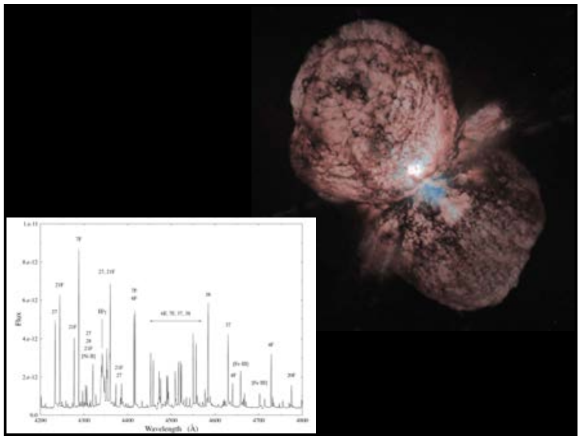
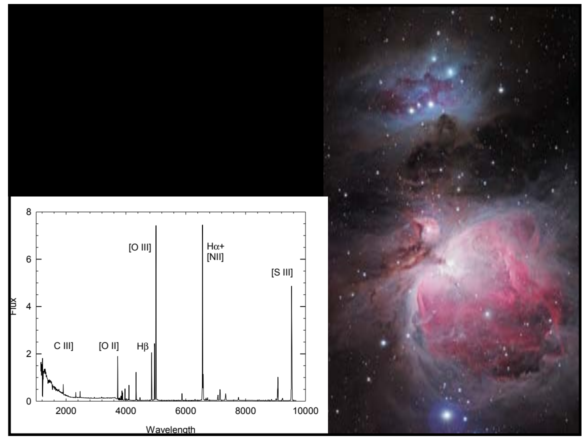
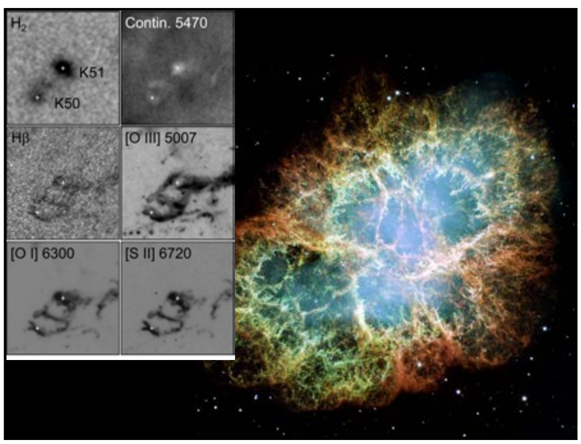
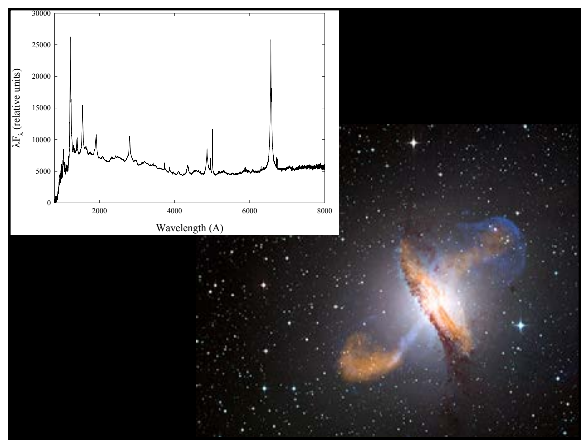
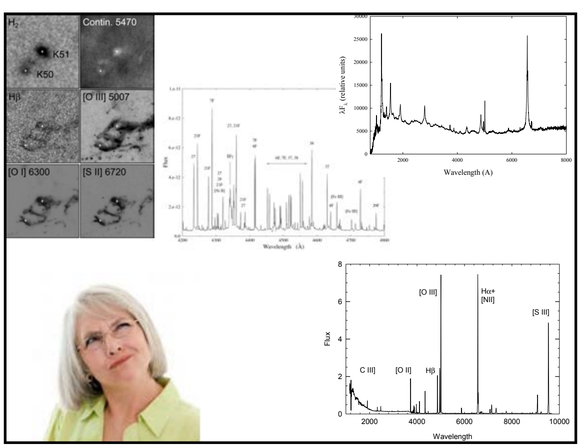
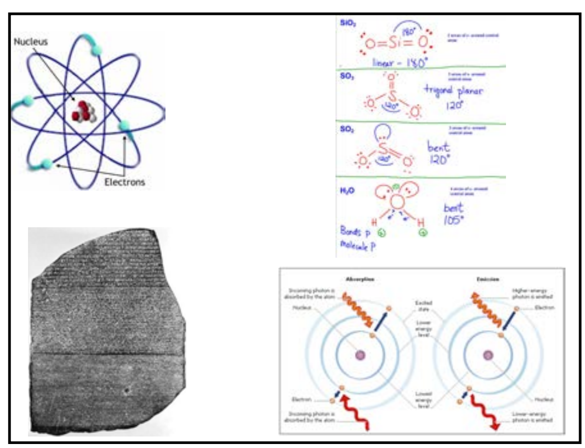

Flux
Wavelength (Å)


Flux
C III]
[O II]
Hβ
[O III]
Hα+
[NII]
[S III]
2000
4000
6000
8000
10000
Wavelength


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


λFλ (relative units)
Wavelength (A)


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


Nucleus
Electrons
Absorption
Emission

$$F = G\frac{m_1 m_2}{d^2}$$

$$\dot{\Psi} = \left(-\frac{\dot{R}}{R^2} + \frac{\mathrm{i}\dot{F}}{R}\sum_{i=1}^{N}\mathbf{x}_i^2 + \frac{\mathrm{i}\dot{\mathbf{G}}}{R}\sum_{i=1}^{N}\mathbf{x}_i + \mathrm{i}\frac{\dot{M}}{R}\right)\mathrm{e}^{\mathrm{i}\phi(x_i,t)}\Phi(\mathbf{y}_i,\tau)$$
$$+\frac{1}{R}\mathrm{e}^{\mathrm{i}\phi(x_i,t)}\sum_{i=1}^{N}\frac{\partial\Phi(\mathbf{y}_i;\tau)}{\partial\mathbf{y}_i}\left[\mathbf{x}_i\left(-\frac{\dot{L}}{L^2}\right)+\dot{\mathbf{S}}(t)\right]+\frac{1}{R}\mathrm{e}^{\mathrm{i}\phi(x_i,t)}\frac{\partial\Phi(\mathbf{y}_i;\tau)}{\partial\tau}\dot{\tau}, \qquad \text{(A.2)}$$

Cloudy QSG Chapter 1

- **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) for 1 and 2 electron atoms
  - 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 is a microphysics code

- **Emphasis is on getting the atomic and molecular physics right**
- **If we get the microphysics right, the macrophysics will take care of itself**
- **Other codes have dynamics, shocks, 3D, as an emphasis, sometimes using Cloudy to get the microphysics**

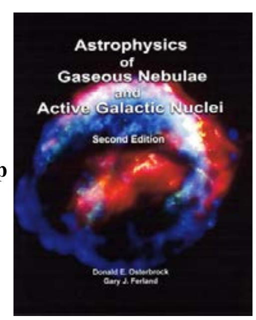
On the web

http://cloud9.pa.uky.edu/~gary/cloudy/CloudySummerSchool

- **Agenda for the workshop**
  - Includes copies of presentations
- **Participant interests**
- **ftp site with documentation, and examples**

Osterbrock & Ferland
Astrophysics of Gaseous Nebulae

- **There are three versions, this is the 3rd**
  - Don called this on AGN3
- **Any version is OK**
- **PDFs of some sections are in the docs folder of the ftp site**

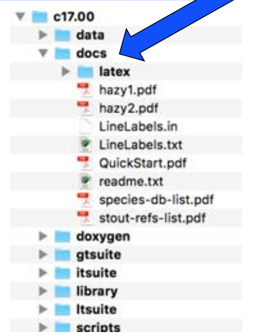


Cloudy version C17

- We set this up, ran a model, and created plots, as our homework last week
- PDFs of the Quick Start Guide, and the first two volumes of Hazy, its documentation, are in the docs folder of the ftp site
- Copies of the last three major reviews of Cloudy are also in the docs folder of the ftp site

Documentation

- QSG 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 *C17*

Cloudy & Associates
www.nublado.org
May 27, 2017

Cloudy & Associates
Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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

C17.00, is released. This paper discusses what is new. Follow the StepByStep instructions for downloading and installing the code, or go straight to the DownloadLinks page to obtain it. NewC17 explains improvements and changes.

Cloudy Workshops Summer 2017

Queen's University Belfast: 31 July - 4 August 2017 We are pleased to announce the Cloudy Workshop 2017, which will be held in the School of Mathematics and Physics at Queen's University Belfast. For more information, or to register, visit this site. **Registration open**

The **Guillermo Haro advanced school** on modelling the ionized universe will be held at INAOE (Instituto Nacional de Astrofísica, Óptica y Electrónica, Tonantzintla, Puebla, Mexico) from July 3rd to 14th, 2017. The school will provide a comprehensive, state-of-the-art, hands-on approach to the modelling of ionized gas in different environments, from AGB stars to active galactic nuclei, to an audience of up to 40 young researchers, mainly PhD students and postdocs. The first week will consist of a Cloudy workshop led by Gary Ferland. The second week will delve further into the topics introduced during the first week, with lectures by Gloria Delgado-Inglada (IA-UNAM), Gary Ferland (University of Kentucky), Christophe Morisset (IA-UNAM), Hagai Netzer (Tel Aviv University), Manuel Peimbert (IA-UNAM), and Mónica Rodríguez (INAOE). This website has further details and instructions for applying for the School. **Registration closed**

Getting started with Cloudy

The VideoPage has a video showing how to build and run Cloudy.

StepByStep instructions for downloading and installing the release version, and running the code on various platforms.

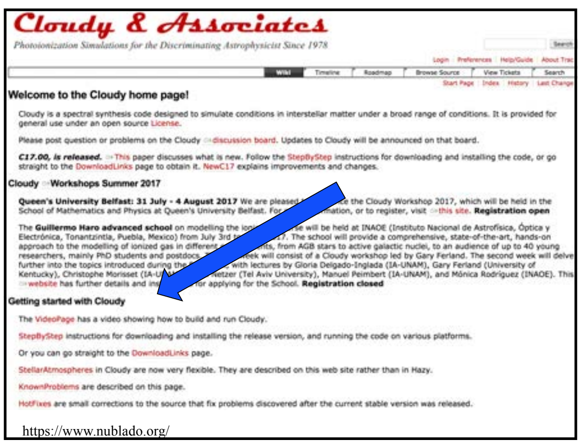
Or you can go straight to the DownloadLinks page.

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.

https://www.nublado.org/



Cloudy & Associates
Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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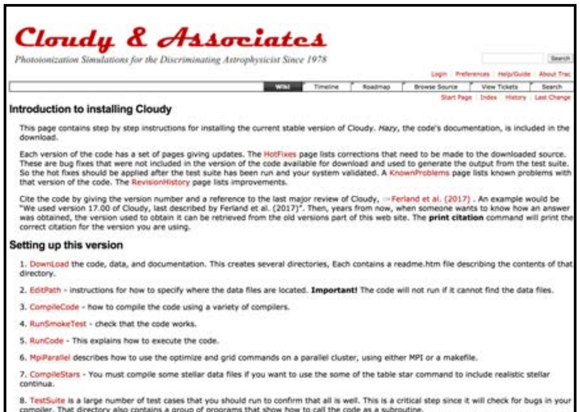

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Photoionization Simulations for the Discriminating Astrophysicist Since 1978

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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, is included in 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 downloaded source. These are bug fixes that were not included in the version of the code available for download and used to generate the output from the test suite. So the hot fixes should be applied after the test suite has been run and your system validated. A KnownProblems page lists known problems with that version of the code. The RevisionHistory page lists improvements.

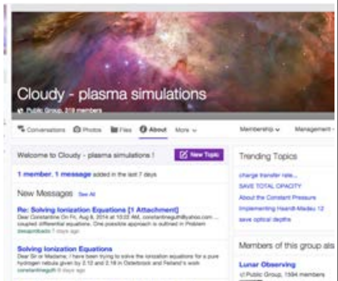
Cite the code by giving the version number and a reference to the last major review of Cloudy, Ferland et al. (2017) . An example would be "We used version 17.00 of Cloudy, last described by Ferland et al. (2017)". Then, years from now, when someone wants to know how an answer was obtained, the version used to obtain it can be retrieved from the old versions part of this web site. The **print citation** command will print the correct citation for the version you are using.

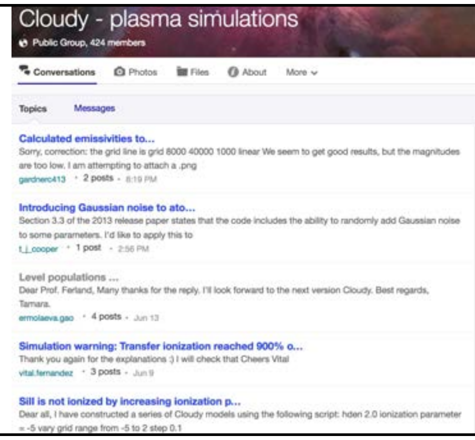
Setting up this version

1. DownLoad the code, data, and documentation. This creates several directories, Each contains a readme.htm file describing the contents of 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 the data files.
3. CompileCode - how to compile the code using a variety of compilers.
4. RunSmokeTest - check that the code works.
5. RunCode - This explains how to execute the code.
6. MpiParallel describes how to use the optimize and grid commands on a parallel cluster, using either MPI or a makefile.
7. CompileStars - You must compile some stellar data files if you want to use the some of the table star command to include realistic stellar continua.
8. 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 check for bugs in 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





Running cloudy

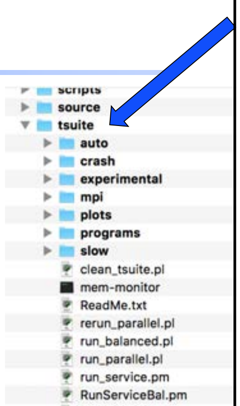
- "run" file contains /Users/gary/cloudy/trunk/source/sys_llvm/cloudy.exe -r $1 2> $1.err
- If file "model.in" contains input, then
- run model &
- Produces output "model.out"
- The model will run in the "background" when the line ends with &

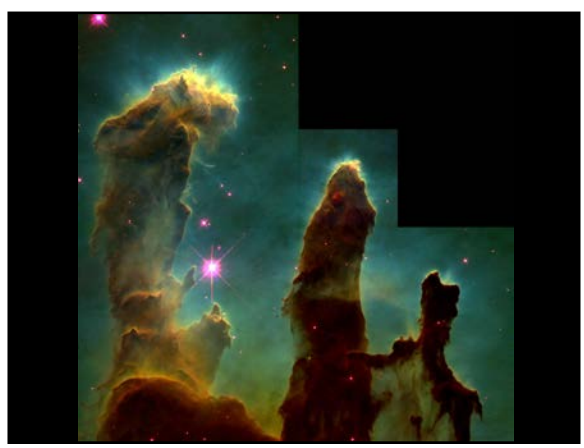
Runtime options

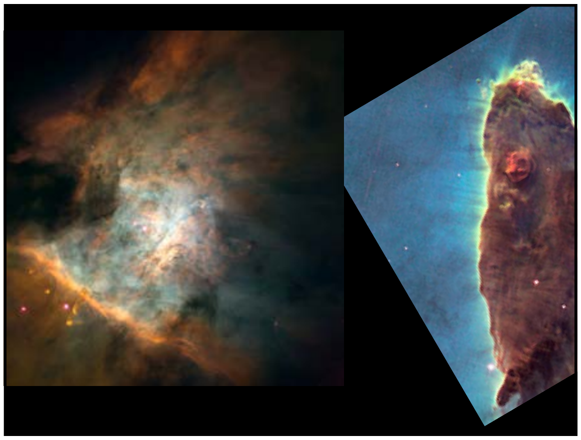
- Appear after cloudy.exe
- Described here
- -r
  - I use this in my workflow
  - Required for grids to work
  - Study the options and consider what is best for your workflow

The test suite

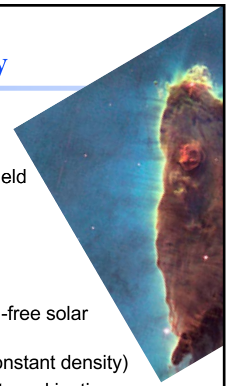
- Fully tests the code after any changes
  - "Monitors" allow automatic comparison of current with previous results
- Provides examples of how to use Cloudy
  - But may include extraneous commands for testing
  - Or backwards compatible
- Useful examples of how to set up a simulation







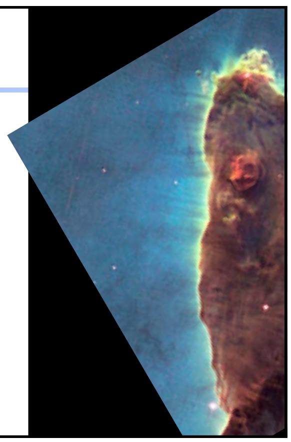
Minimum to run Cloudy



- Hazy 1 Section 1.2
- 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

Let's model a …

- Relatively dense, $n_H = 10^4$ cm^{-3}
- ISM cloud
- Ionized by an O6 star



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
- Rydberg – the ionization potential of hydrogen

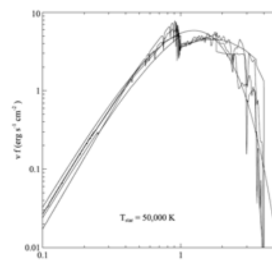


Table 2.3

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.

Command deck to do this

- Blackbody 4.36e4 K

Commands – Hazy1 Chap 3

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

SED brightness

- QSG Chapter 5, Hazy1 Chapter 4 and 5
- The atomic physics is determined by the flux of photons hitting the cloud's illuminated face
- Units
  photons cm^{-2} s^{-1}

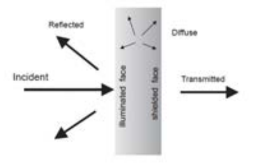


Figure 2.1: Several of the radiation fields that enter in the calculations.

SED brightness

- QSG Chapter 5, Hazy1 Chapter 4 and 5
- Luminosity case
  - Specify total photon luminosity
  - Predict line luminosities
- 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

SED brightness – the luminosity case

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

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Calculated Strömgren radii as function of spectral types spheres

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

Command deck to do this

- Blackbody 4.36e4 K
- Q(H) 49.34

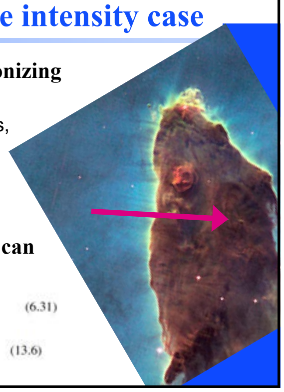
Radius command, Chap 9.10

- If luminosity is set then the radius, the separation between the star and the illuminated face of the cloud, must also be specified
- Radius command
  - log radius in cm by default
  - Linear, or parsecs, can be used by setting optional keywords
- Let's put our cloud 10^{16} cm from the star

Command deck to do this

- Blackbody 4.3e4 K
- Q(H) 49.34
- Radius 16
- We will try different radii later

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)

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

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

Ionization parameter

- Dimensionless ratio of hydrogen to ionizing photon densities

$$U = \frac{1}{4\pi r^2 c n_\mathrm{H}} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu = \frac{Q\,(\mathrm{H}^0)}{4\pi r^2 c n_\mathrm{H}}, \qquad (14.7)$$

$$n(X^{+i}) \int_{\nu_i}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(X^{+i}) d\nu = n(X^{+i}) \Gamma(X^{+i}) = n(X^{+i+1}) n_e \alpha_G(X^{+i}, T), \qquad (2.30)$$

Xi – an x-ray ionization parameter

Hazy 1

5.16 xi -0.1

Tarter et al. (1969); Krolik et al. (1981); Kallman and Bautista (2001) define an ionization parameter ξ given by

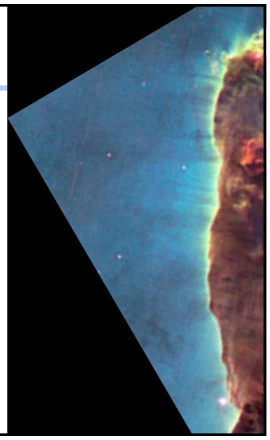
$$\xi = (4\pi)^2 \int_{1R}^{1000R} J_\nu d\nu / n(\mathrm{H}) \approx \frac{L_{ion}}{n(\mathrm{H}) r^2} [\mathrm{erg\ cm\ s^{-1}}] \qquad (5.12)$$

Cloud density, Hazy 1 Chap 8

- "hden" command, Chapt 8.8, sets log of total 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

Let's model a …

- Relatively dense, $n_H = 10^4$ cm^{-3}
- ISM cloud
- Ionized by an O6 star

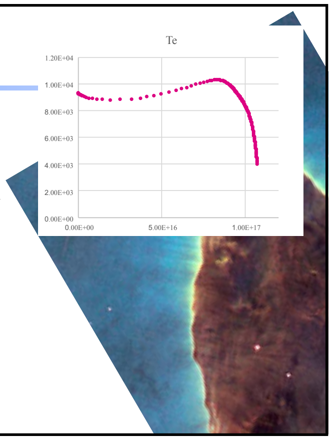


Command deck to do this

- Blackbody 4.3e4 K
- Q(H) 49.34
- Radius 16
- Hden 4

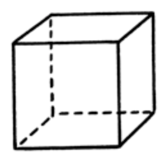
"zones"

- Divide cloud into thin layers called "zones"
- Temperature and ionization within each zone does not change



A "unit cell"

- We will sometimes model a cubic cm of matter
- Lots faster 7 simpler
- 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



Command deck so far

- Blackbody 4.3e4 K
- Q(H) 49.34
- Radius 16
- Hden 4
- stop zone 1
- set dr 0

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

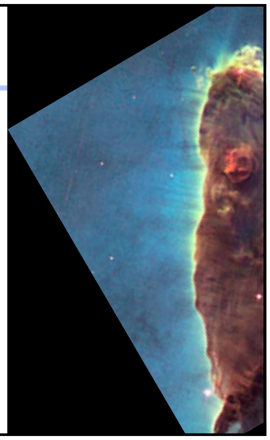
```
                         Gas Phase Chemical Composition
H :  0.0000  He: -1.0223  Li:-10.2676  B :-10.0506  C : -3.5229  N : -4.1549  O : -3.3979  Ne: -4.2218  Na: -6.5229
Mg: -5.5229  Al: -6.6990  Si: -5.3979  P : -6.7959  S : -5.0000  Cl: -7.0000  Ar: -5.5229  K : -7.9586  Ca: -7.6990
     Ti: -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
```

Let's model a …

- Relatively dense, $n_H = 10^4$ cm^{-3}
- ISM cloud
- Ionized by an O6 star

- The ISM is dusty, and some elements are depleted by condensation onto dust
- Abundances ISM
  - Chapt 7.4.3



Command deck so far

- Blackbody 4.36e4 K
- Q(H) 49.34
- Radius 16
- Hden 4
- stop zone 1
- set dr 0
- Abundances ISM

Background cosmic rays

- Interstellar chemistry requires a source of ionization to work
  - To get over "activation barrier" in reactions
- The chemistry network will fail in unphysical ways if ionization is not present
- Galactic background cosmic rays provide this ionization in nature
- Cosmic rays background, Chapt 11.6.1

Command deck so far

- Blackbody 4.3e4 K
- Q(H) 49.34
- Radius 16
- Hden 4
- stop zone 1
- set dr 0
- Abundances ISM
- Cosmic rays background

"Save" output

- Requested with various "save" commands
  - Hazy 1 Section16.35 and later
- This is the main way I extract results
- Keyword to specify what to save
- Filename to set where to save it

- Set save prefix "name"
  - Prepends "name" to all save files

A note on quotation marks

- Office products will put "smart quotes" in our examples
- C++ requires straight quotes.

```
set path "example"
save overview ".ovr"
```

Save files

- **Save emitted continuum "filename"**
  - Photon energy is Rydberg by default
  - Change to microns with keyword units
  - Units microns
- **Save overview**
  - Useful information such as gas temperature and ionization
- **Save element *name***
  - Saves ionization of element specified

Command deck so far

- Set save prefix "HII"
- Blackbody 4.3e4 K
- Q(H) 49.34
- Radius 16
- Hden 4
- stop zone 1
- set dr 0
- Abundances ISM
- Cosmic rays background
- Save overview ".ovr" last no hash
- Save element hydrogen ".hyd" last no hash
- Save emitted continuum ".econ" units microns

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**

Warnings, cautions, notes

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

```
 Calculation stopped because NZONE reached. Iteration 1 of 1
 The geometry is plane-parallel.
-Continuum zero at some energies.
-The H Lyman continuum is thin, and I assumed that it was thick.  Use the ITERATE command to do more iterations.
-The He II continuum is thin and I assumed that it was thick.  Use the ITERATE command to do more iterations.
-The He I continuum is thin and I assumed that it was thick.  Use the ITERATE command to do more iterations.
!Destruction of He 2TriS reached 32.0% of the total He0 dest rate at zone 1, 32.0% of that was photoionization.
!Non-collisional excitation of [O III] 4363 reached 12.61% of the total.
!AGE: Cloud age was not set.  Longest timescale was 5.40e+08 s = 1.71e+01 years.
!Local grain-gas photoelectric heating rate reached  63.5% of the total.
!Grain photoelectric heating is VERY important.
!The CMB was not included.  This is added with the CMB command.
```

Check end of output

```
 Cloudy ends: 1 zone, 1 iteration, 4 cautions. (single thread) ExecTime(s) 8.80
 [Stop in cdMain at ../maincl.cpp:517, Cloudy exited OK]
```

Break into 6 groups, do 6 radii

- **Radius. (log, cm)**
  - 13
  - 15
  - 17
  - 19
  - 21
  - 23