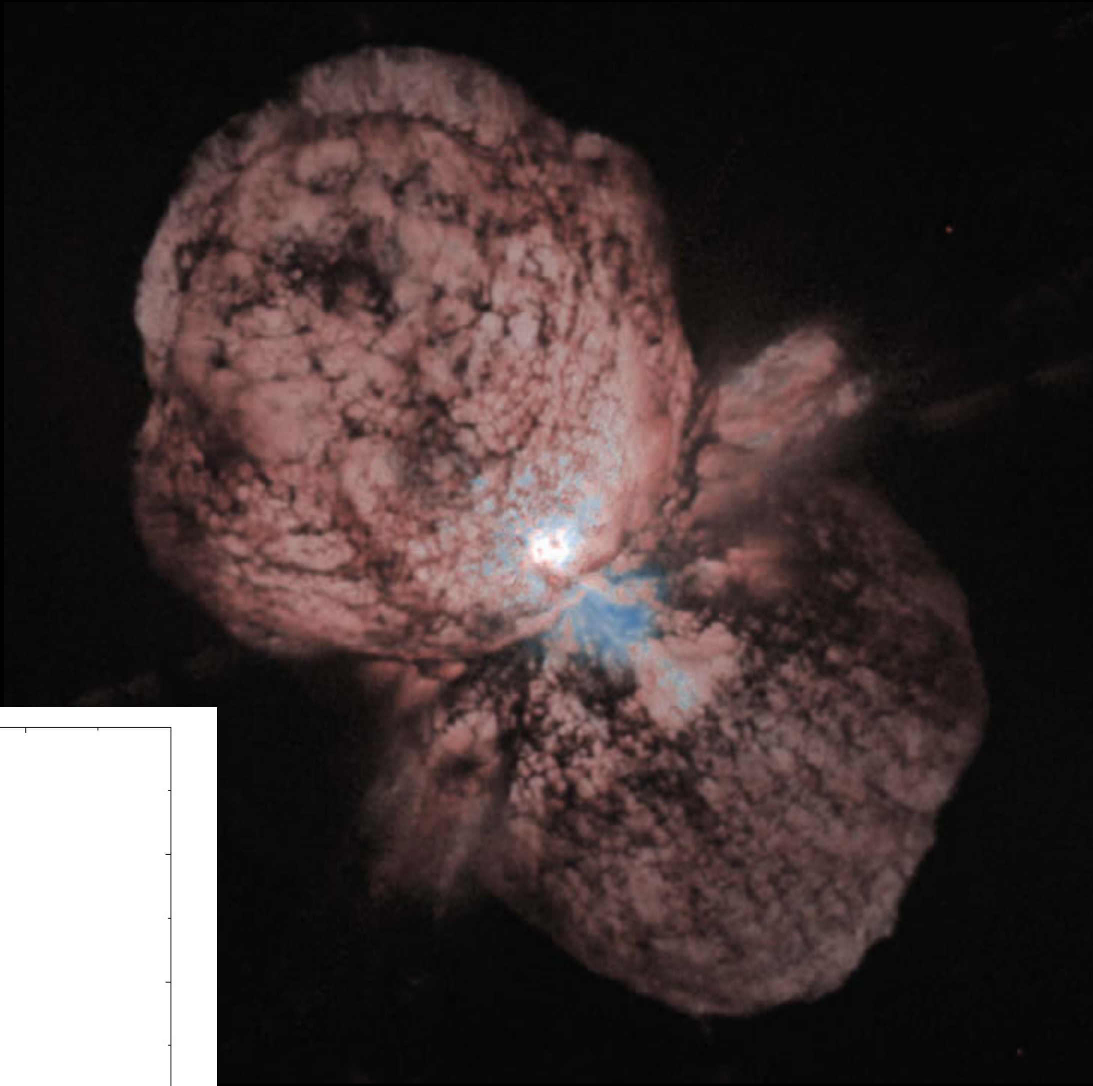
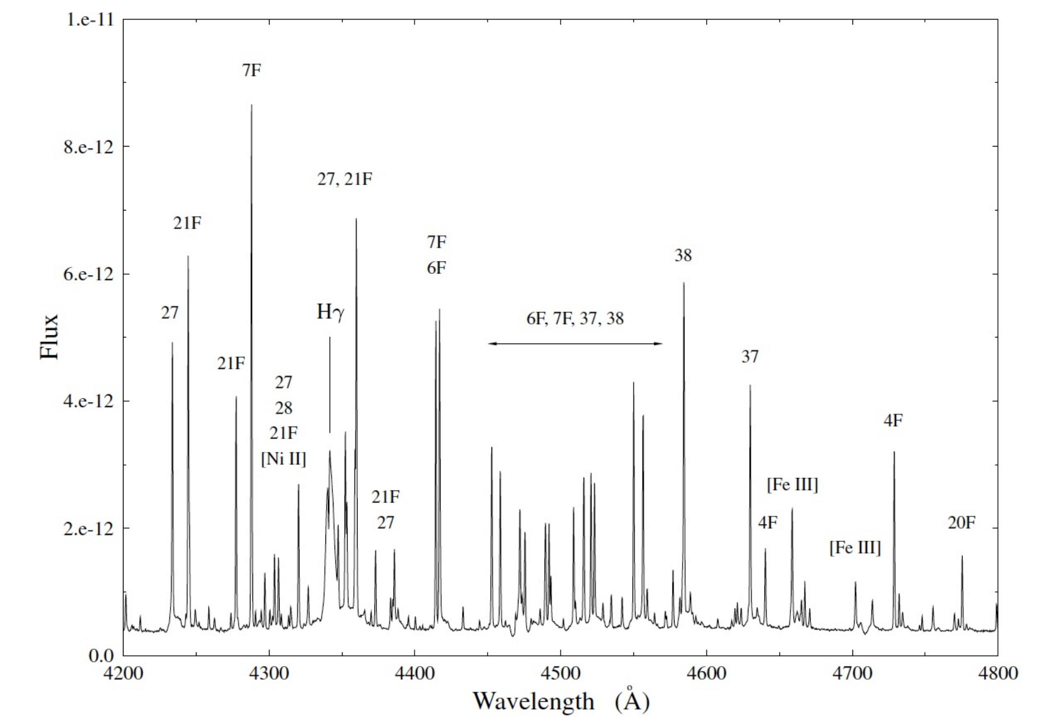
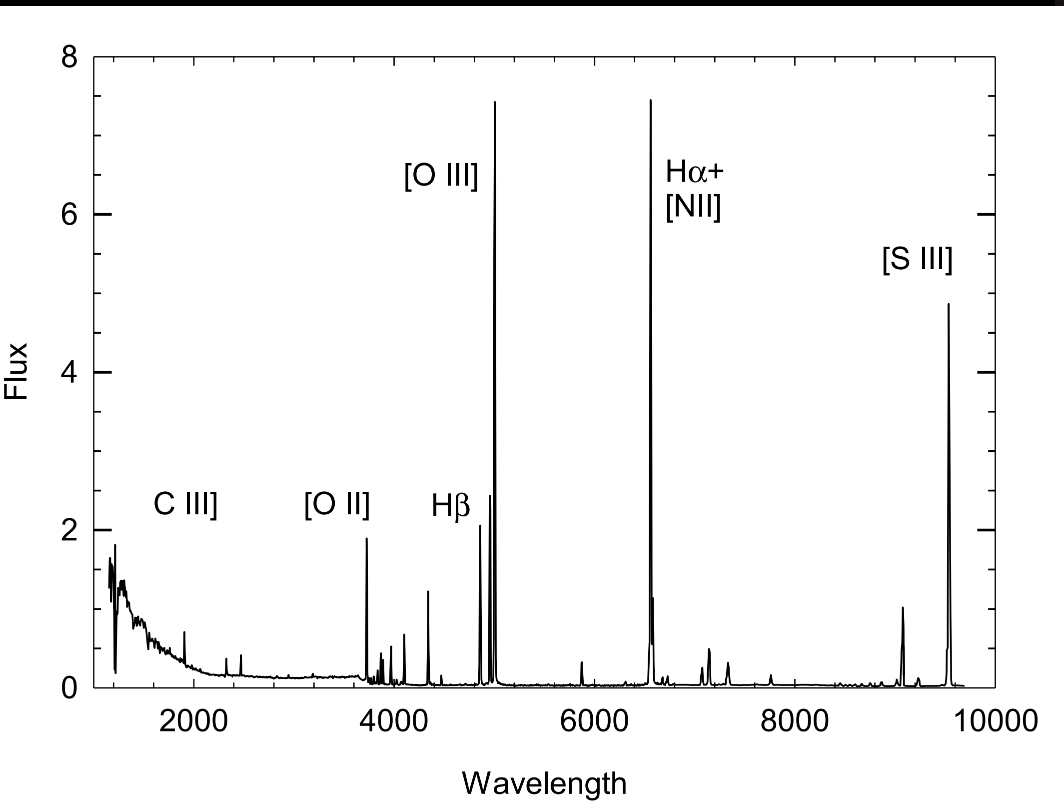
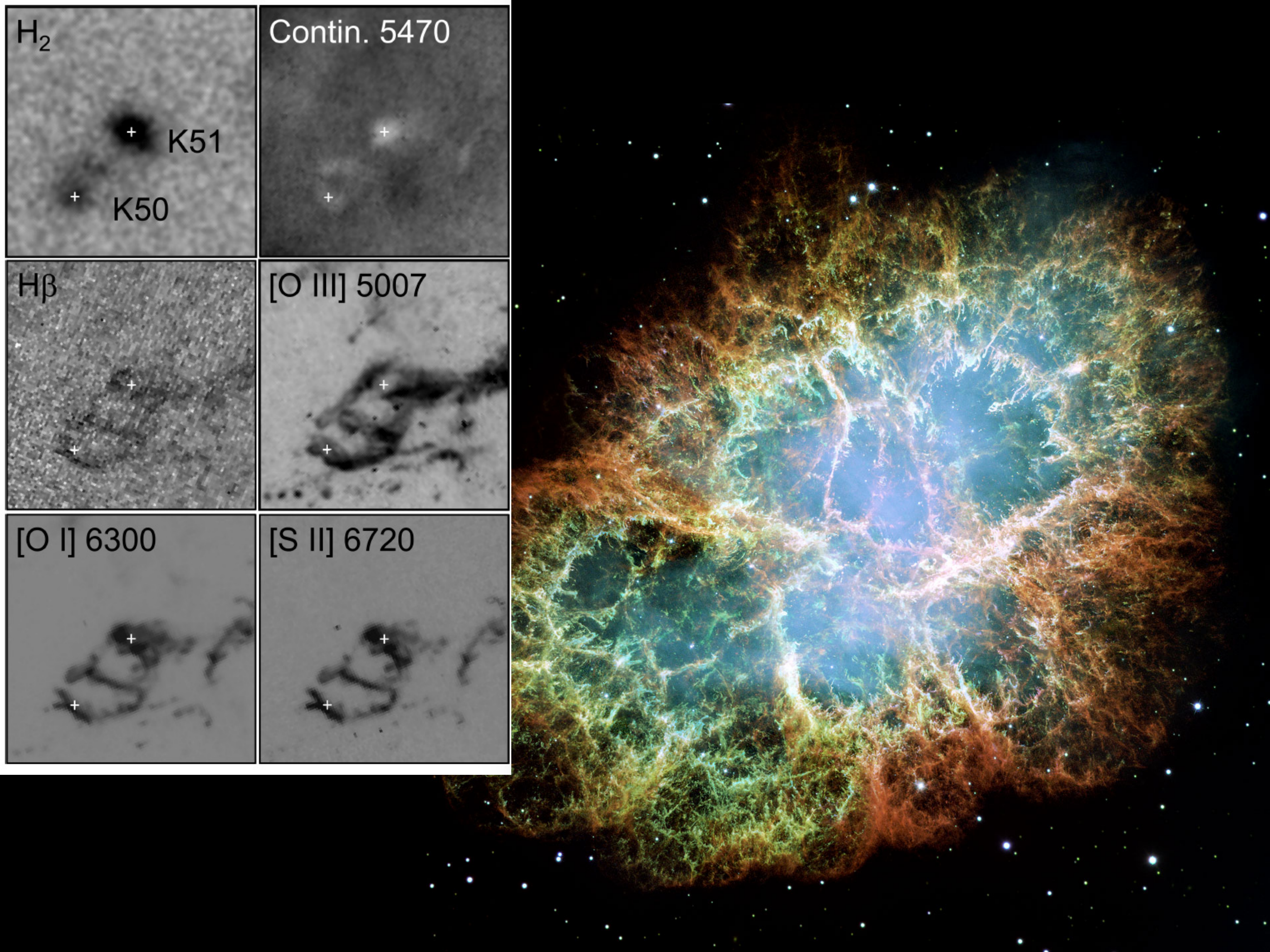
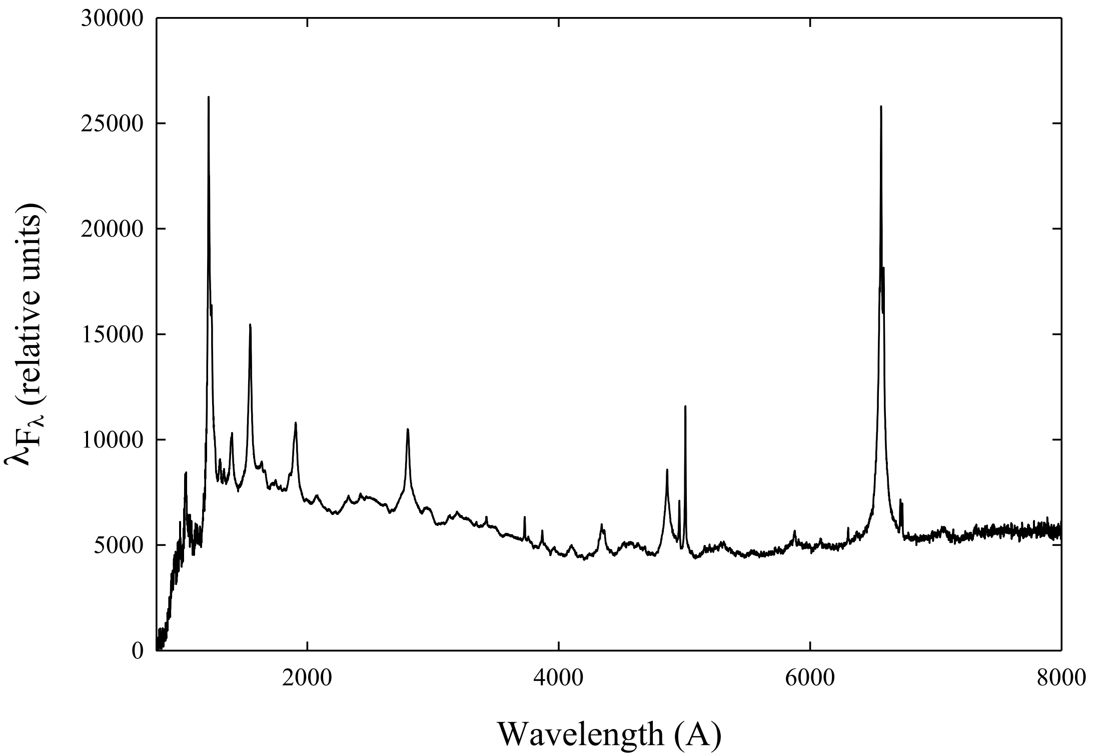




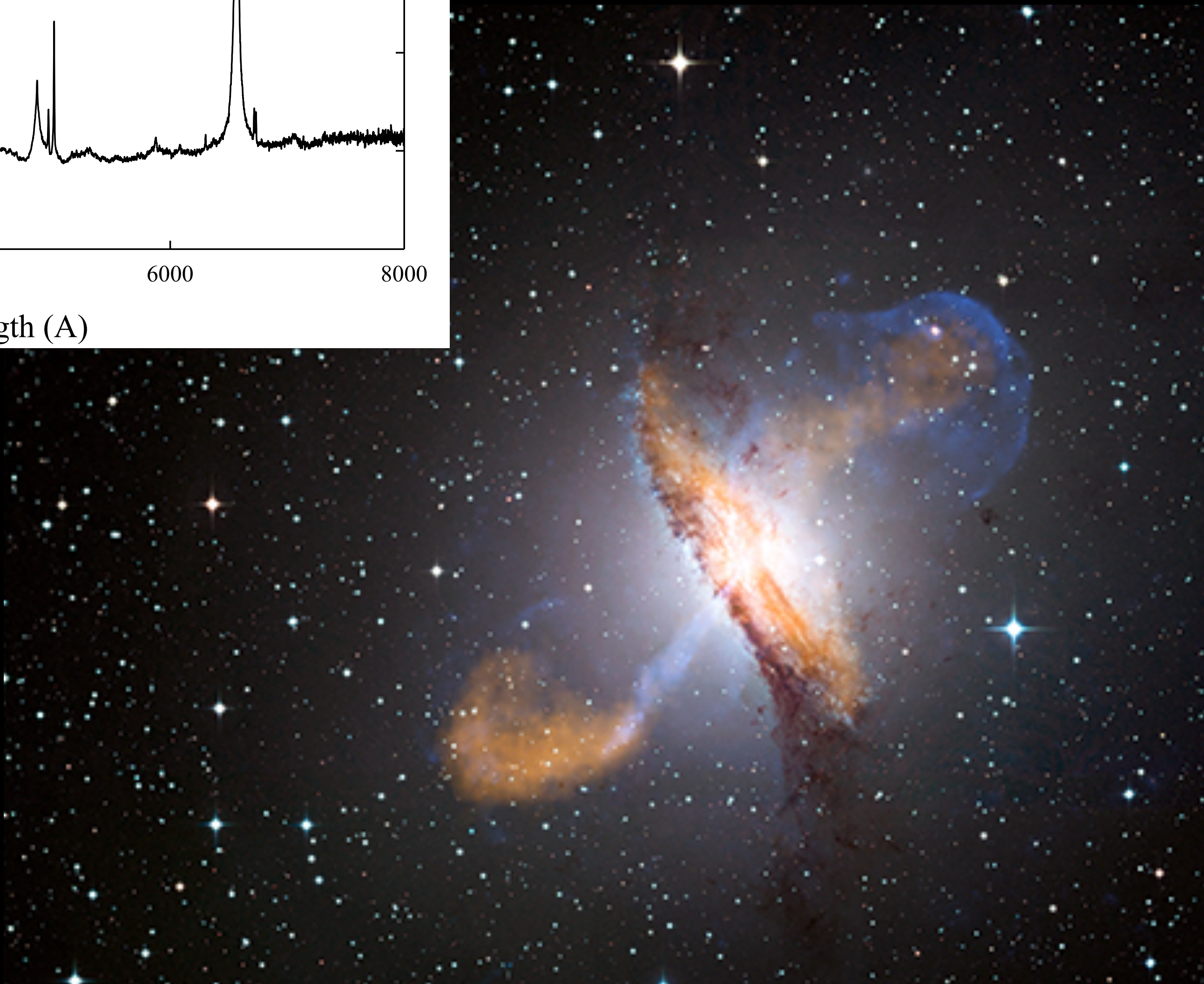
1.e-11
8.e-12
6.e-12
4.e-12
2.e-12
0.0
Flux
4200
4300
4400
4500
4600
4700
4800
Wavelength (Å)
7F
21F
27
21F
27
28
21F
[Ni II]
Hγ
27, 21F
21F
27
7F
6F
6F, 7F, 37, 38
38
37
4F
[Fe III]
[Fe III]
4F
20F

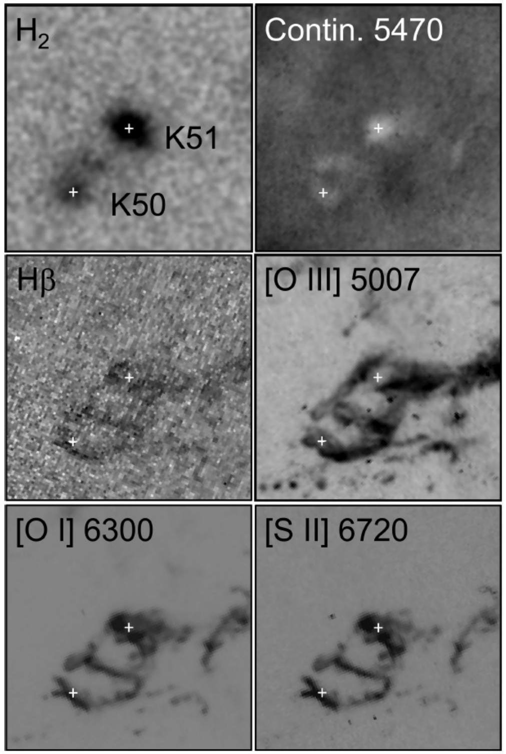

8
6
4
2
0
Flux
2000
4000
6000
8000
10000
Wavelength
C III]
[O II]
Hβ
[O III]
Hα+
[NII]
[S III]


H2
K51
K50
Contin. 5470
Hβ
[O III] 5007
[O I] 6300
[S II] 6720

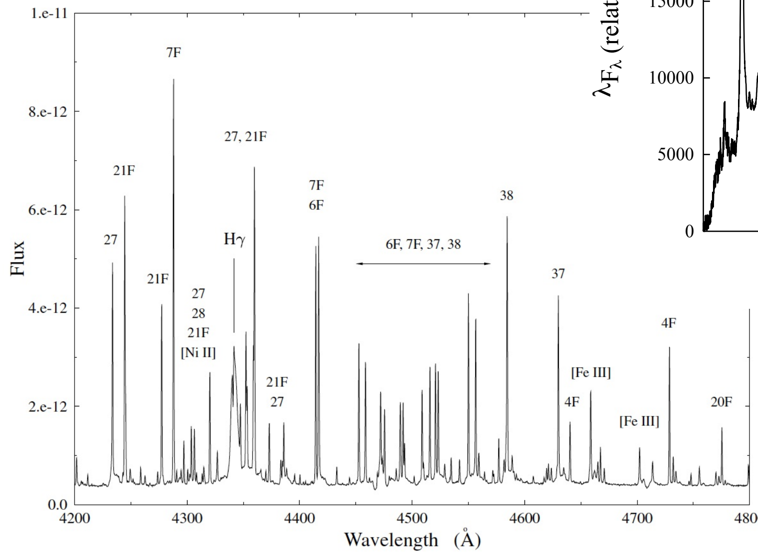


30000
25000
20000
15000
10000
5000
0
2000
4000
6000
8000
λF_λ (relative units)
Wavelength (A)

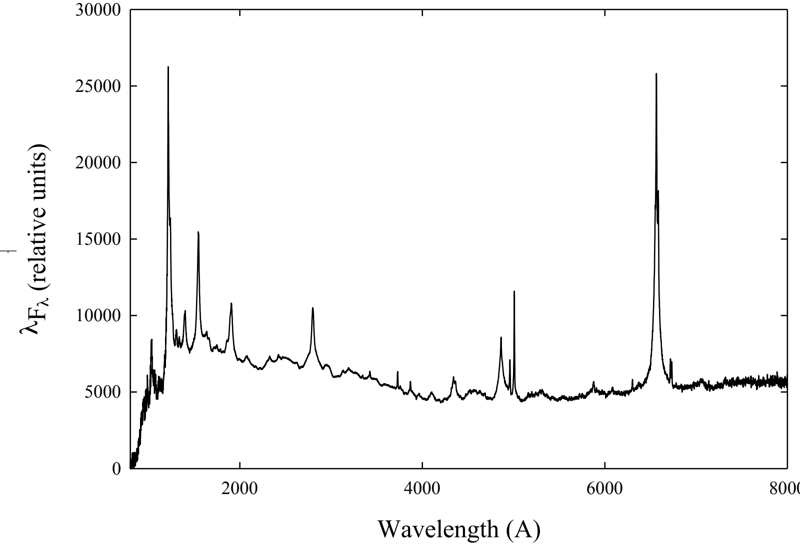




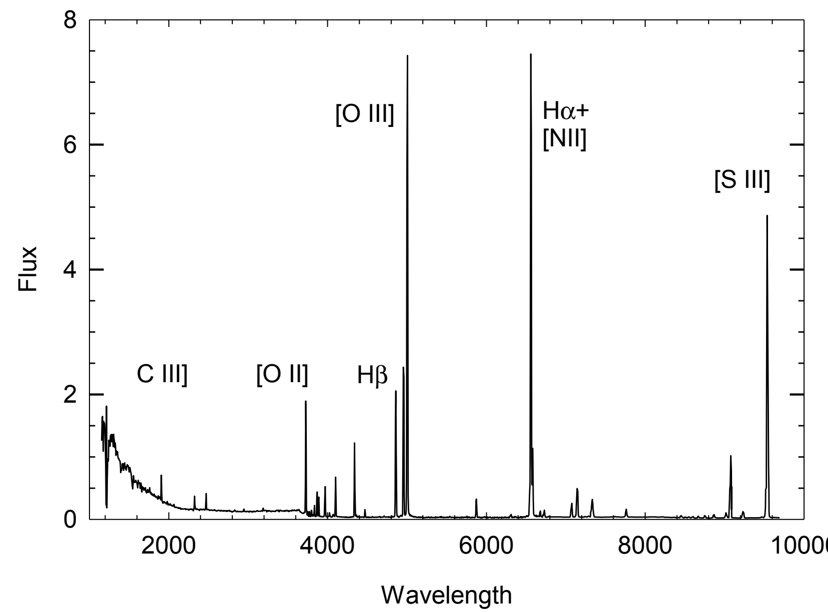
H2
K51
K50
Contin. 5470
Hβ
[O III] 5007
[O I] 6300
[S II] 6720



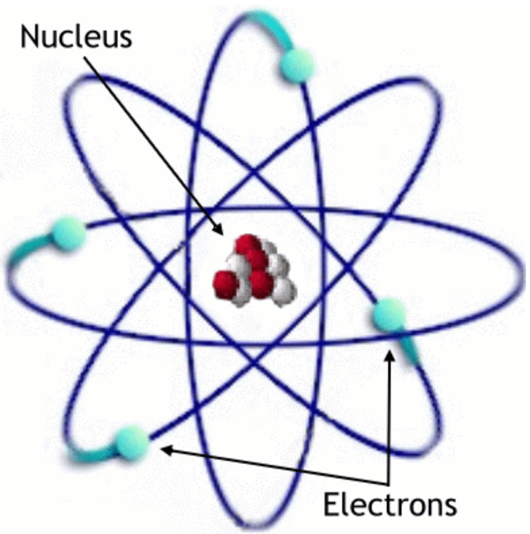
Flux
Wavelength (Å)
7F
21F
27
21F
27
28
21F
[Ni II]
Hγ
27, 21F
21F
27
7F
6F
6F, 7F, 37, 38
38
37
[Fe III]
4F
[Fe III]
4F
20F

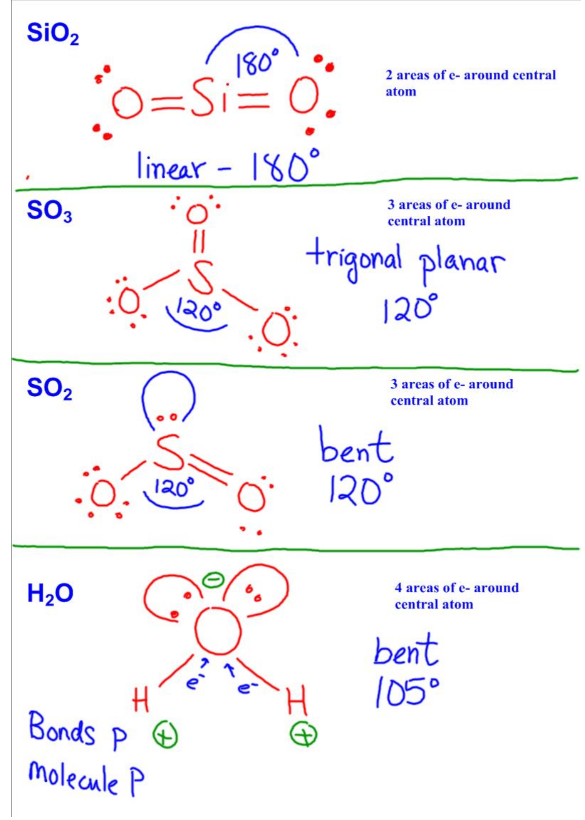


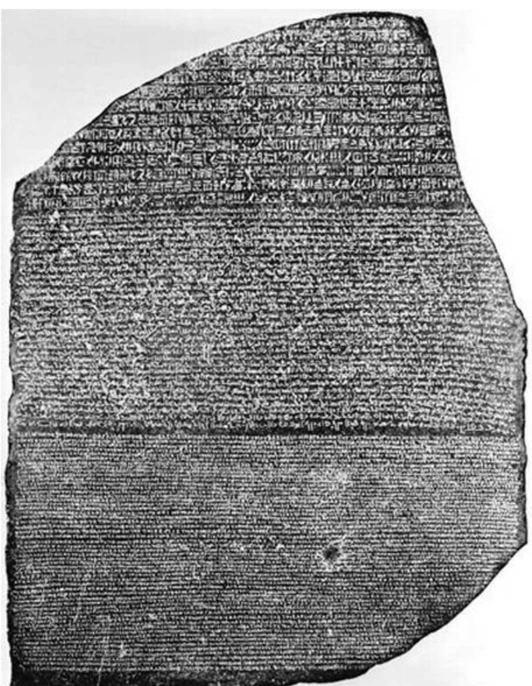
λFλ (relative units)
Wavelength (A)

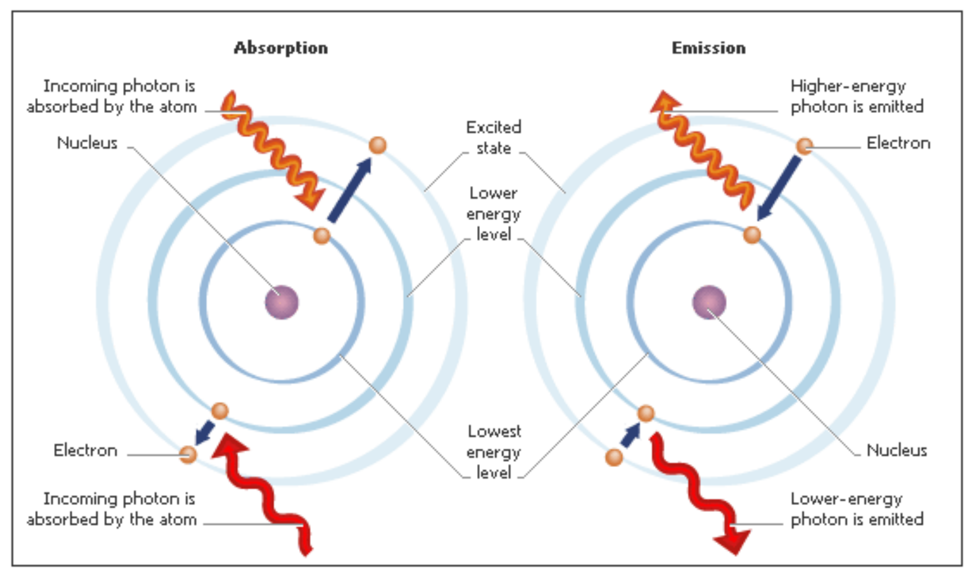


Flux
Wavelength
C III]
[O II]
Hβ
[O III]
Hα+
[NII]
[S III]


Nucleus
Electrons


SiO2
O=Si=O
180°
2 areas of e- around central atom
linear - 180°
SO3
3 areas of e- around central atom
trigonal planar
120°
SO2
3 areas of e- around central atom
bent
120°
H2O
4 areas of e- around central atom
bent
105°
Bonds P
Molecule P




Absorption
Emission
Incoming photon is absorbed by the atom
Nucleus
Excited state
Lower energy level
Lowest energy level
Electron
Incoming photon is absorbed by the atom
Higher-energy photon is emitted
Electron
Nucleus
Lower-energy photon is emitted

Cloudy

- **Accurate simulation of physical processes at the atomic & molecular level**
  - "universal fitting formulae" to atomic processes fail when used outside realm of validity, and are not used
- **Assumptions:**
  - energy is conserved
  - (usually) atomic processes have reached steady state
- **Limits:**
  - Kinetic temperature 2.7 K < T < 10^{10} K
  - No limits to density (low density limit, LTE, STE)
  - Radiation field 30 m to 100 MeV

Simultaneous solution of

- **Gas ionization**
  - From ionization balance equations
- **Chemistry**
  - Large network based on UMIST
- **Gas kinetic temperature**
  - Heating and cooling
- **Level populations and emission**
- **Grain physics**
  - Charging, CX, photoejection, quantum heating
- **The observed spectrum**
  - Radiative transport

Cloudy and its physics

- **Osterbrock & Ferland 2006, *Astrophysics of Gaseous Nebulae and Active Galactic Nuclei*, 2nd edition (AGN3)**
- **Ferland+2013, Rev Mex 49, 137, *The 2013 Release of Cloudy***
- **Ferland 2003, ARA&A, 41, 517, *Quantitative Spectroscopy of Photoionized Clouds***

Some applications to astronomy

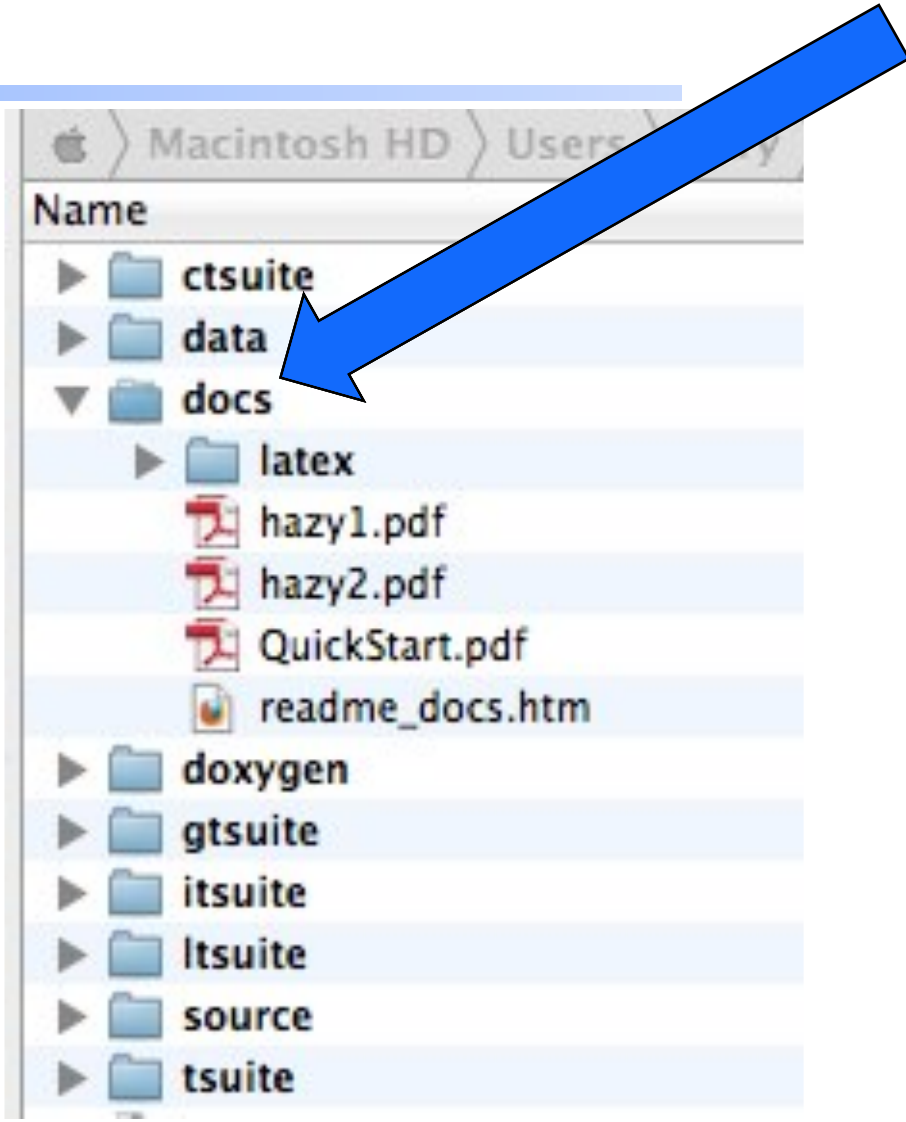
- **Hamann & Ferland, ARA&A, 37, 487,** ***Elemental Abundances in Quasistellar Objects: Star Formation and Galactic Nuclear Evolution at High Redshifts***
- **Ferland 2001, PASP, 113, 41,** ***Physical Conditions in the Orion H II Region***
- **And the ~250 papers that cite its documentation each year, here, and here**

Open source since 1978

- All versions, all data, on svn at nublado.org
- You are most welcome to help!

Documentation

- Quick start guide
- Hazy 1, all commands
- Hazy 2, description of output, comparison with observations
- Hazy 3, not compiled, badly out of date, some physics is described there



Quick Start Guide to CLOUDY *C13.1*

Cloudy & Associates
www.nublado.org

June 4, 2013

Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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Welcome to the Cloudy home page!

Cloudy is a spectral synthesis code designed to simulate conditions in interstellar matter under a broad range of conditions.

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Summer school on Cloudy, and the physics and spectroscopy of the interstellar medium Summer 2012 in Lexington. More details on the Summer School page.

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StepByStep instructions for downloading and installing the release version.

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Introduction to installing Cloudy

This page contains step by step instructions for installing the current stable version of Cloudy. *Hazy*, the code's documentation, the download.

Each version of the code has a set of pages giving updates. The HotFixes page lists corrections that need to be made to the do source. These are bug fixes that were not included in the version of the code available for download and used to generate the the test suite. So the hot fixes should be applied after the test suite has been run and your system validated. A KnownProblem known problems with that version of the code. The RevisionHistory page lists improvements.

Cite the code by giving the version number and a reference to the last major review of Cloudy, Ferland et al. (1998; PASP, 110 available here). An example would be "We used version 05.07b of Cloudy, last described by Ferland et al. (1998)". Then, ye when someone wants to know how an answer was obtained, the version used to obtain it can be retrieved from the old version web site. The **print citation** command will print the correct citation for the version you are using.

Setting up this version

1. DownLoad the code, data, and documentation. This creates several directories, Each contains a readme.htm file describing t that directory.
2. EditPath - instructions for how to specify where the data files are located. **Important!** The code will not run if it cannot find
3. CompileCode - how to compile the code using a variety of compilers.
4. RunCode - This explains how to execute the code and run a smoke test.
5. MpiParallel describes how to use the optimize and grid commands on a parallel cluster, using either MPI or a makefile.
6. CompileStars - You must compile some stellar data files if you want to use the some of the table star command to include re continua.
7. TestSuite is a large number of test cases that you should run to confirm that all is well. This is a critical step since it will che your compiler. That directory also contains a group of programs that show how to call the code as a subroutine.

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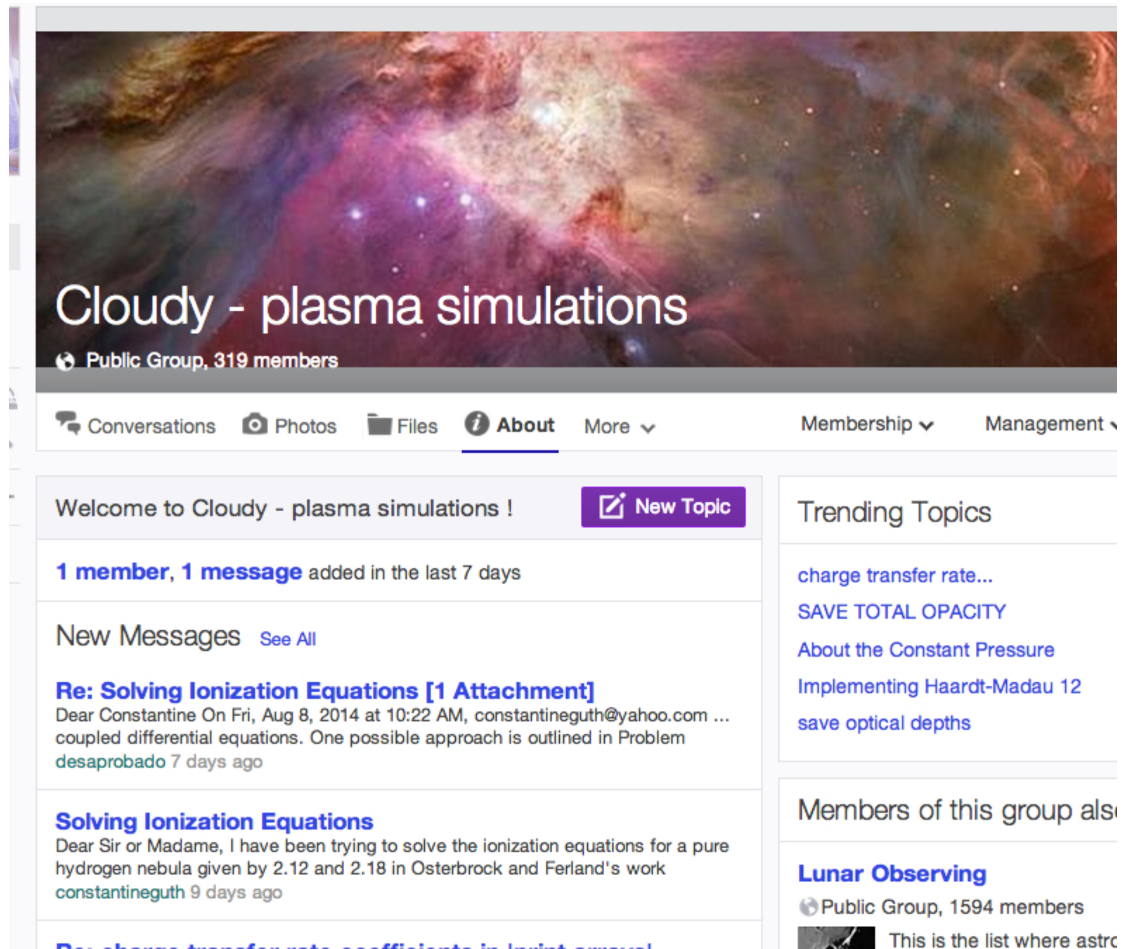
Where to go for help

- https://groups.yahoo.com/neo/groups/cloudy_simulations/info



Cloudy - plasma simulations

Public Group, 424 members

Conversations | Photos | Files | About | More

Topics | Messages

Calculated emissivities to...

Sorry, correction: the grid line is grid 8000 40000 1000 linear We seem to get good results, but the magnitudes are too low. I am attempting to attach a .png

gardnerc413 • 2 posts • 8:19 PM

Introducing Gaussian noise to ato...

Section 3.3 of the 2013 release paper states that the code includes the ability to randomly add Gaussian noise to some parameters. I'd like to apply this to

t_j_cooper • 1 post • 2:56 PM

Level populations ...

Dear Prof. Ferland, Many thanks for the reply. I'll look forward to the next version Cloudy. Best regards, Tamara.

ermolaeva.gao • 4 posts • Jun 13

Simulation warning: Transfer ionization reached 900% o...

Thank you again for the explanations :) I will check that Cheers Vital

vital.fernandez • 3 posts • Jun 9

SiII is not ionized by increasing ionization p...

Dear all, I have constructed a series of Cloudy models using the following script: hden 2.0 ionization parameter = -5 vary grid range from -5 to 2 step 0.1

Definitions

- **Ionization fractions**
  - Fraction of an element in that ionization state
- **Kirchoff's laws of spectroscopy**
  - Hot transparent gas makes emission lines
  - Cool gas in front of continuum source make absorption lines
  - Warm optically thick makes continuum, perhaps blackbody
- **Luminosity**
  - Energy emitted per second

Definitions

- **Emissivity 4*πj***
  - Emission per unit volume, per second
- **Optical depth τ**
  - Number of mean free paths through a medium
- **Opacity κ**
  - $\tau = \kappa n$
- **Planck function *B* = *j*/κ**
- **Rob Rutten's course notes describes this and more**
  - http://www.staff.science.uu.nl/~rutte101/Radiative_Transfer.html

Two yahoo groups

- **For this workshop**
  - https://groups.yahoo.com/neo/groups/CloudySummerSchool/info
- **For Cloudy in general**
  - https://groups.yahoo.com/neo/groups/cloudy_simulations/info

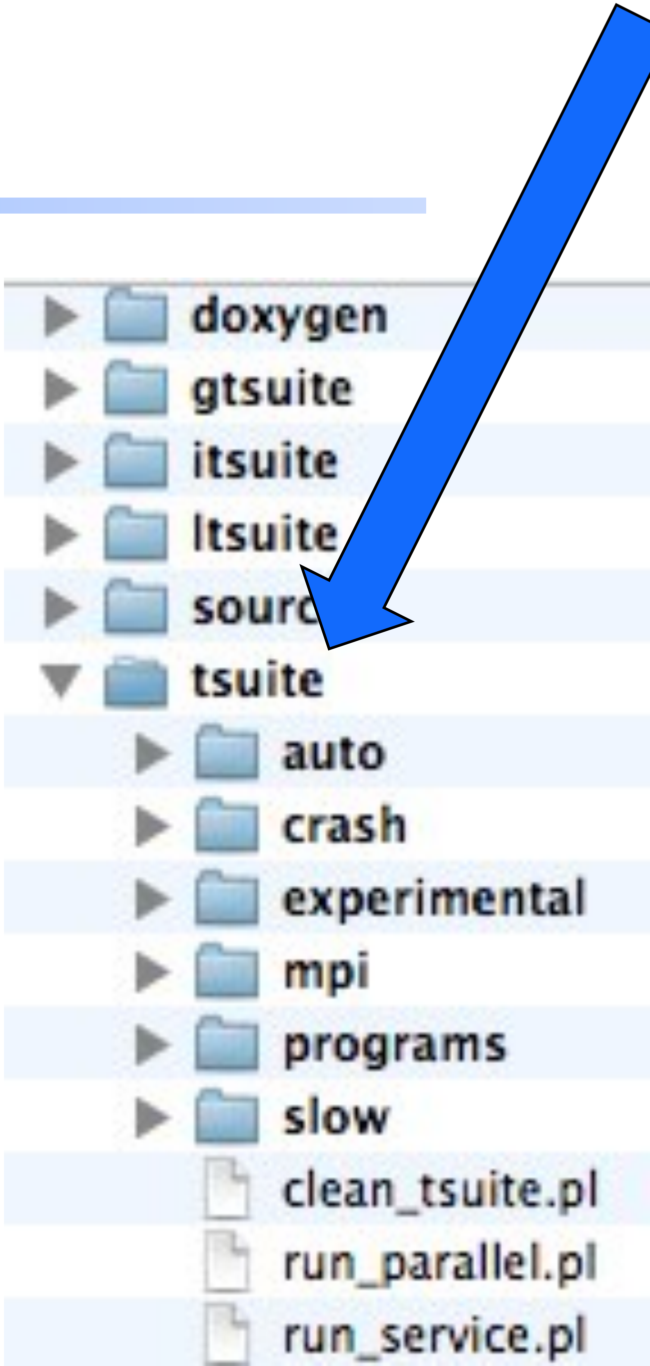
Running cloudy

- **“run” file contains**
  path-to-cloudy.exe -r $

- **If file “model.in” contains input, then**
- **run model &**
- **Produces output “model.out”**

The test suite

- **Fully tests the code after any changes**
  - "Monitors" allow automatic comparison of current with previous results
- **Provides examples of how to use Cloudy**
  - But may include extraneous commands for testing
  - Or backwards compatible
- **Useful examples of how to set up a simulation**



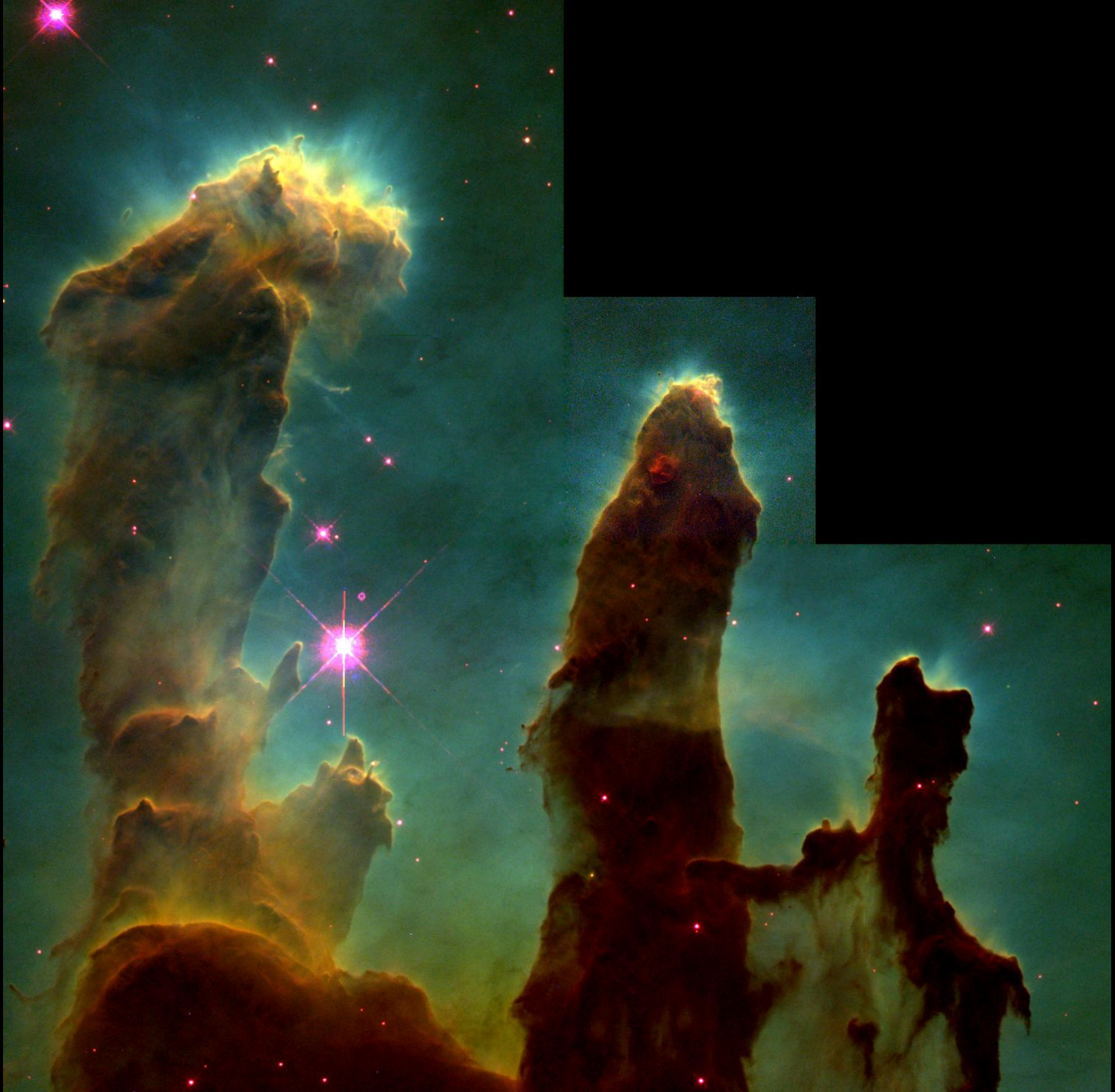
The "main output"

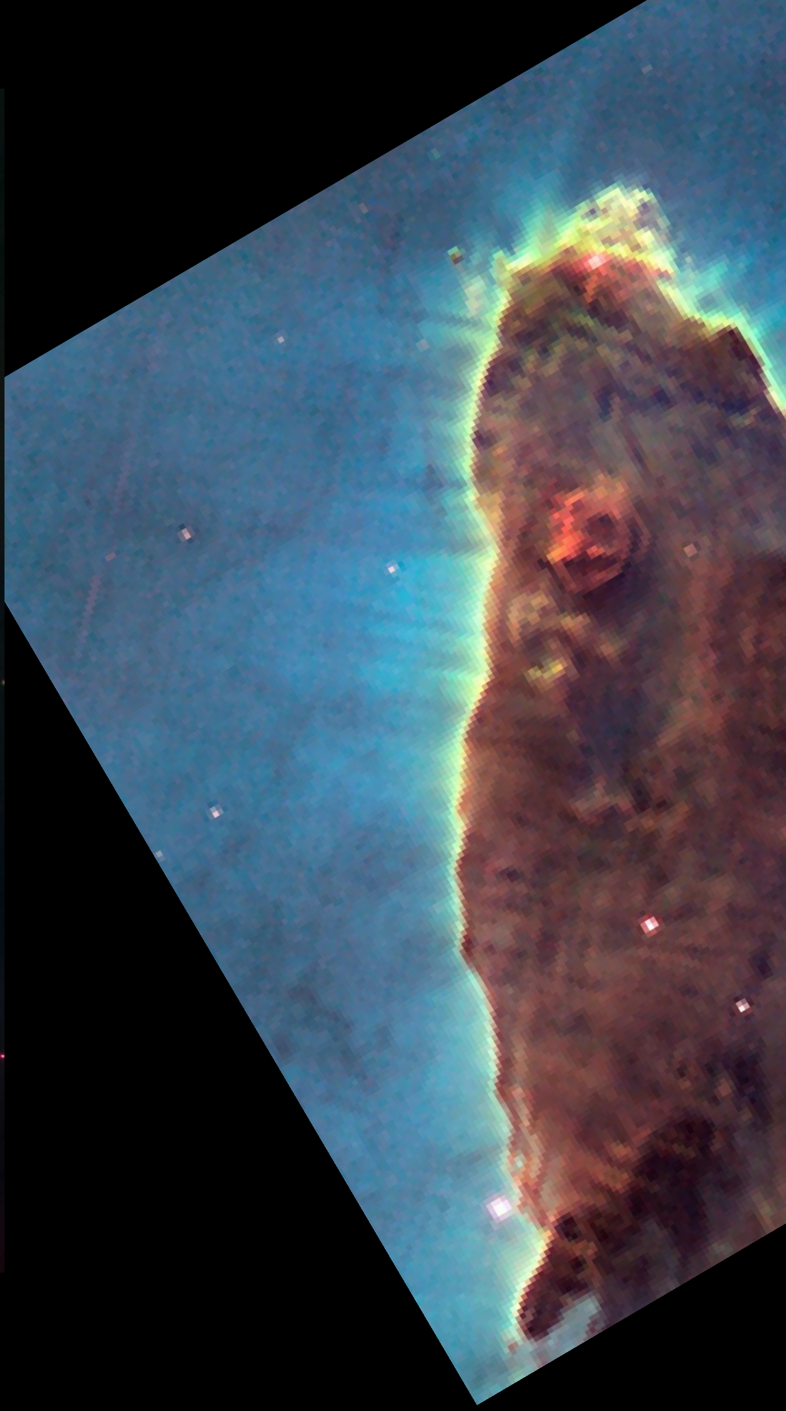
- The *.out file created when code is executed
  - QSG 7.1 & Hazy 2 Chapter 1
- Gas & grain composition
- Physical conditions in first and last zone
- Emission-line spectrum
- Mean quantities

- Cloudy is designed to be autonomous and self aware
- Will generate notes, cautions, or warnings, is conditions are not appropriate.

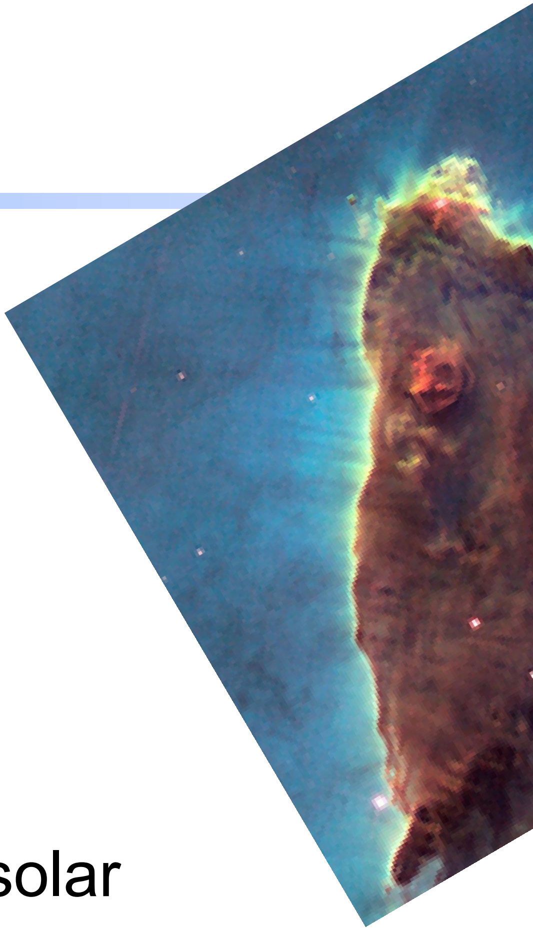
“Save” output

- **Requested with various “save” commands**
  - Hazy 1 Section16.35 and later
- **The main way the code reports its results**



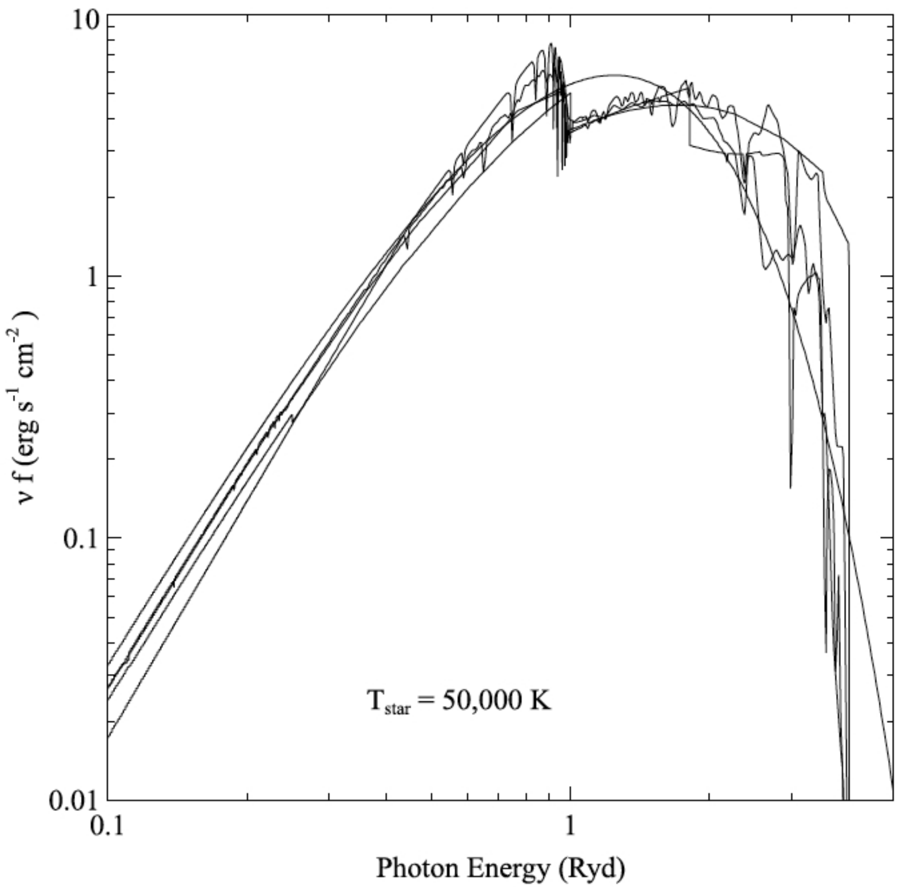
Minimum to run Cloudy



- **Must specify**
  - SED – shape of the radiation field striking the cloud
  - Flux of photons per unit area
  - Gas density
- **May also specify**
  - Gas composition, grains (grain-free solar composition by default)
  - Gas equation of state (often constant density)
  - Stopping criterion, often lowest gas kinetic temperature or physical thickness

Parameters – the SED shape

- Quick start guide Chapter 5
- Hazy 1, Chapters 4, 6
- Can be specified as a fundamental shape such as a blackbody
- Or by interpolation on a table of points



SED brightness

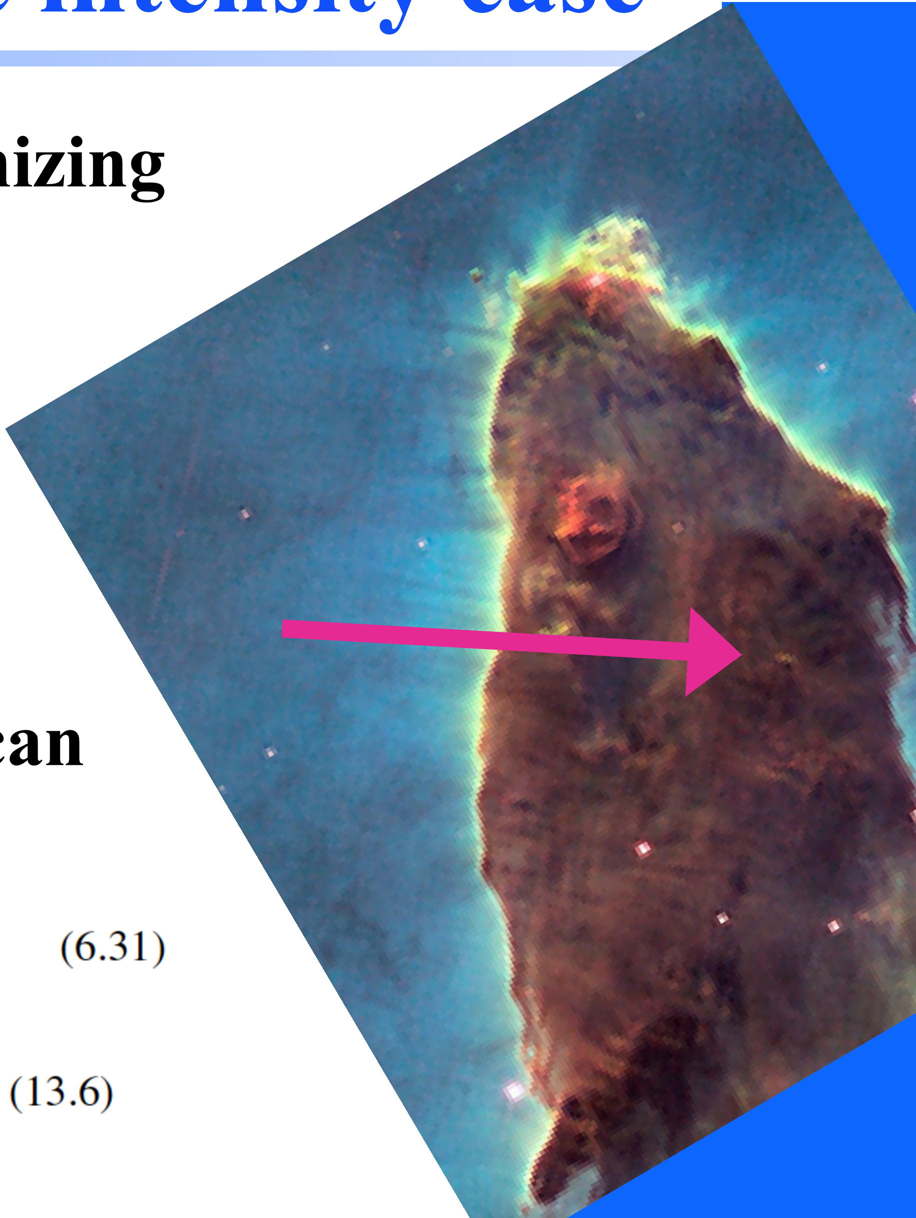
- **QSG Chapter 5, Hazy1 Chapt 4 and 5**
- **Two cases occur in nature**
- **Intensity case**
  - In a resolved source, often work with surface brightness, or line intensity
  - Specify flux of photons striking cloud, predict emission per unit volume
- **Luminosity case**
  - Specify total photon luminosity
  - Predict line luminosities

SED brightness – the intensity case

- **Specify φ(H) – flux of H ionizing photons per unit area**
  - predicts surface brightness, emission per unit area erg cm^{-2} s^{-1}
  - Inner radius of cloud does not need to be specified
- **Ionization parameter also can be used to set φ(H)**

$$\phi(H^0) = \frac{Q(H^0)}{4\pi r^2} = \int_{\nu_0}^{\infty} \frac{\pi F_\nu}{h\nu} d\nu, \qquad (6.31)$$

$$U = \frac{1}{4\pi r^2 c n_H} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu \qquad (13.6)$$

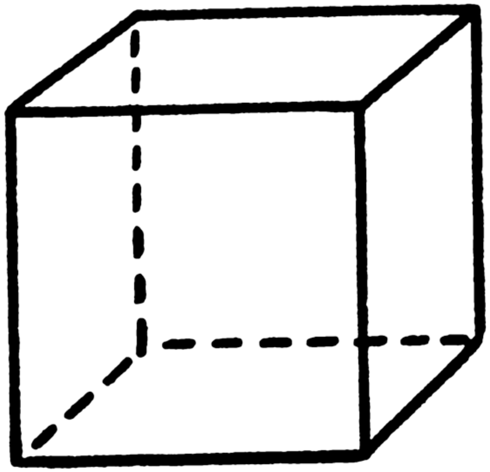


SED brightness – the luminosity case

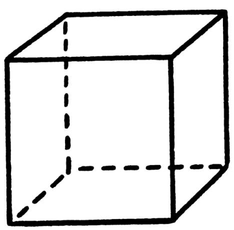
- **Specify Q(H) – the number of ionizing photons**
  - AGN3 p18 $Q(\mathrm{H}^0) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu$
  - Inner radius of cloud must be specified, since φ (H) = Q(H) / 4π r^2
  - predicts emission line luminosities erg s^{-1}

A “unit cell”

- We will sometimes model a cubic cm of matter in many of the atomic calculations
- A “unit cell”, 1 cm^3
- These commands do a single “zone” that is log(dr)=0 (or 1 cm) thick
  - stop zone 1
  - set dr 0



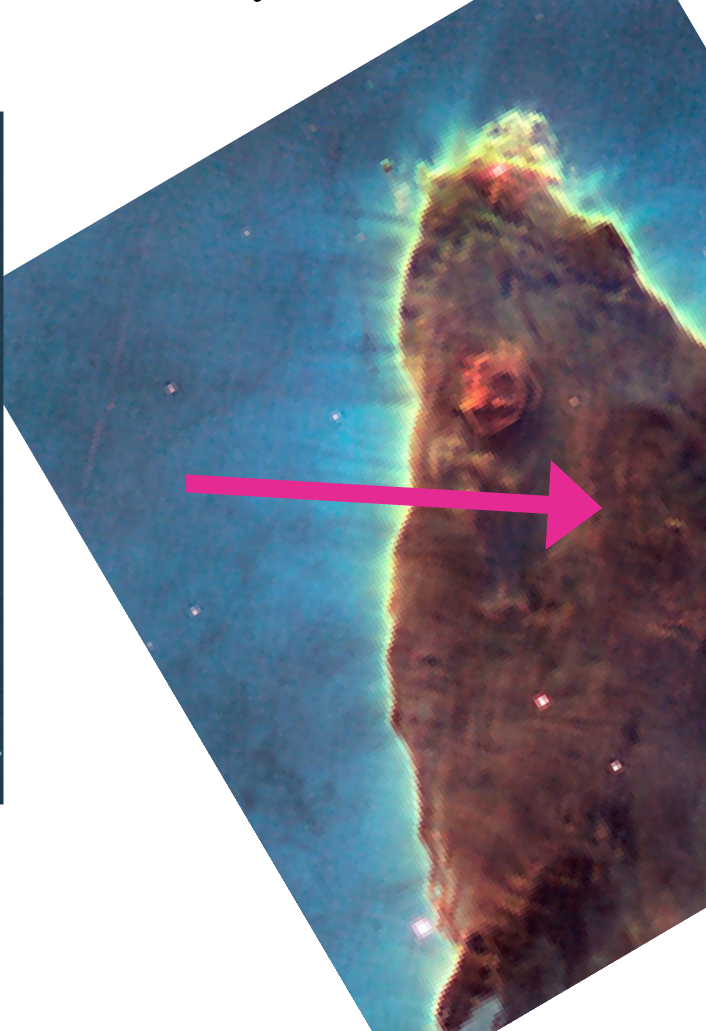
The three geometries



Unit cell

Luminosity case

Intensity case



Cloud density, Hazy 1 Chap 8

- **“hden” command sets log of hydrogen density, cm^{-3}**
- **Constant density by default**
  - the H density is the same across the cloud
- **Other equations of state possible**
  - Constant pressure, dynamical flows, power-laws

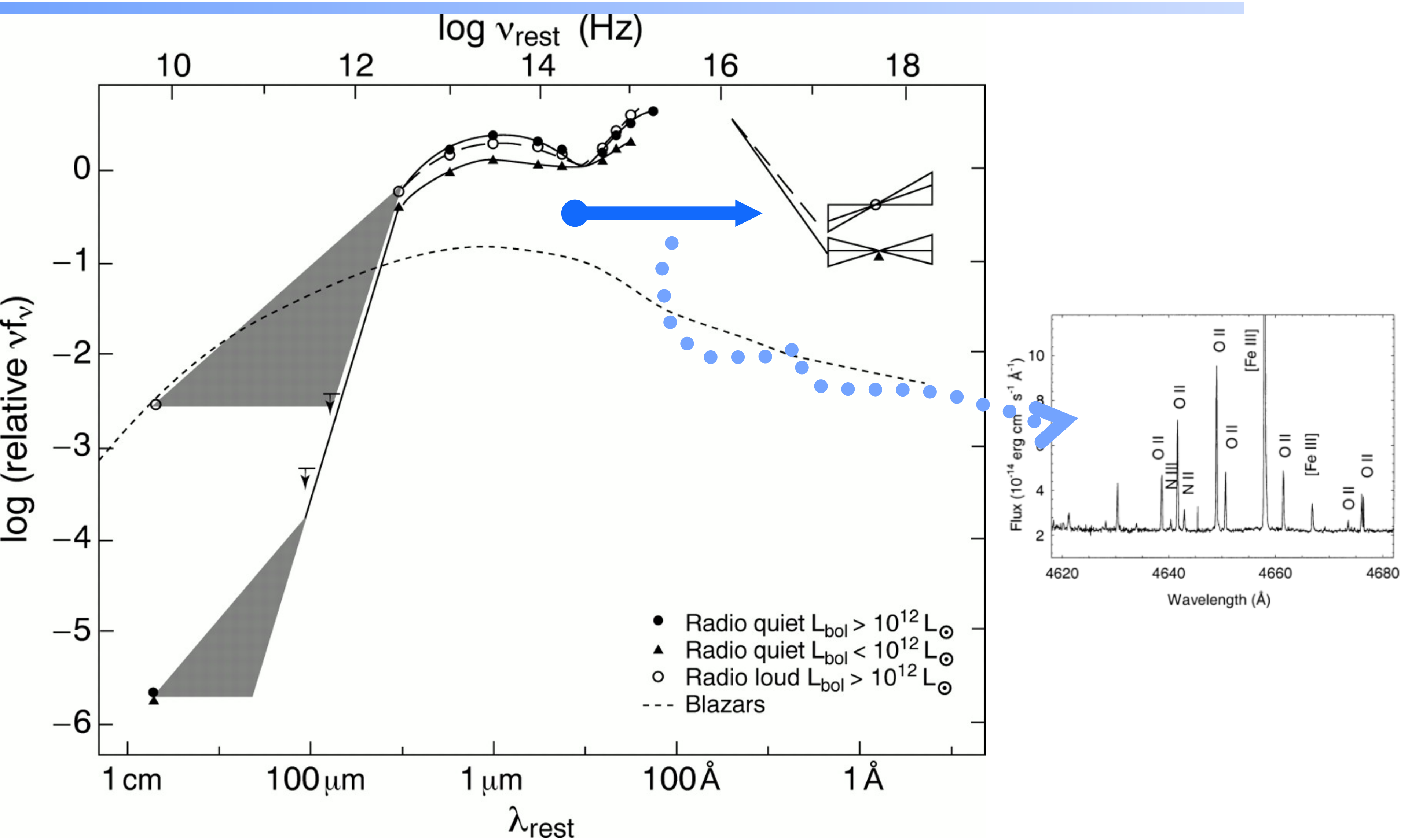
Composition, Hazy 1 Chap 7

- Solar, no grains, by default
- Other standard mixtures possible,
- Stored in data / abundances
- The composition used is reported at the top of the main output

```
                                           Gas Phase Chemical Composition
 H :   0.0000   He: -1.0223   Li:-10.2676   B :-10.0506   C : -3.5229   N : -4.1549   O : -3.3979   Ne: -4.2218   Na: -6.5229
 Mg: -5.5229   Al: -6.6990   Si: -5.3979   P : -6.7959   S : -5.0000   Cl: -7.0000   Ar: -5.5229   K : -7.9586   Ca: -7.6990
         Ti: -9.2366   V :-10.0000   Cr: -8.0000   Mn: -7.6383   Fe: -5.5229   Ni: -7.0000   Cu: -8.8239   Zn: -7.6990

                                             Grain Chemical Composition
                           C : -3.6259   O : -3.9526   Mg: -4.5547   Si: -4.5547   Fe: -4.5547
```

The “primary mechanism”
Continuum → emission lines



The AGN3 p17-18 H II region

At a typical point in a nebula, the ultraviolet radiation field is so intense that the H is almost completely ionized. Consider, for example, a point in an H II region, with density 10 H atoms and ions per cm^3, 5 pc from a central O7.5 star with $T_* =$ 39,700 K. We will examine the numerical values of all the other variables later, but for the moment, we can adopt the following very rough values:

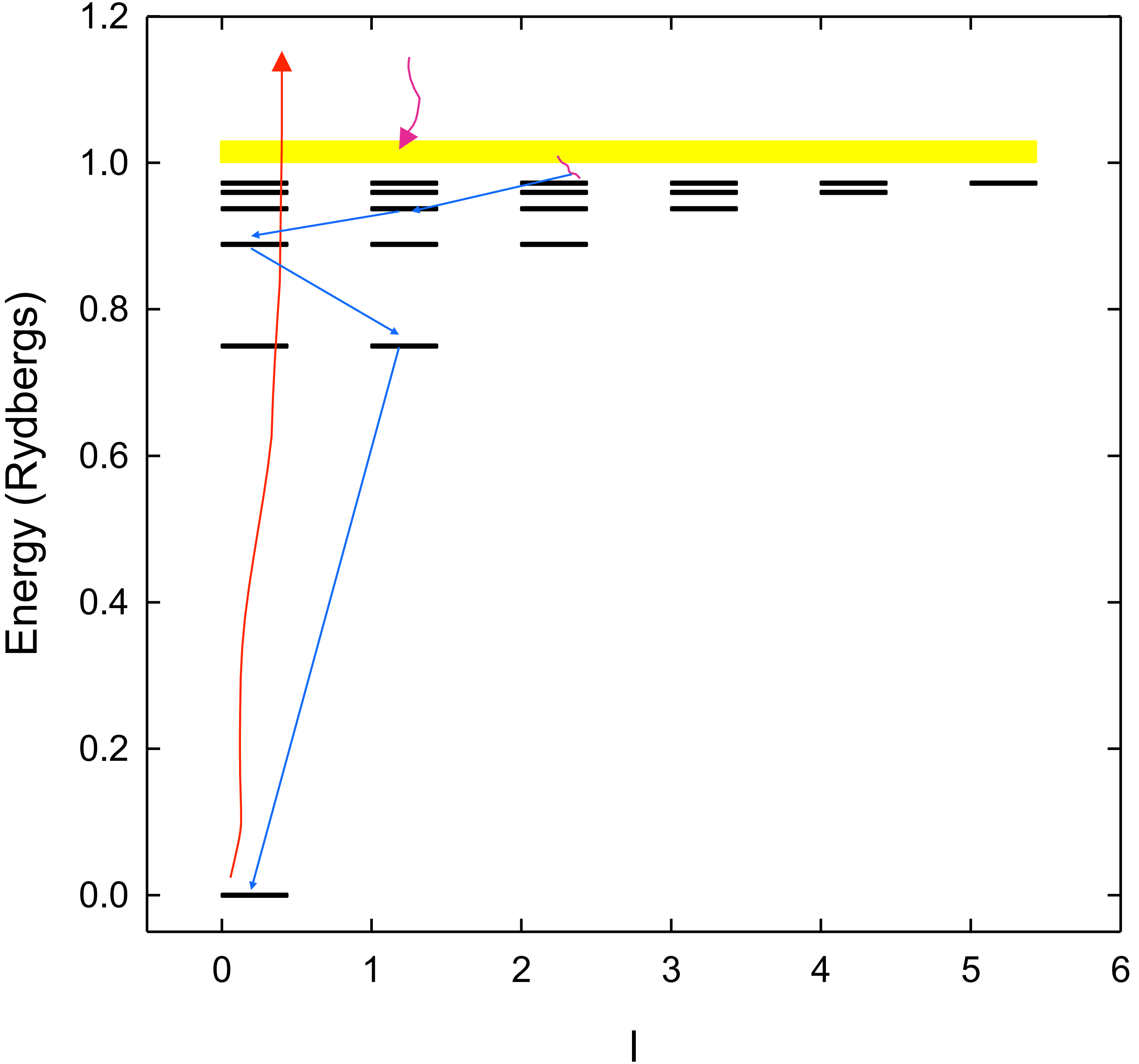
$$Q(\mathrm{H}^0) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu \approx 1 \times 10^{49} \text{ [photons s}^{-1}\text{]};$$

Commands – Hazy1 Chap 3

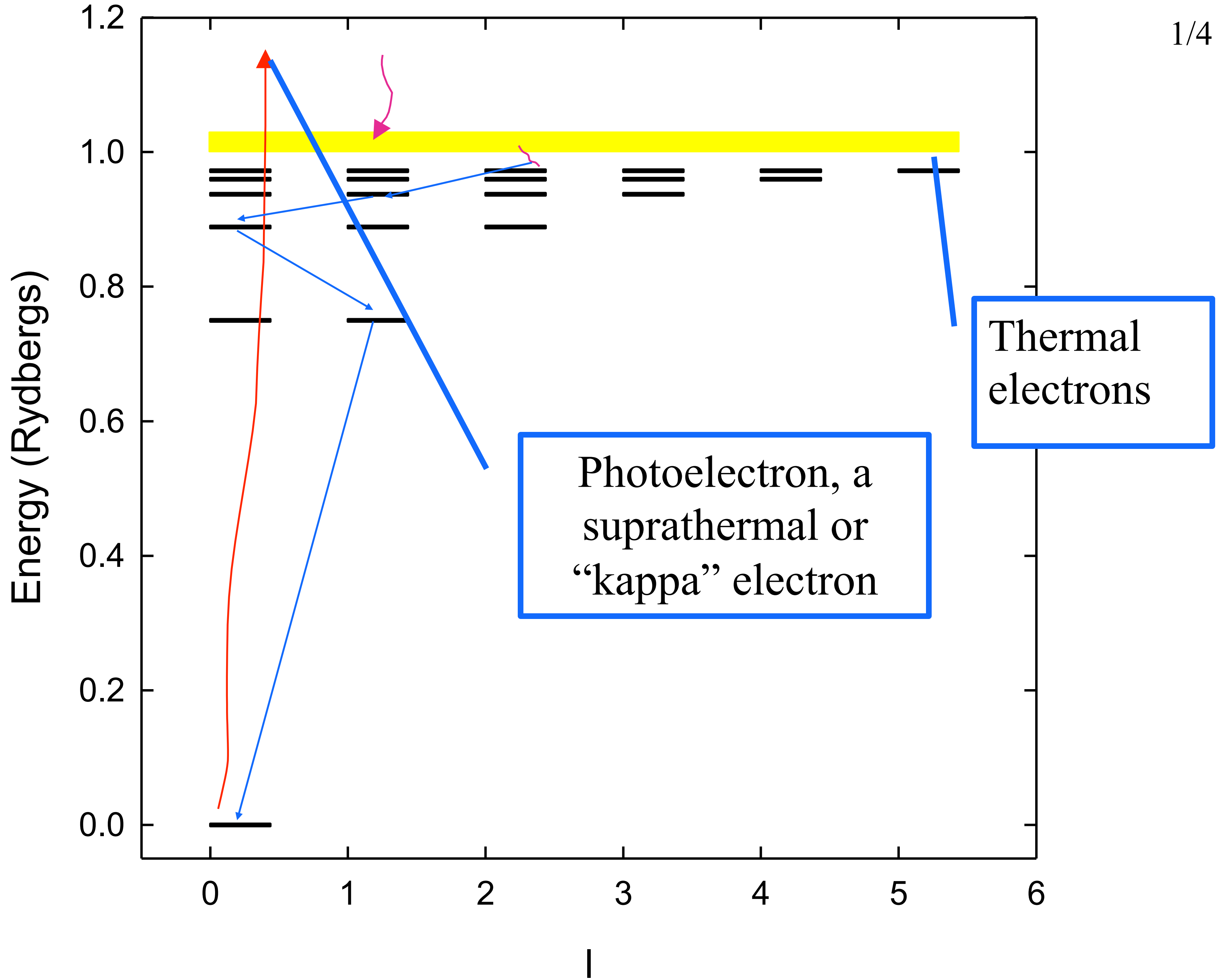
- Free format keywords and numbers
- Commands end with empty line or *****
- Many numbers are logs, check Hazy1 carefully

Incident, total radiation fields

- **Plot the radiation field of the simple H II region we computed**
- **The file hiis.con has the radiation field**
  - Column 1 is wavelength in microns
  - Column 2 is incident radiation field νL_ν erg s^{-1}
  - Column 7 is the radiation field emitted by the surrounding cloud



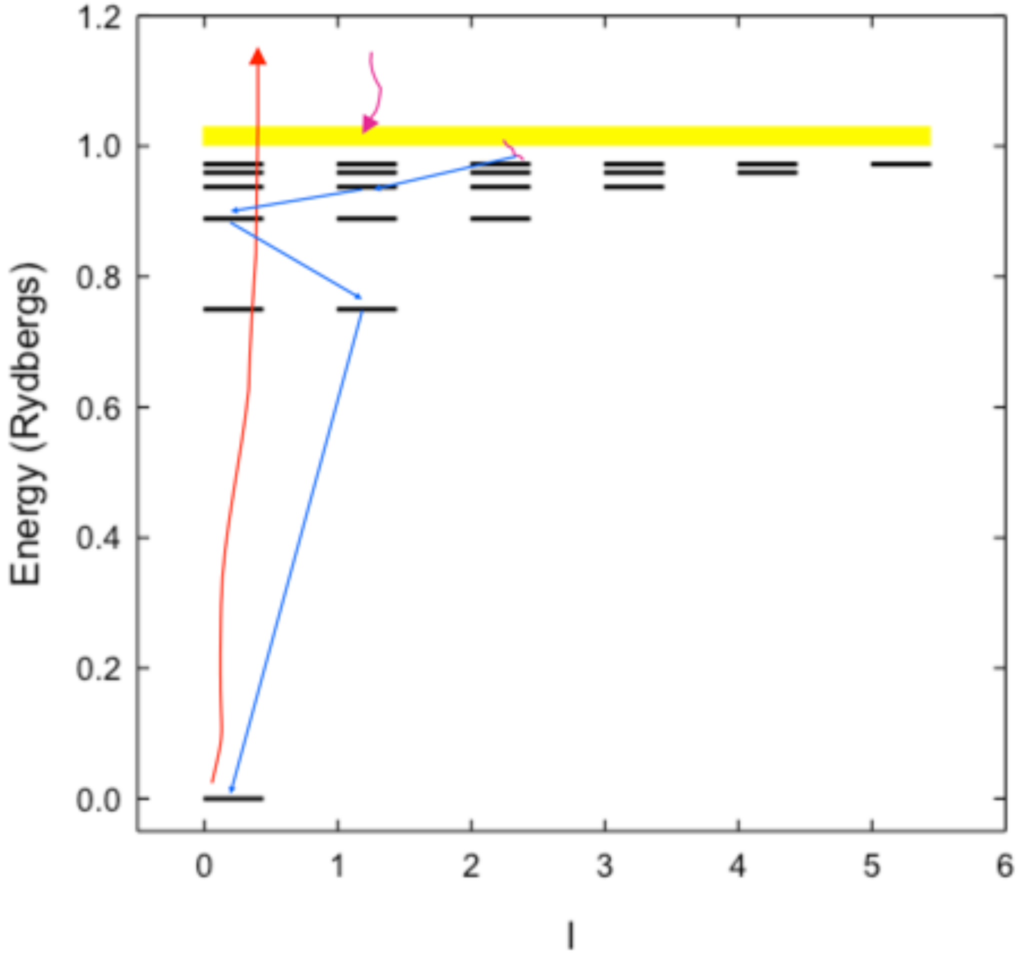
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Energy (Rydbergs)
0
1
2
3
4
5
6
l



Energy (Rydbergs)
1.2
1.0
0.8
0.6
0.4
0.2
0.0
0
1
2
3
4
5
6
l
Thermal electrons
Photoelectron, a suprathermal or “kappa” electron

Life history of an Orion electron

- **H^0 ground state**
  - 1 day
- **Suprathermal**
  - 1 second
- **Thermal**
  - 1 yr
- **H^0 excited states**
  - 10^{-7} s
- **H^0 ground state**



Let's model a …

- Relatively dense, $n_H = 10^4$ cm^{-3}
- ISM cloud
- One parsec away from an
- O6 star

Table 2.3

Calculated Strömgren radii as function of spectral types spheres

AGN3

Spectral type	T_* (K)	M_V	log $Q(H^0)$ (photons/s)	log $n_e n_p r_1^3$ n in cm^{-3}; r_1 in pc	log $n_e n_p r_1^3$ n in cm^{-3}; r_1 in pc	r_1 (pc) $n_e = n_p = 1$ cm^{-3}
O3 V	51,200	−5.78	49.87	49.18	6.26	122
O4 V	48,700	−5.55	49.70	48.99	6.09	107
O4.5 V	47,400	−5.44	49.61	48.90	6.00	100
O5 V	46,100	−5.33	49.53	48.81	5.92	94
O5.5 V	44,800	−5.22	49.43	48.72	5.82	87
O6 V	43,600	−5.11	49.34	48.61	5.73	81
O6.5 V	42,300	−4.99	49.23	48.49	5.62	75
O7 V	41,000	−4.88	49.12	48.34	5.51	69
O7.5 V	39,700	−4.77	49.00	48.16	5.39	63
O8 V	38,400	−4.66	48.87	47.92	5.26	57
O8.5 V	37,200	−4.55	48.72	47.63	5.11	51
O9 V	35,900	−4.43	48.56	47.25	4.95	45
O9.5 V	34,600	−4.32	48.38	46.77	4.77	39
B0 V	33,300	−4.21	48.16	46.23	4.55	33
B0.5 V	32,000	−4.10	47.90	45.69	4.29	27
O3 III	50,960	−6.09	49.99	49.30	6.38	134
B0.5 III	30,200	−5.31	48.27	45.86	4.66	36
O3 Ia	50,700	−6.4	50.11	49.41	6.50	147
O9.5 Ia	31,200	−6.5	49.17	47.17	5.56	71

Note: $T = 7{,}500$ K assumed for calculating α_B.

definitions

- **Illuminated and shielded face**
- **Incident, transmitted, emitted, reflected, components of radiation field**
  - Hazy 1, section 2.2

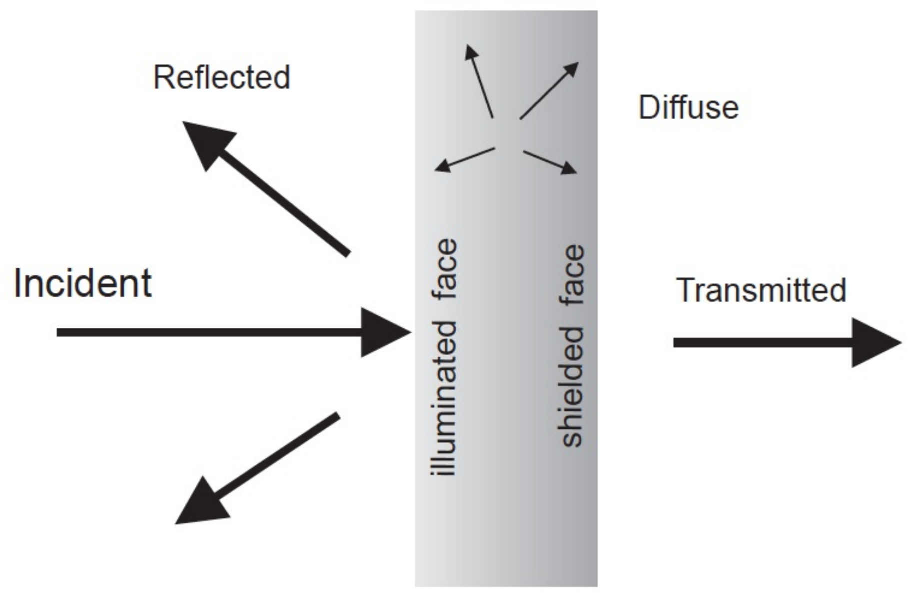


Figure 2.1: Several of the radiation fields that enter in the calculations.

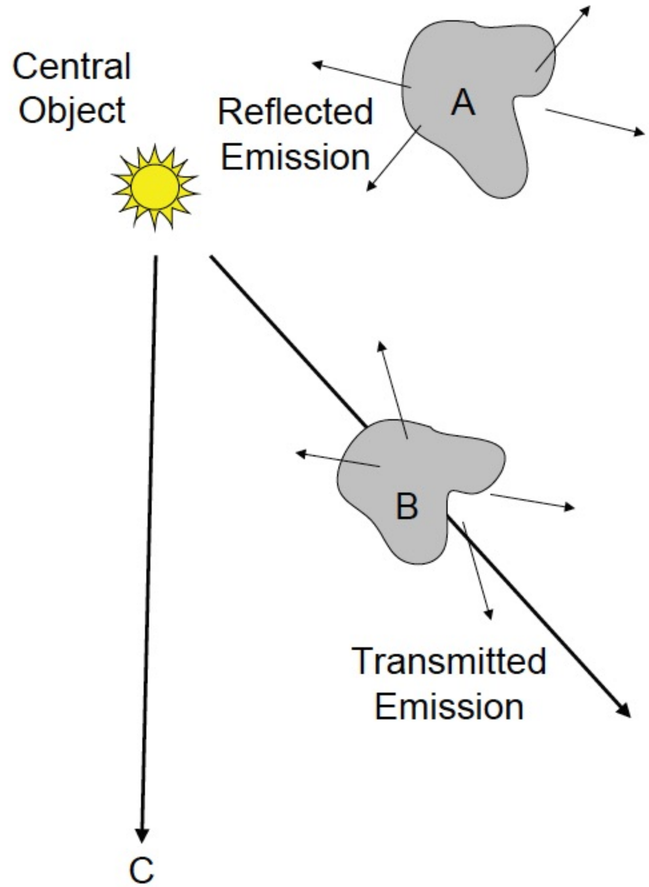
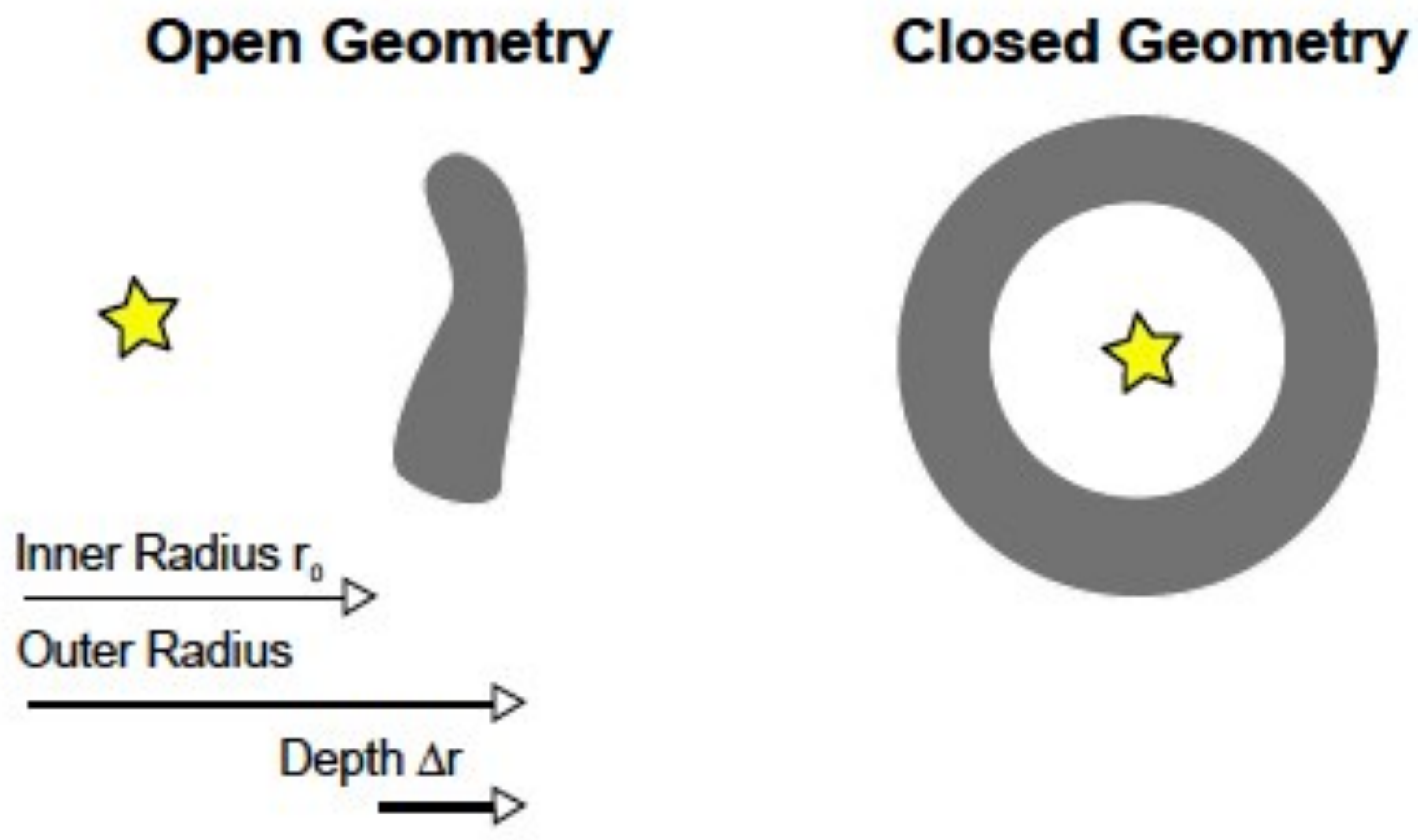


Figure 16.2: This figure illustrates several components of the radiation field that enter in the calculations.

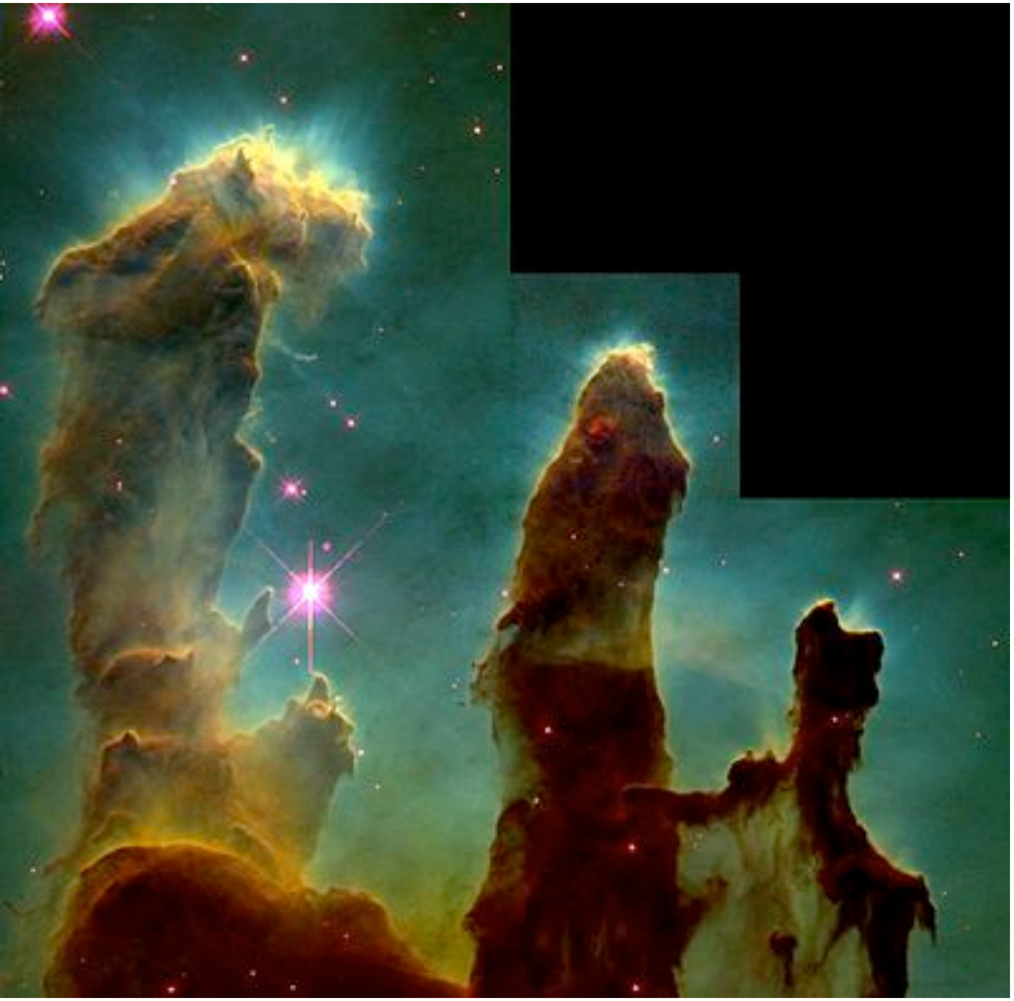
Open vs closed geometry Hazy 2.3



Plot components of radiation field

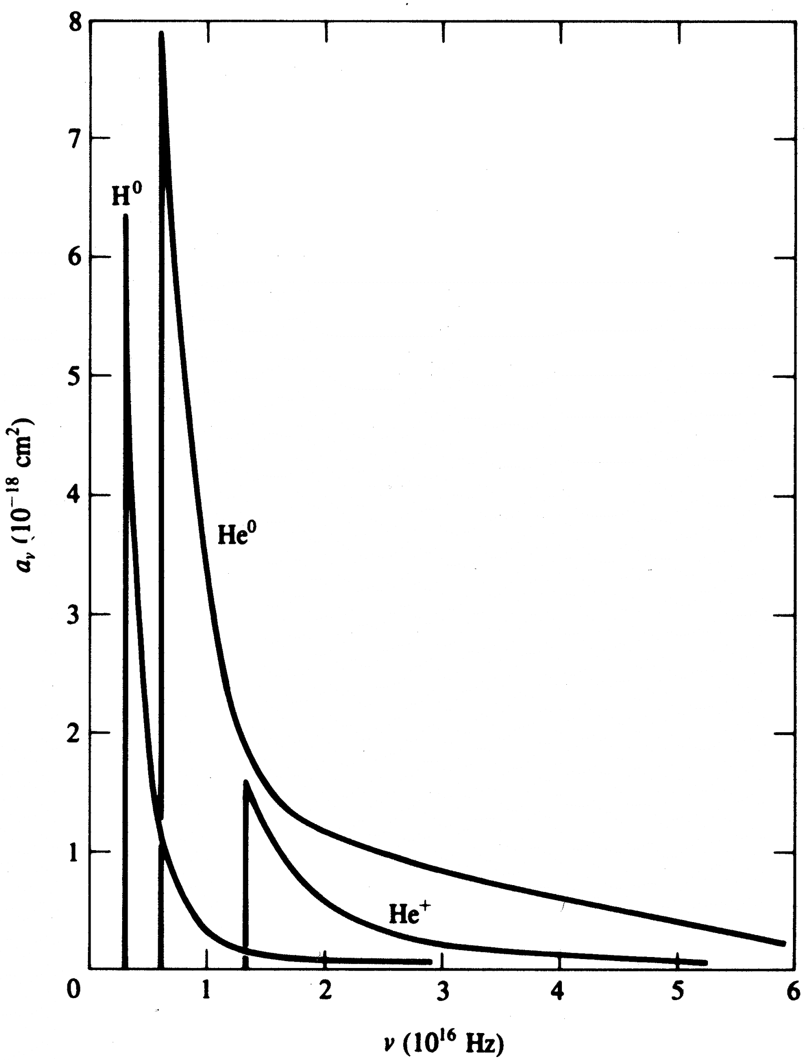
- **Incident stellar continuum**
- **Total continuum produced**
- **Reflected continuum**

Strömgren length



Photoionization

- Highest cross section at lowest photon energies
- AGN3 Fig 2.2



Make plot of total opacity for zone 1 of H II region

- **Nb – make this plot so that it can be directly compared with hardening of radiation field example on next day**
- **Do in ryd and list important edges**

Recombination AGN3 Chap 2

- Electron and ion recombine, emitting energy
- Radiative recombination for H and He
- Dielectronic recombination for heavy elements

Table 2.7

Recombination coefficients (in $cm^3\ s^{-1}$) for H-like ions

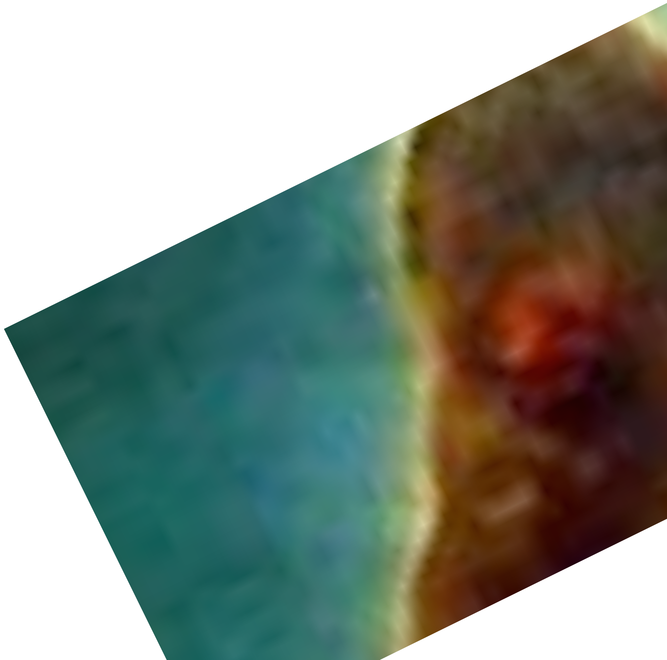
	T				
	1,250 K	2,500 K	5,000 K	10,000 K	20,000 K
$\alpha_A = \sum_1^\infty \alpha_n$	1.74×10^{-12}	1.10×10^{-12}	6.82×10^{-13}	4.18×10^{-13}	2.51×10^{-13}
$\alpha_B = \sum_2^\infty \alpha_n$	1.28×10^{-12}	7.72×10^{-13}	4.54×10^{-13}	2.59×10^{-13}	1.43×10^{-13}
$\alpha_C = \sum_3^\infty \alpha_n$	1.03×10^{-12}	5.99×10^{-13}	3.37×10^{-13}	1.87×10^{-13}	9.50×10^{-14}
$\alpha_D = \sum_4^\infty \alpha_n$	8.65×10^{-13}	4.86×10^{-13}	2.64×10^{-13}	1.37×10^{-13}	6.83×10^{-14}

Strömgren length

- **Number of ionizing photons entering layer is balance by number of recombinations along it**

$$\varphi(H) = n_e n_p \alpha \quad L$$

$$L \propto \frac{\varphi(H)}{n_e n_p \alpha}$$



Matter vs radiation bounded

Beyond the H^+ layer

- Little H^+ ionizing radiation gets past the H^+ layer
- Deeper regions are atomic or molecular
- Also cold and produce little visible light
- Large extinction due to dust

Why did the simulation stop?

- **Make plot of H^+ fraction vs depth**
- **Various stopping reasons given in Hazy 2, Sec 7.6**
- **Default is to stop when gas temperature falls below 4000 K, probably a region near the H^+ - H^0 ionization front.**
  - But is this what you want?