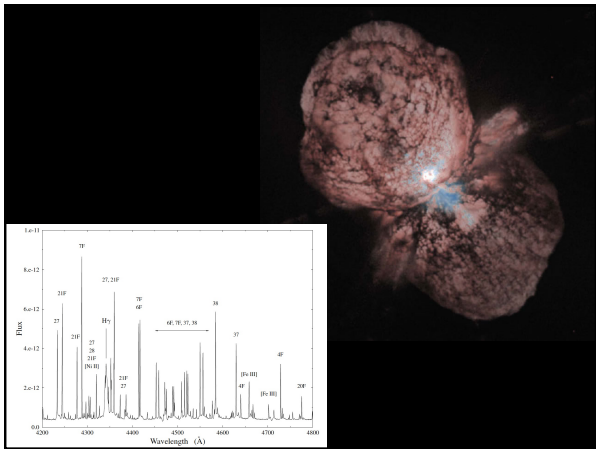
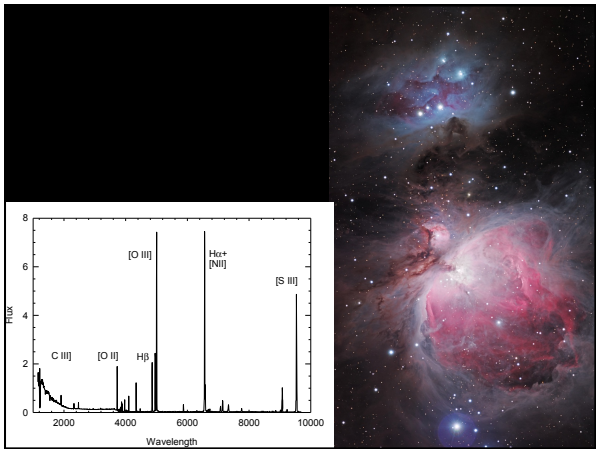
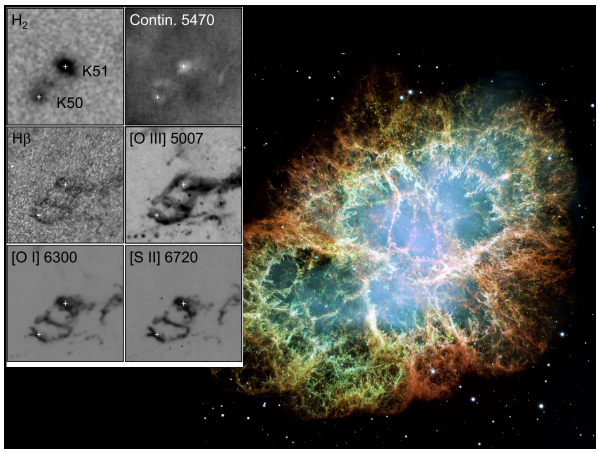
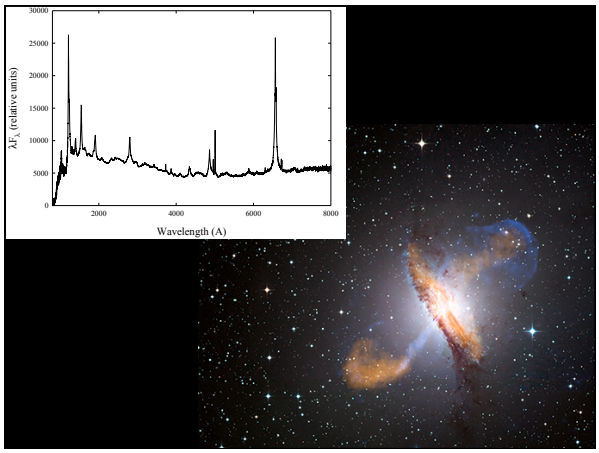
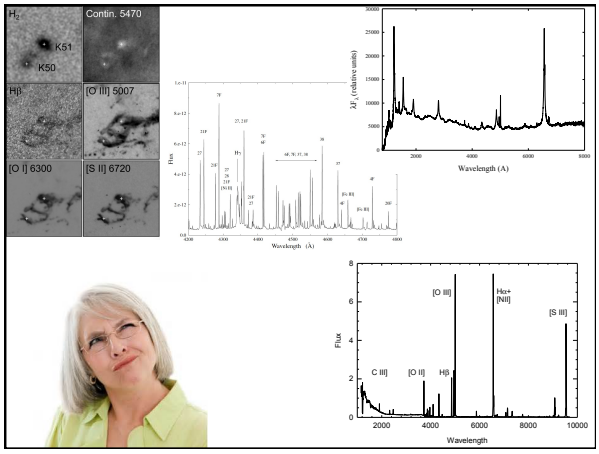
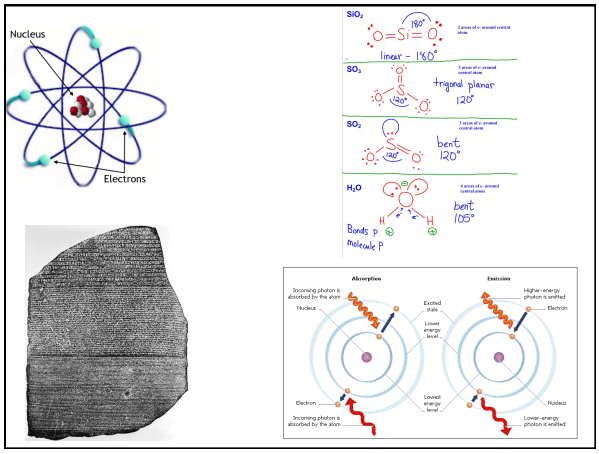

Flux
Wavelength (Å)


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


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


λF_λ (relative units)
Wavelength (A)





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 10 m to 100 MeV

Simultaneous solution of

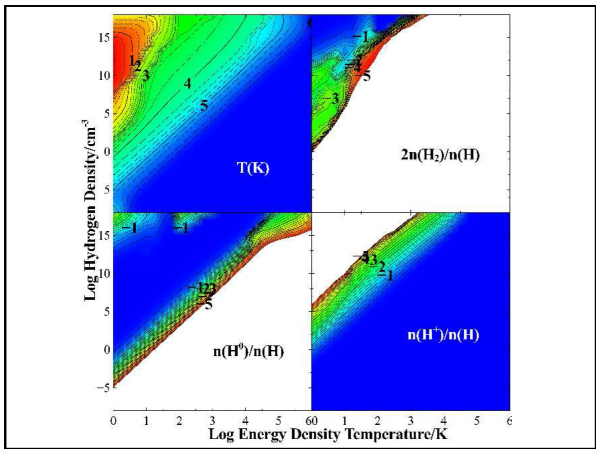
- **Gas ionization**
  - From ionization balance equations
- **Chemistry**
  - Large network based on UMIST
- **Gas kinetic temperature**
  - Heating and cooling
- **Grain physics**
  - Charging, CX, photoejection, quantum heating
- **The observed spectrum**
  - Radiative transport

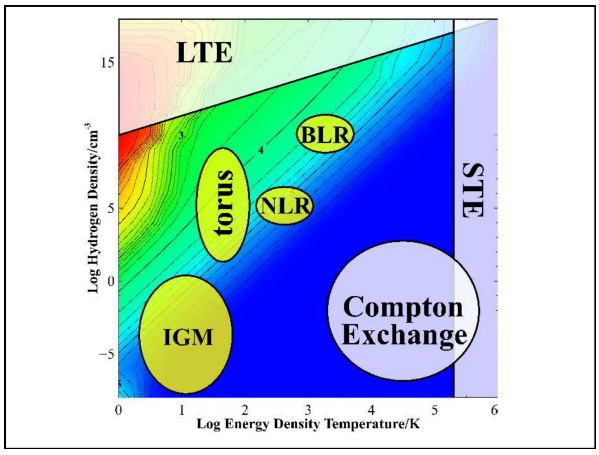
Cloudy and its physics

- 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 ~200 papers that cite its documentation each year



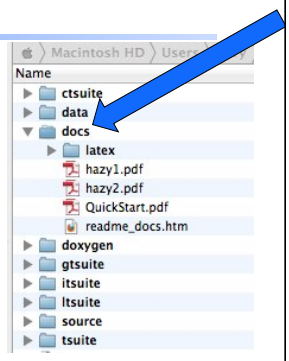


Open source since 1978

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

Documentation

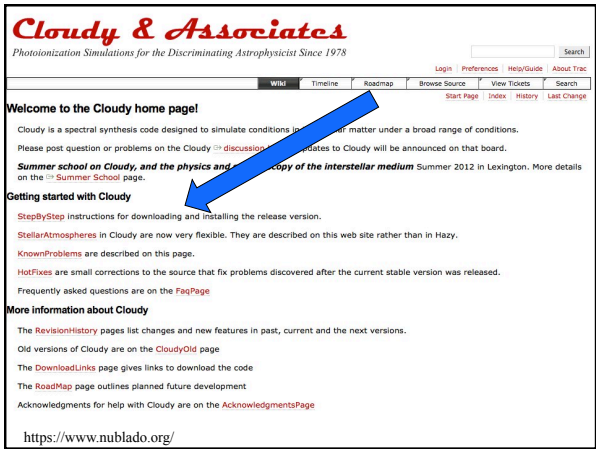
- Quick start guide
- Hazy 1, all commands
- Hazy 2, description of output, comparison with observations
- Hazy 3, not compiled, badly out of date, some physics is described there

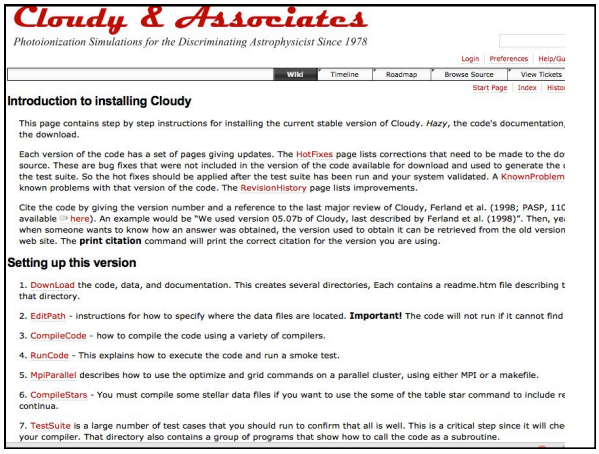


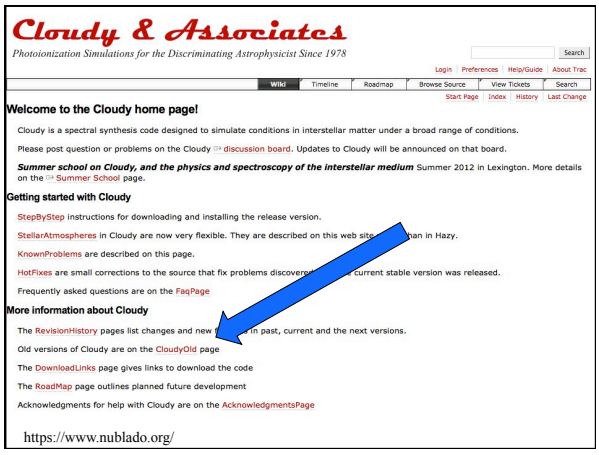
Quick Start Guide to CLOUDY *C13.1*

Cloudy & Associates
www.nublado.org
June 4, 2013

https://www.nublado.org/

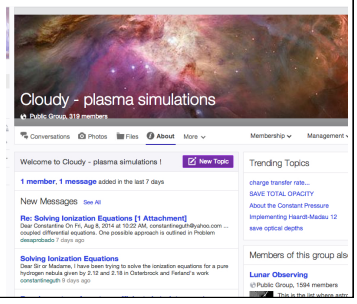


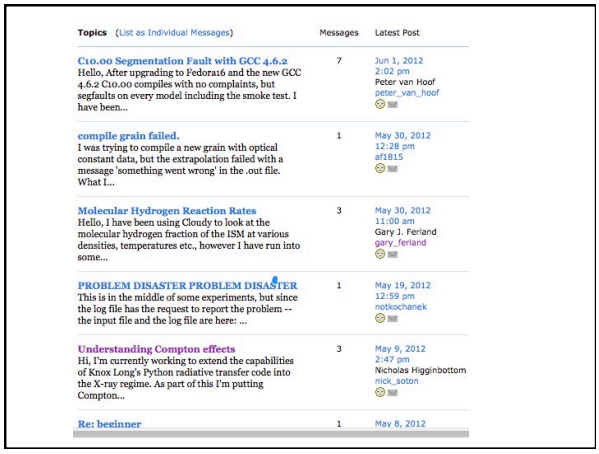




Where to go for help

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





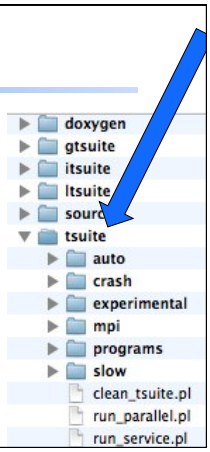
Topics (List as Individual Messages)	Messages	Latest Post
C10.00 Segmentation Fault with GCC 4.6.2 Hello, After upgrading to Fedora16 and the new GCC 4.6.2 C10.00 compiles with no complaints, but segfaults on every model including the smoke test. I have been...	7	Jun 1, 2012 2:02 pm Peter van Hoof peter_van_hoof
compile grain failed. I was trying to compile a new grain with optical constant data, but the extrapolation failed with a message 'something went wrong' in the .out file. What I...	1	May 30, 2012 12:28 pm af1815
Molecular Hydrogen Reaction Rates Hello, I have been using Cloudy to look at the molecular hydrogen fraction of the ISM at various densities, temperatures etc., however I have run into some...	3	May 30, 2012 11:00 am Gary J. Ferland gary_ferland
PROBLEM DISASTER PROBLEM DISASTER This is in the middle of some experiments, but since the log file has the request to report the problem -- the input file and the log file are here: ...	1	May 19, 2012 12:59 pm notkochanek
Understanding Compton effects Hi, I'm currently working to extend the capabilities of Knox Long's Python radiative transfer code into the X-ray regime. As part of this I'm putting Compton...	3	May 9, 2012 2:47 pm Nicholas Higginbottom nick_soton
Re: beginner	1	May 8, 2012

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

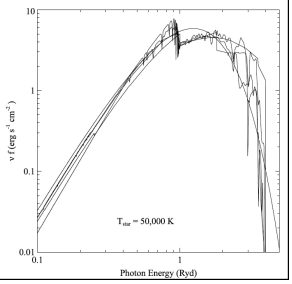
- **Requested with various "save" commands**
  - Hazy 1 Section16.35 and later
- **The main way the code reports its results**

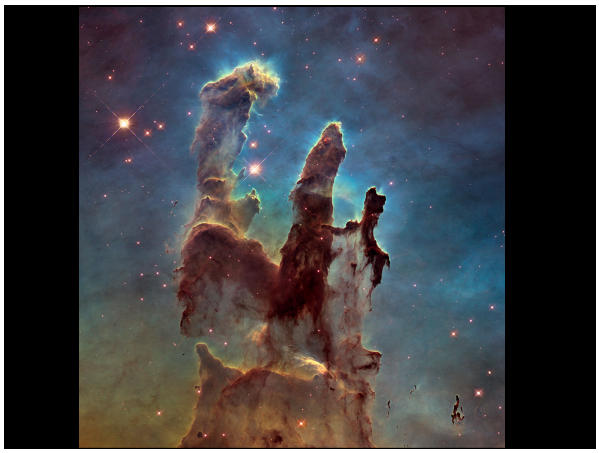
Minimum to run Cloudy

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

Parameters – the SED shape

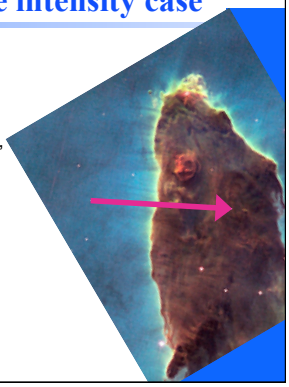
- **Quick start guide Chapter 5**
- **Hazy 1, Chapters 4, 6**
- **Can be specified as a fundamental shape such as a blackbody**
- **Generally entered as table of points**





SED brightness – the intensity case

- **Specify φ(H) – flux of photons per unit area**
  - The "intensity case"
  - predicts surface brightness, emission per unit area erg cm^{-2} s^{-1}
  - Inner radius of cloud does not need to be specified

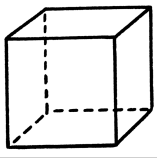


SED brightness – the luminosity case

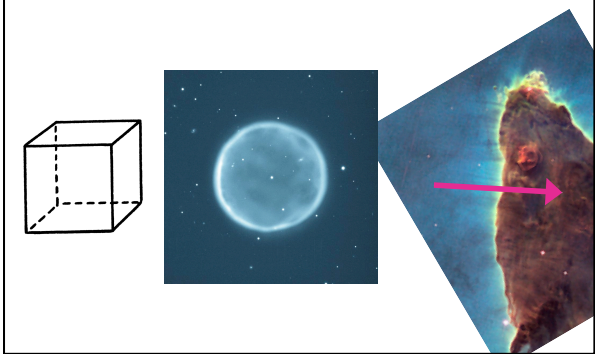
- **Specify Q (H) – photon luminosity**
  - Inner radius of cloud must be specified, since $\varphi(H) = Q(H) / 4\pi r^2$
  - predicts emission line luminosities erg s^{-1}

A "unit cell"

- **We will model a cubic cm of matter in many of the atomic calculations**
- **A "unit cell", 1 cm^3**
- **Intensity case plus commands**
  - Stop zone 1
  - Set dr 0



The three geometries



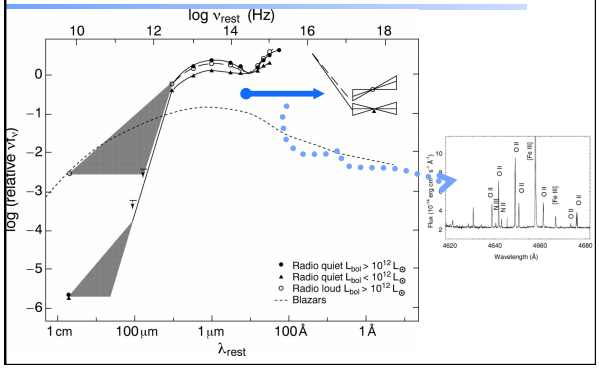
Cloud density, Hazy 1 Chap 8

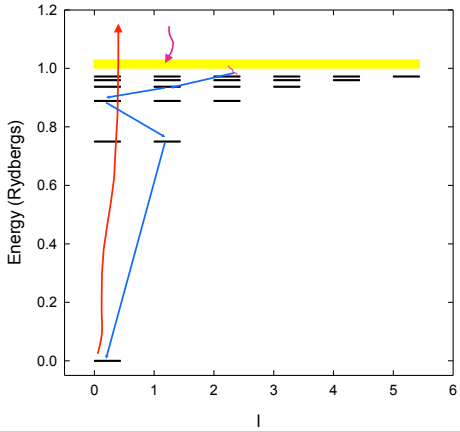
- **"hden" command set H density cm^{-3}**
- **Constant density by default**
  - the H density is the same across the cloud
- **Other equations of state possible**
  - Constant pressure, flows, power-laws

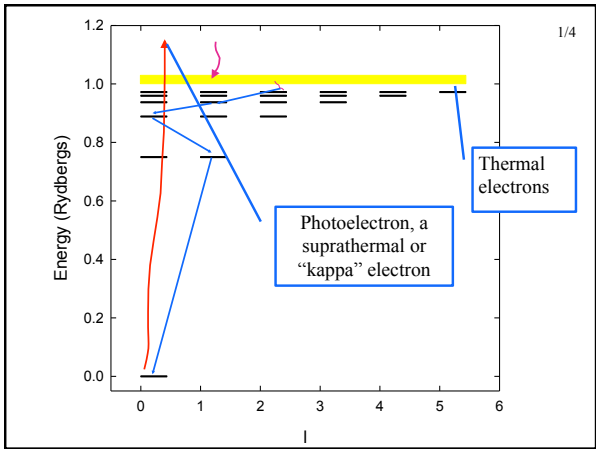
Composition, Hazy 1 Chap 7

- **Solar, no grains, by default**
- **Other standard mixtures possible,**
- **Stored in data / abundances**

The "primary mechanism" Continuum → emission lines

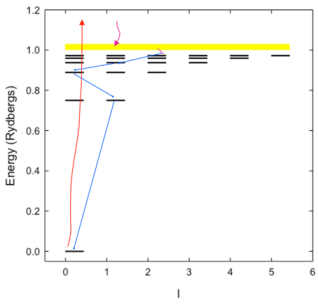






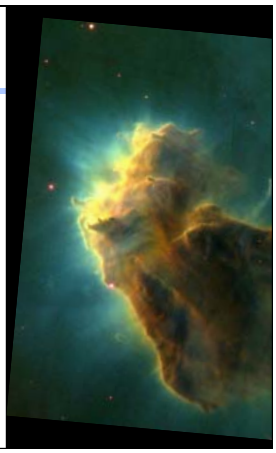
Life history of an Orion electron

- **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**



definitions

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

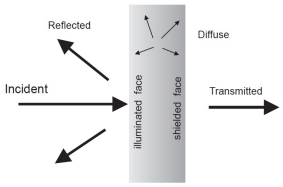


Figure 2.1: Several of the radiation fields that enter in the calculations.

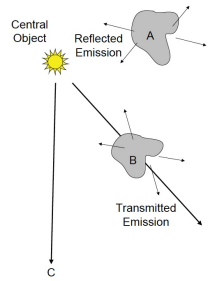
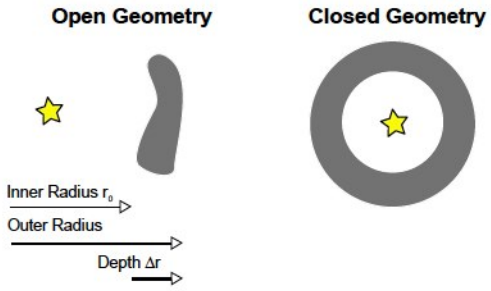
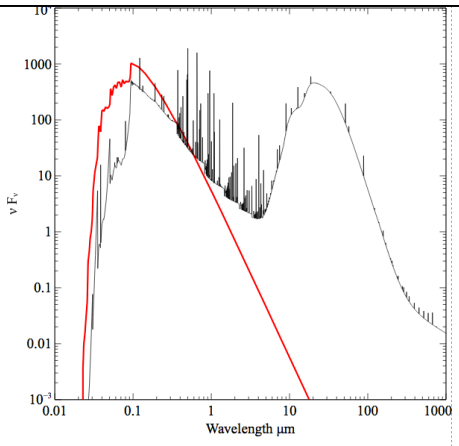


Figure 16.2: This figure illustrates several components of the radiation field that enter in the calculations.

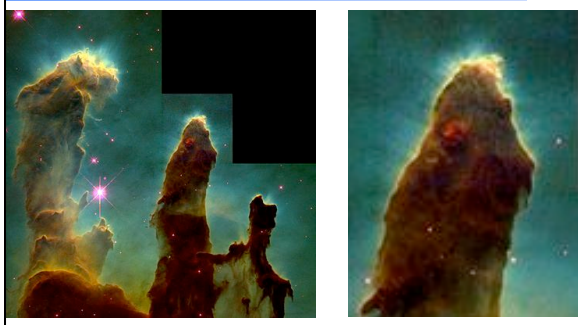
Open vs closed geometry Hazy 2.3



2014 Cloudy workshop

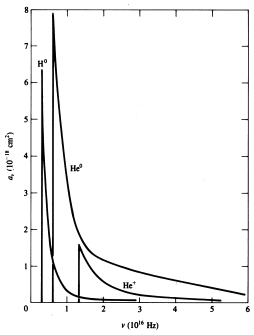


Strömgren length



Photoionization

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



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

Recombination AGN3

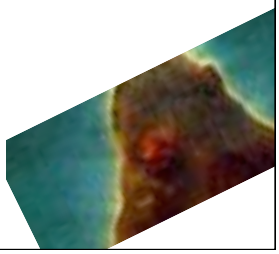
- Electron and ion recombine, emitting energy
- Radiative recombination for H and He
- Dielectronic recombination for heavy element
- Print arrays command (a debugging tool) will report recombination rates (s^{-1})

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?

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

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