nebula. *ArXiv e-prints*, December 2012.
- M. Röllig, N. P. Abel, T. Bell, F. Bensch, J. Black, G. J. Ferland, B. Jonkheid, I. Kamp, M. J. Kaufman, J. Le Bourlot, F. Le Petit, R. Meijerink, O. Morata, V. Ossenkopf, E. Roueff, G. Shaw, M. Spaans, A. Sternberg, J. Stutzki, W.-F. Thi, E. F. van Dishoeck, P. A. M. van Hoof, S. Viti, and M. G. Wolfire. A photon dominated region code comparison study. *A&A*, 467:187–206, May 2007. doi: 10.1051/0004-6361:20065918.
- F. Rouleau and P. G. Martin. Shape and clustering effects on the optical properties of amorphous carbon. *ApJ*, 377:526–540, August 1991. doi: 10.1086/170382.
- T. Rowan. *Functional Stability Analysis of Numerical Algorithms*. PhD thesis, Univ. Texas at Austin, January 1990.
- R. H. Rubin. The effect of heavy element opacity on the structure of H II regions. *ApJ*, 274:671–676, November 1983. doi: 10.1086/161480.

- R. H. Rubin, J. P. Simpson, M. R. Haas, and E. F. Erickson. Axisymmetric model of the ionized gas in the Orion Nebula. *ApJ*, 374:564–579, June 1991. doi: 10.1086/170145.
- R. H. Rubin, R. J. Dufour, and D. K. Walter. Silicon and carbon abundances in the Orion nebula. *ApJ*, 413: 242–250, August 1993. doi: 10.1086/172992.
- G. B. Rybicki and A. P. Lightman. *Radiative processes in astrophysics*. New York, Wiley-Interscience, 1979. 393 p.
- B. D. Savage and K. R. Sembach. Interstellar Abundances from Absorption-Line Observations with the Hubble Space Telescope. *ARA&A*, 34:279–330, 1996. doi: 10.1146/annurev.astro.34.1.279.
- F. L. Schöier, F. F. S. van der Tak, E. F. van Dishoeck, and J. H. Black. An atomic and molecular database for analysis of submillimetre line observations. *A&A*, 432:369–379, March 2005.
- A. Schuster. Radiation Through a Foggy Atmosphere. *ApJ*, 21:1, January 1905. doi: 10.1086/141186.
- W. A. Schutte, A. G. G. M. Tielens, and L. J. Allamandola. Theoretical modeling of the infrared fluorescence from interstellar polycyclic aromatic hydrocarbons. *ApJ*, 415:397–414, September 1993. doi: 10.1086/173173.
- S. Sciortino, G. S. Vaiana, F. R. Harnden, Jr., M. Ramella, C. Morossi, R. Rosner, and J. H. M. M. Schmitt. Relationship between optical and X-ray properties of O-type stars surveyed with the Einstein Observatory. *ApJ*, 361:621–643, October 1990. doi: 10.1086/169225.
- K. Sellgren, A. T. Tokunaga, and Y. Nakada. The 3.3 micron feature, H<sub>2</sub>, and ionized gas in the Orion bar. *ApJ*, 349:120–125, January 1990. doi: 10.1086/168299.
- F. H. Sellmaier, T. Yamamoto, A. W. A. Pauldrach, and R. H. Rubin. A possible solution for the [Ne III] problem in HII regions. *A&A*, 305:L37+, January 1996.
- N. I. Shakura and R. A. Sunyaev. Black holes in binary systems. Observational appearance. *A&A*, 24: 337–355, 1973.
- G. Shaw, G. J. Ferland, N. P. Abel, P. C. Stancil, and P. A. M. van Hoof. Molecular Hydrogen in Star-forming Regions: Implementation of its Microphysics in CLOUDY. *ApJ*, 624:794–807, May 2005. doi: 10.1086/429215.
- G. Shaw, G. J. Ferland, R. Srianand, N. P. Abel, P. A. M. van Hoof, and P. C. Stancil. On the Enhanced Cosmic-Ray Ionization Rate in the Diffuse Cloud toward  $\zeta$  Persei. *ApJ*, 675:405–412, March 2008. doi: 10.1086/526395.
- J. M. Shull. Heating and ionization by X-ray photoelectrons. *ApJ*, 234:761–764, December 1979. doi: 10.1086/157553.
- J. M. Shull and M. E. van Steenberg. X-ray secondary heating and ionization in quasar emission-line clouds. *ApJ*, 298:268–274, November 1985. doi: 10.1086/163605.
- M. Sikora, M. C. Begelman, and B. Rudak. Relativistic neutrons in active galactic nuclei. *ApJ*, 341: L33–L36, June 1989. doi: 10.1086/185451.
- T. P. Snow and A. N. Witt. Interstellar Depletions Updated: Where All the Atoms Went. *ApJ*, 468:L65+, September 1996. doi: 10.1086/310225.
- T. P. Snow, J. D. Destree, and A. G. Jensen. The Abundance of Interstellar Fluorine and Its Implications. *ApJ*, 655:285–298, January 2007. doi: 10.1086/510187.
- T. P. Snow, Jr. and S. L. Dodgen. A search for interstellar scandium. *ApJ*, 237:708–710, May 1980. doi: 10.1086/157918.
- T. P. Snow, Jr. and D. G. York. The detection of interstellar fluorine in the line of sight toward Delta Scorpii. *ApJ*, 247:L39–L41, July 1981. doi: 10.1086/183585.
- L. Spitzer. *Physical processes in the interstellar medium*. New York Wiley-Interscience, 1978. 333 p.

- L. Spitzer, Jr. Average density along interstellar lines of sight. *ApJ*, 290:L21–L24, March 1985. doi: 10.1086/184434.
- L. J. Spitzer. The Temperature of Interstellar Matter. I. *ApJ*, 107:6, January 1948. doi: 10.1086/144984.
- L. J. Spitzer and M. G. Tomasko. Heating of H I Regions by Energetic Particles. *ApJ*, 152:971, June 1968. doi: 10.1086/149610.
- U. Springmann. Multiple resonance line scattering and the 'momentum problem' in Wolf-Rayet star winds. *A&A*, 289:505–523, September 1994.
- G. Stasińska and R. Szczerba. The dust content of planetary nebulae: a reappraisal. *A&A*, 352:297–307, December 1999.
- W. Steenbock and H. Holweger. Statistical equilibrium of lithium in cool stars of different metallicity. *A&A*, 130:319–323, January 1984.
- A. Sternberg and D. A. Neufeld. The Ratio of Ortho- to Para-H<sub>2</sub> in Photodissociation Regions. *ApJ*, 516: 371–380, May 1999. doi: 10.1086/307115.
- R. Stognienko, T. Henning, and V. Ossenkopf. Optical properties of coagulated particles. *A&A*, 296:797, April 1995.
- P. J. Storey and D. G. Hummer. Recombination line intensities for hydrogenic ions-IV. Total recombination coefficients and machine-readable tables for  $Z=1$  to 8. *MNRAS*, 272:41–48, January 1995. on the web at <http://adc.gsfc.nasa.gov/adc-cgi/cat.pl?/catalogs/6/6064/>.
- R. H. Stoy. The temperatures of the nuclei of planetary nebulae. *MNRAS*, 93:588, June 1933.
- A. Suchkov, R. J. Allen, and T. M. Heckman. Cosmic-ray-dominated dense molecular gas in normal and starburst galaxies. *ApJ*, 413:542–547, August 1993. doi: 10.1086/173023.
- J. Takahashi. The Ortho/Para Ratio of H<sub>2</sub> Newly Formed on Dust Grains. *ApJ*, 561:254–263, November 2001. doi: 10.1086/322954.
- J. Takahashi and H. Uehara. H<sub>2</sub> Emission Spectra with New Formation Pumping Models. *ApJ*, 561: 843–857, November 2001. doi: 10.1086/323364.
- C. B. Tarter. *Radiative Transfer in a Gas Excited by X-Rays*. PhD thesis, AA(CORNELL UNIVERSITY.), 1967.
- C. B. Tarter, W. H. Tucker, and E. E. Salpeter. The Interaction of X-Ray Sources with Optically Thin Environments. *ApJ*, 156:943, June 1969. doi: 10.1086/150026.
- A. G. G. M. Tielens and D. Hollenbach. Photodissociation regions. I - Basic model. II - A model for the Orion photodissociation region. *ApJ*, 291:722–754, April 1985a. doi: 10.1086/163111.
- A. G. G. M. Tielens and D. Hollenbach. Photodissociation Regions - Part Two - a Model for the Orion Photodissociation Region. *ApJ*, 291:747, April 1985b. doi: 10.1086/163112.
- C. A. Tout, O. R. Pols, P. P. Eggleton, and Z. Han. Zero-age main-sequence radii and luminosities as analytic functions of mass and metallicity. *MNRAS*, 281:257–262, July 1996.
- P. A. M. van Hoof. *Photo-ionization studies of nebulae*. PhD thesis, Rijksuniversiteit Groningen, 1997.
- P. A. M. van Hoof, J. C. Weingartner, P. G. Martin, K. Volk, and G. J. Ferland. Grains in Photo-Ionized Environments. In G. Ferland and D. W. Savin, editors, *Spectroscopic Challenges of Photoionized Plasmas*, volume 247 of *Astronomical Society of the Pacific Conference Series*, page 363, 2001.
- P. A. M. van Hoof, J. C. Weingartner, P. G. Martin, K. Volk, and G. J. Ferland. Grain size distributions and photoelectric heating in ionized media. *MNRAS*, 350:1330–1341, June 2004. doi: 10.1111/j.1365-2966.2004.07734.x.
- H. Vedel, U. Hellsten, and J. Sommer-Larsen. Formation of disc galaxies in the presence of a background UVX radiation field. *MNRAS*, 271:743, December 1994.

- D. A. Verner and D. G. Yakovlev. Analytic FITS for partial photoionization cross sections. *A&AS*, 109: 125–133, January 1995.
- D. A. Verner, G. J. Ferland, K. T. Korista, and D. G. Yakovlev. Atomic Data for Astrophysics. II. New Analytic FITS for Photoionization Cross Sections of Atoms and Ions. *ApJ*, 465:487, July 1996. doi: 10.1086/177435.
- E. M. Verner, D. A. Verner, K. T. Korista, J. W. Ferguson, F. Hamann, and G. J. Ferland. Numerical Simulations of Fe II Emission Spectra. *ApJS*, 120:101–112, January 1999. doi: 10.1086/313171.
- G. S. Voronov. A Practical Fit Formula for Ionization Rate Coefficients of Atoms and Ions by Electron Impact:  $Z = 1-28$ . *Atomic Data and Nuclear Data Tables*, 65:1, 1997. doi: 10.1006/adnd.1997.0732.
- N. V. Voshchinnikov and J. S. Mathis. Calculating Cross Sections of Composite Interstellar Grains. *ApJ*, 526:257–264, November 1999. doi: 10.1086/307997.
- L. Vriens and A. H. M. Smeets. Cross-section and rate formulas for electron-impact ionization, excitation, deexcitation, and total depopulation of excited atoms. *Phys. Rev. A*, 22:940–951, September 1980. doi: 10.1103/PhysRevA.22.940.
- D. Vranceanu and M. R. Flannery. Classical and quantal collisional Stark mixing at ultralow energies. *Phys. Rev. A*, 63(3):032701, March 2001. doi: 10.1103/PhysRevA.63.032701.
- W. R. Webber. A New Estimate of the Local Interstellar Energy Density and Ionization Rate of Galactic Cosmic Rays. *ApJ*, 506:329–334, October 1998. doi: 10.1086/306222.
- J. C. Weingartner and B. T. Draine. Photoelectric Emission from Interstellar Dust: Grain Charging and Gas Heating. *ApJS*, 134:263–281, June 2001a. doi: 10.1086/320852.
- J. C. Weingartner and B. T. Draine. Dust Grain-Size Distributions and Extinction in the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud. *ApJ*, 548:296–309, February 2001b. doi: 10.1086/318651.
- J. C. Weingartner, B. T. Draine, and D. K. Barr. Photoelectric Emission from Dust Grains Exposed to Extreme Ultraviolet and X-Ray Radiation. *ApJ*, 645:1188–1197, July 2006. doi: 10.1086/504420.
- J. C. Weisheit. X-Ray Ionization Cross-Sections and Ionization Equilibrium Equations Modified by Auger Transitions. *ApJ*, 190:735–740, June 1974. doi: 10.1086/152933.
- R. E. White. Interstellar lithium - Differential depletion in diffuse clouds. *ApJ*, 307:777–786, August 1986. doi: 10.1086/164463.
- B. J. Wilkes, H. Tananbaum, D. M. Worrall, Y. Avni, M. S. Oey, and J. Flanagan. The Einstein database of IPC x-ray observations of optically selected and radio-selected quasars, 1. *ApJS*, 92:53–109, May 1994. doi: 10.1086/191959.
- D. T. Wilkinson. Measurements of cosmic microwave radiation. In M. P. Ulmer, editor, *13th Texas Symposium on Relativistic Astrophysics*, pages 209–218, 1987.
- J. P. Williams, E. A. Bergin, P. Caselli, P. C. Myers, and R. Plume. The Ionization Fraction in Dense Molecular Gas. I. Low-Mass Cores. *ApJ*, 503:689, August 1998. doi: 10.1086/306034.
- R. E. Williams. The Ionization and Thermal Equilibrium of a Gas Excited by Ultraviolet Synchrotron Radiation. *ApJ*, 147:556, February 1967. doi: 10.1086/149035.
- R. E. Williams. Incorporation of density fluctuations into photoionization calculations. *ApJ*, 392:99–105, June 1992. doi: 10.1086/171409.
- B. J. Wills, H. Netzer, and D. Wills. Broad emission features in QSOs and active galactic nuclei. II - New observations and theory of Fe II and H I emission. *ApJ*, 288:94–116, January 1985. doi: 10.1086/162767.
- T. L. Wilson and R. Rood. Abundances in the Interstellar Medium. *ARA&A*, 32:191–226, 1994. doi: 10.1146/annurev.aa.32.090194.001203.

- D. M. Worrall, H. Tananbaum, P. Giommi, and G. Zamorani. X-ray studies of quasars with the Einstein Observatory. IV - X-ray dependence on radio emission. *ApJ*, 313:596–606, February 1987. doi: 10.1086/164999.
- S. A. Wrathmall, A. Gusdorf, and D. R. Flower. The excitation of molecular hydrogen by atomic hydrogen in astrophysical media. *MNRAS*, 382:133–138, November 2007. doi: 10.1111/j.1365-2966.2007.12420.x.
- Y. Xu and R. McCray. Energy degradation of fast electrons in hydrogen gas. *ApJ*, 375:190–201, July 1991. doi: 10.1086/170180.
- D. G. York, M. Meneguzzi, and T. P. Snow. Upper limits for interstellar boron and beryllium abundances toward zeta Ophiuchi. *ApJ*, 255:524–526, April 1982. doi: 10.1086/159852.
- G. Zamorani, J. P. Henry, T. Maccacaro, H. Tananbaum, A. Soltan, Y. Avni, J. Liebert, J. Stocke, P. A. Strittmatter, R. J. Weymann, M. G. Smith, and J. J. Condon. X-ray studies of quasars with the Einstein Observatory. II. *ApJ*, 245:357–374, April 1981. doi: 10.1086/158815.
- W. Zheng, G. A. Kriss, R. C. Telfer, J. P. Grimes, and A. F. Davidsen. A Composite HST Spectrum of Quasars. *ApJ*, 475:469, February 1997. doi: 10.1086/303560.
- J. Zsargó and S. R. Federman. Nonthermal Chemistry in Diffuse Clouds with Low Molecular Abundances. *ApJ*, 589:319–337, May 2003. doi: 10.1086/374617.