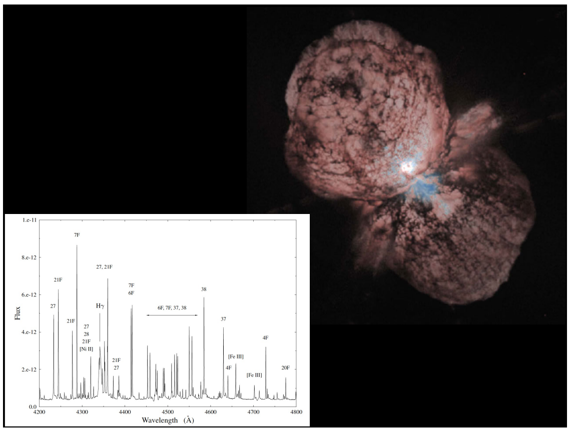
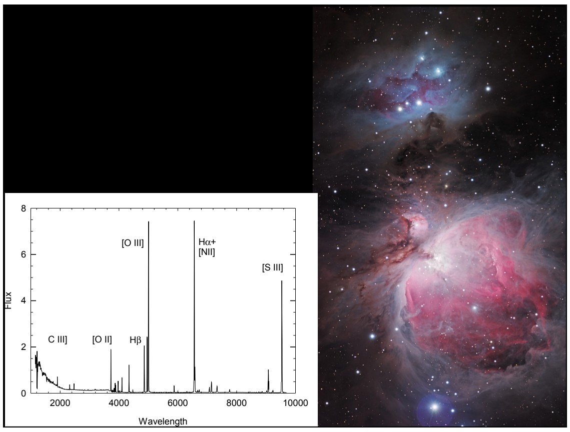
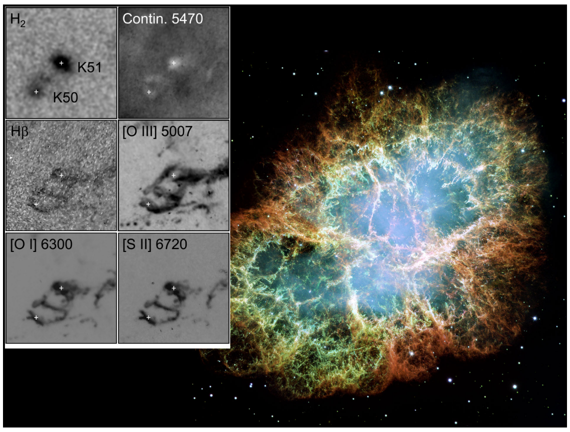
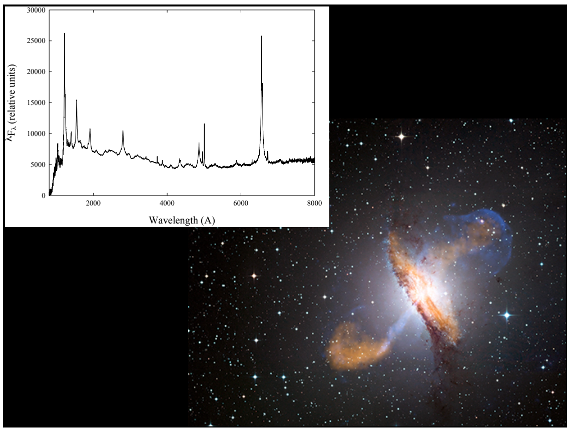
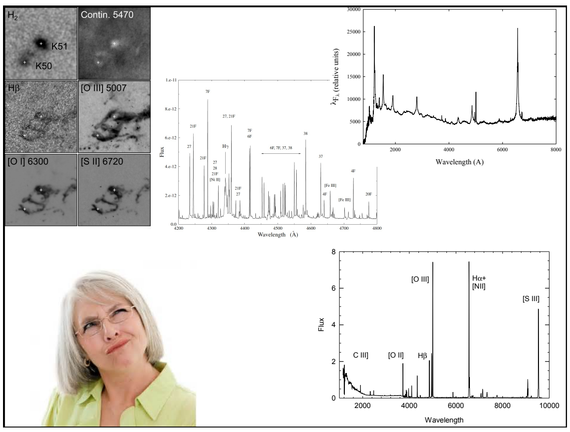
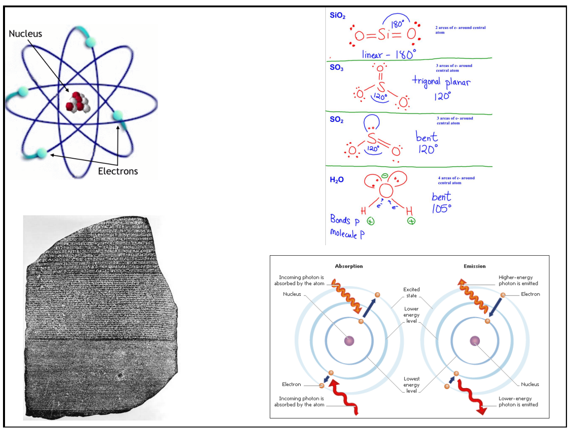

Flux
Wavelength (Å)


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


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


λFλ (relative units)
Wavelength (A)


H2
Contin. 5470
K51
K50
Hβ
[O III] 5007
[O I] 6300
[S II] 6720
λFλ (relative units)
Wavelength (A)
Flux
Wavelength (Å)
C III]
[O II]
Hβ
[O III]
Hα+
[NII]
[S III]
Flux
Wavelength


Nucleus
Electrons
SiO2
linear - 180°
SO3
trigonal planar
120°
SO2
bent
120°
H2O
bent
105°
Absorption
Emission

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

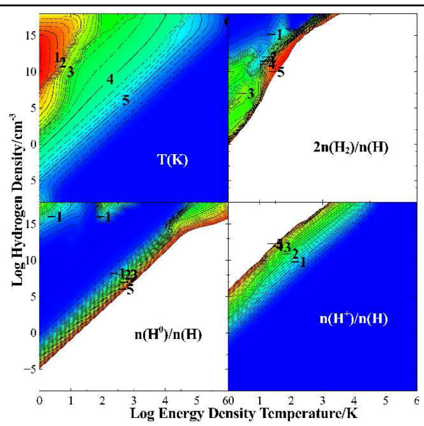
- **Gas ionization**
  - From ionization balance equations
- **Chemistry**
  - Large network based on UMIST
- **Gas kinetic temperature**
  - Heating and cooling
- **Grain physics**
  - Charging, CX, photoejection, quantum heating
- **The observed spectrum**
  - Radiative transport

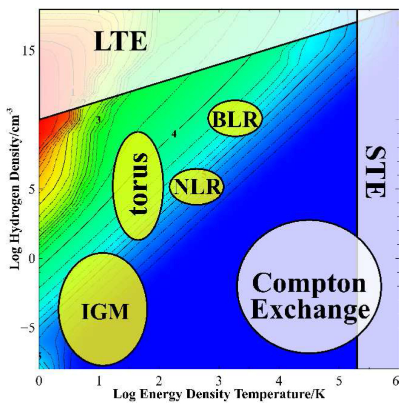
Cloudy and its physics

- **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**



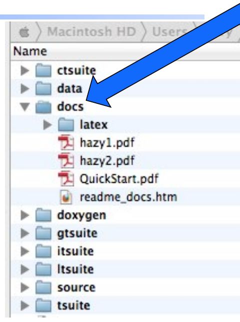


Open source since 1978

- 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

Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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.

Please post question or problems on the Cloudy discussion board. Updates to Cloudy will be announced on that board.

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

Getting started with Cloudy

StepByStep instructions for downloading and installing the release version.

StellarAtmospheres in Cloudy are now very flexible. They are described on this web site rather than in Hazy.

KnownProblems are described on this page.

HotFixes are small corrections to the source that fix problems discovered after the current stable version was released.

Frequently asked questions are on the FaqPage

More information about Cloudy

The RevisionHistory pages list changes and new features in past, current and the next versions.

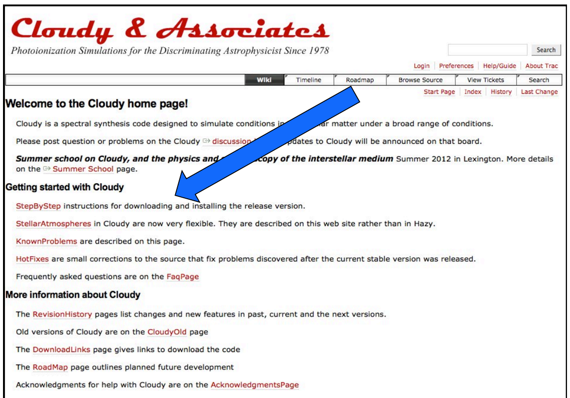
Old versions of Cloudy are on the CloudyOld page

The DownloadLinks page gives links to download the code

The RoadMap page outlines planned future development

Acknowledgments for help with Cloudy are on the AcknowledgmentsPage

https://www.nublado.org/



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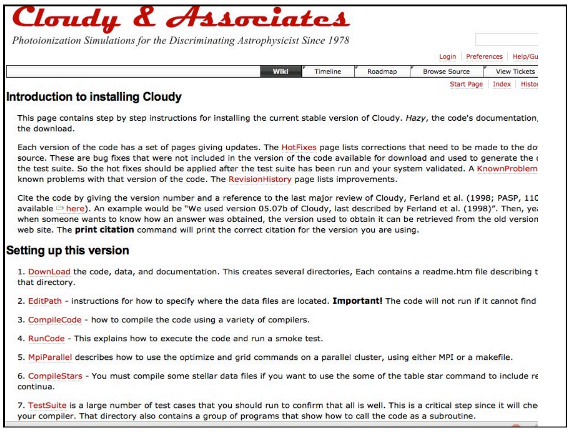


Cloudy & Associates

Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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.

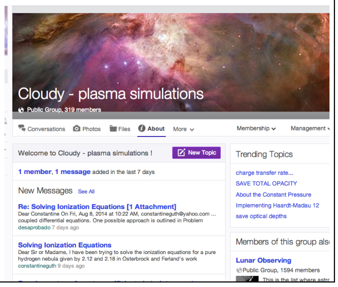
Cite the code by giving the version number and a reference to the last major review of Cloudy, Ferland et al. (1998; PASP, 110 available here). An example would be "We used version 05.07b of Cloudy, last described by Ferland et al. (1998)". Then, ye when someone wants to know how an answer was obtained, 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.

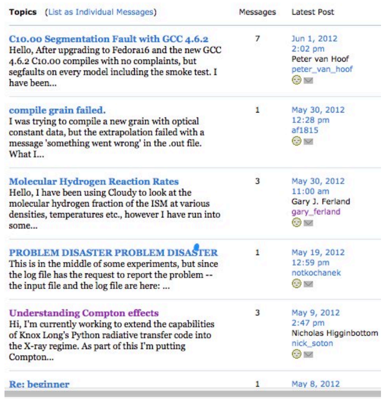
Setting up this version

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.

Where to go for help

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





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

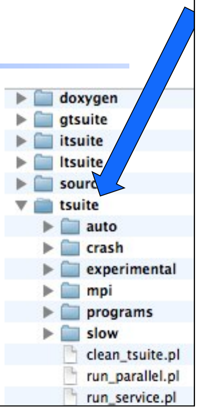
- **Emissivity $4\pi j$**
  - Emission per unit volume, per second
- **Optical depth τ**
  - Number of mean free paths through a medium
- **Opacity κ**
  - $\tau = \kappa n$
- **Planck function $B = j/\kappa$**
- **Rob Rutten's course notes describes this and more**
  - http://www.staff.science.uu.nl/~rutte101/Radiative_Transfer.html

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

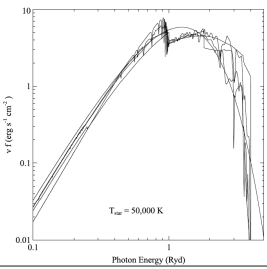
- **Must specify**
  - SED – shape of the radiation field
  - Flux of photons per unit area
  - Gas density
- **May specify**
  - Gas composition, grains (grain-free solar by default)
  - Gas equation of state (often constant density)
  - Stopping criterion, often physical thickness

Parameters – the SED shape

- **Quick start guide Chapter 5**
- **Hazy 1, Chapters 4, 6**

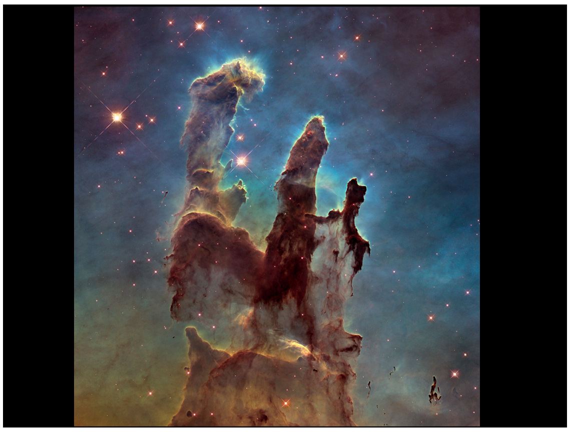
- **Can be specified as a fundamental shape such as a blackbody**

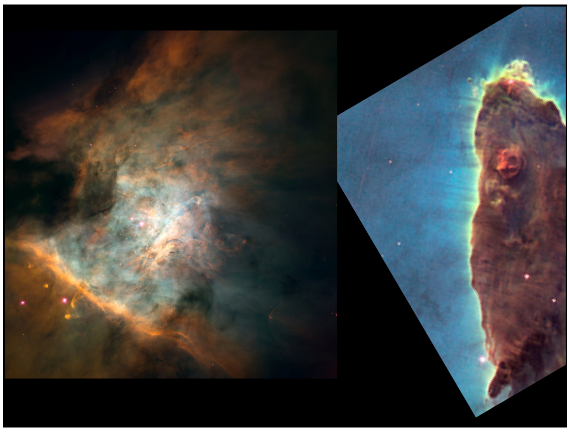
- **Generally entered as table of points**



SED brightness – the luminosity case

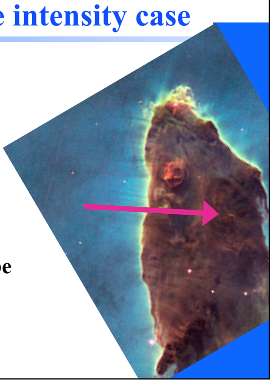
- **Specify Q (H) – photon luminosity**
  - Inner radius of cloud must be specified, since φ (H) = Q(H) / 4π r^2
  - predicts emission line luminosities erg s^{-1}





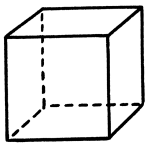
SED brightness – the intensity case

- **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
- **Ionization parameter can be used to set φ(H)**

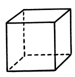


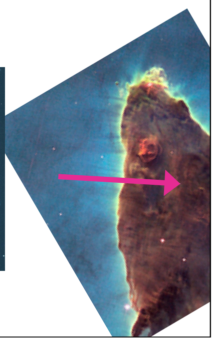
A “unit cell”

- **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





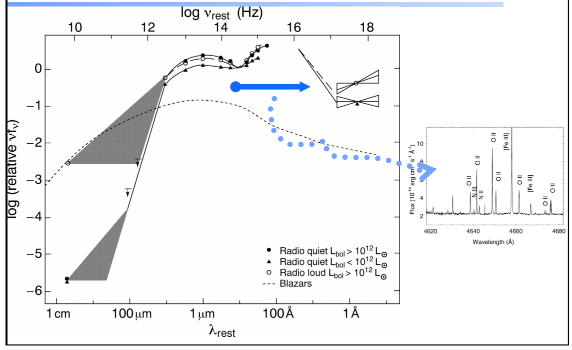
Cloud density, Hazy 1 Chap 8

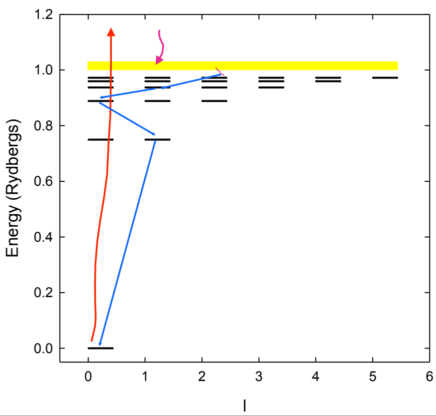
- **“hden” command set H density cm^{-3}**
- **Constant density by default**
  - the H density is the same across the cloud
- **Other equations of state possible**
  - Constant pressure, flows, power-laws

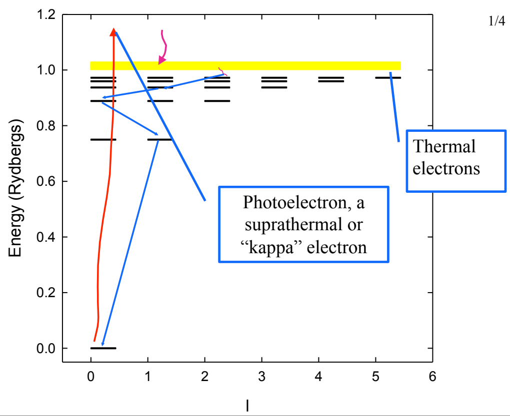
Composition, Hazy 1 Chap 7

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

The "primary mechanism" Continuum → emission lines

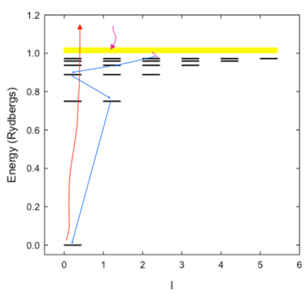






Life history of an Orion electron

- 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

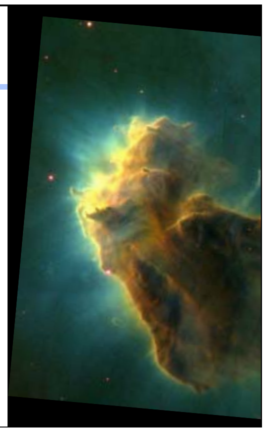


Table 2.3
Calculated Strömgren radii as function of spectral types spheres

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

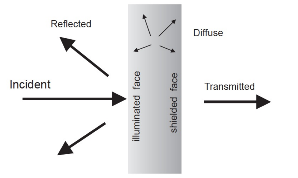


Figure 2.1: Several of the radiation fields that enter in the calculations.

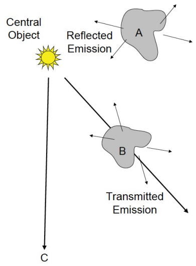
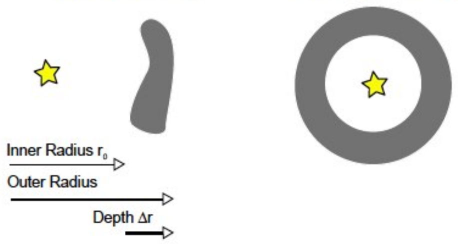


Figure 16.2: This figure illustrates several components of the radiation field that enter in the calculations.

Open vs closed geometry Hazy 2.3

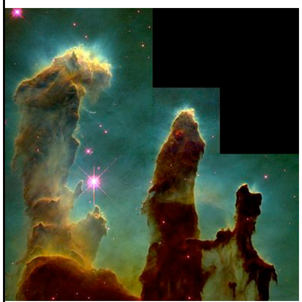


2014 Cloudy workshop

Plot components of radiation field

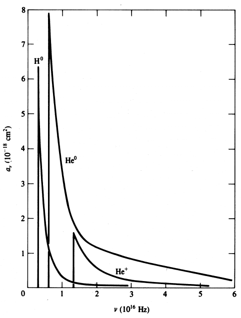
- Incident stellar continuum
- Total continuum produced
- Reflected continuum

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

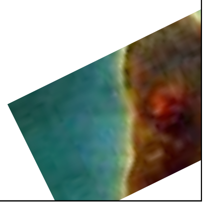
	T				
	1,250 K	2,500 K	5,000 K	10,000 K	20,000 K
$\alpha_A = \sum_1^\infty \alpha_n$	1.74×10^{-12}	1.10×10^{-12}	6.82×10^{-13}	4.18×10^{-13}	2.51×10^{-13}
$\alpha_B = \sum_2^\infty \alpha_n$	1.28×10^{-12}	7.72×10^{-13}	4.54×10^{-13}	2.59×10^{-13}	1.43×10^{-13}
$\alpha_C = \sum_3^\infty \alpha_n$	1.03×10^{-12}	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?