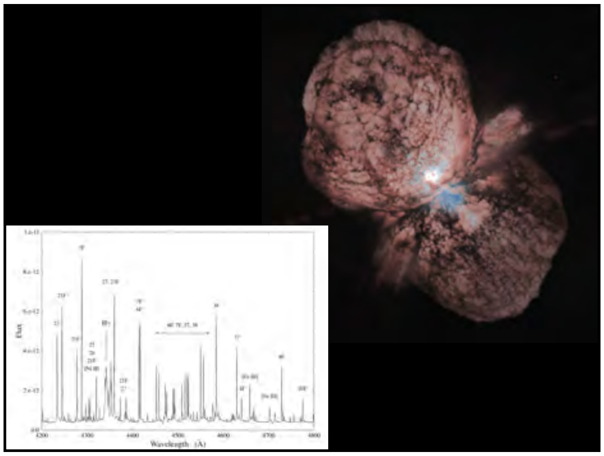
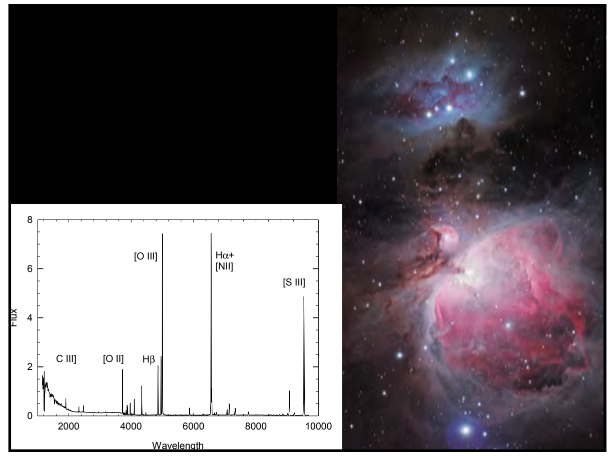
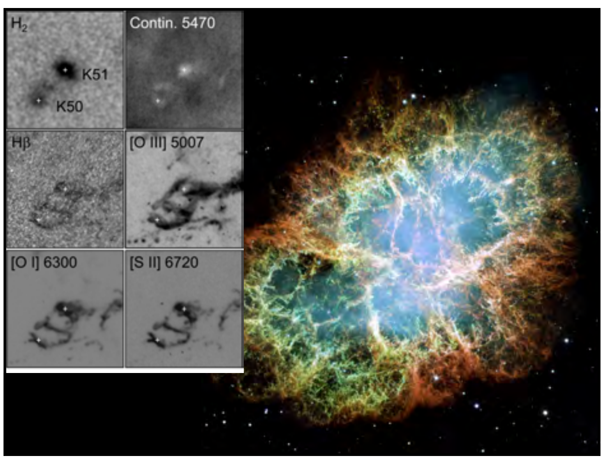
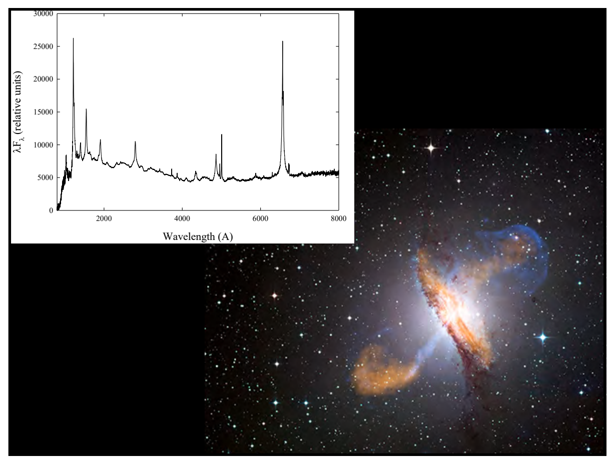
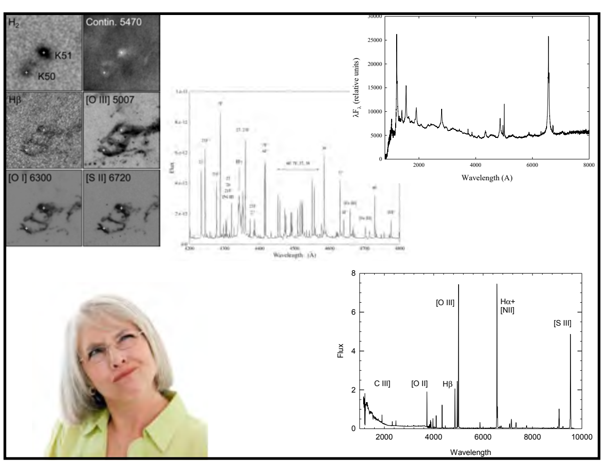
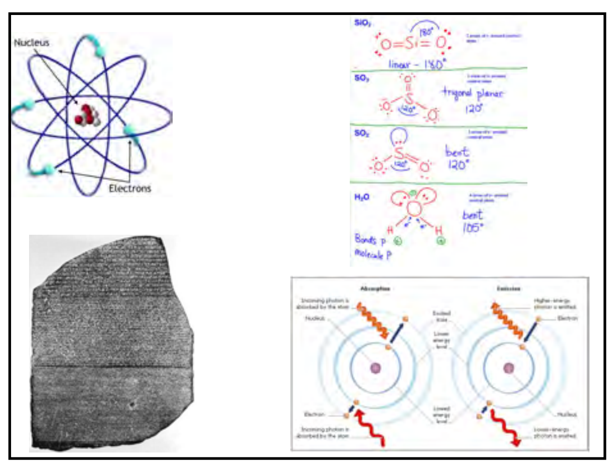

Flux
Wavelength (Å)


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


Nucleus
Electrons
linear - 180°
trigonal planar
120°
bent
120°
bent
105°

Documentation

- In docs directory in Cloudy download
- Also on web share under "docs" folder

THE 2017 RELEASE OF CLOUDY

Review

THE 2017 RELEASE OF Cloudy

G. J. Ferland[1], M. Chatzikos[1], F. Guzmán[1], M. L. Lykins[1], P. A. M. van Hoof[2], R. J. R. Williams[3], N. P. Abel[4], N. R. Badnell[5], F. P. Keenan[6], R. L. Porter[7], P. C. Stancil[7]

RESUMEN

Quick Start Guide to CLOUDY *C17*

Cloudy & Associates
www.nublado.org
June 1, 2017

Quick Start Guide to CLOUDY *C17*

- Introduction
- Two very simple models
- Geometry
- Composition and density
- The incident radiation field
- Other commands
- The code's predictions
- Example calculations
- How to make this plot
- REFERENCES
- Veusz Cookbook

Cloudy QSG Chapter 1

- **Accurate simulation of physical processes at the atomic & molecular level**
  - Physical processes treated from first principles, not with sub-grid physics or simple fitting formulae
- **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

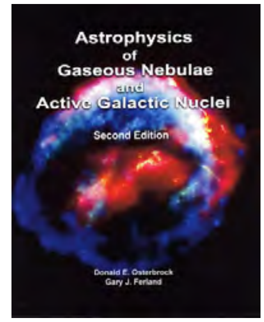
- **Gas ionization**
  - From ionization balance equations
- **Chemistry**
  - Large chemical network based on UMIST
- **Gas kinetic temperature**
  - Heating and cooling
- **Level populations and emission**
- **Grain physics**
  - Charging, CX, photoejection, quantum heating
- **The observed spectrum**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

Cloudy is a microphysics code

- Emphasis is on doing the atomic and molecular physics from first principles
- If we get the microphysics right, the macrophysics will take care of itself
- Many codes have dynamics, shocks, or 3D, as an emphasis, sometimes using Cloudy to get the microphysics

Osterbrock & Ferland Astrophysics of Gaseous Nebulae

- There were three versions, this is the 3rd
  - Don called this "AGN3"
- Any version is OK
- PDFs of chapters we will use are in the docs folder of the web share

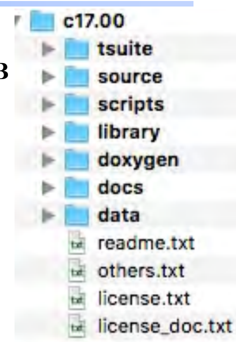


Cloudy version C17.01

- We set this up, ran a model, and created plots, as our homework
- The last three major Cloudy reviews are also in the docs folder of the web share

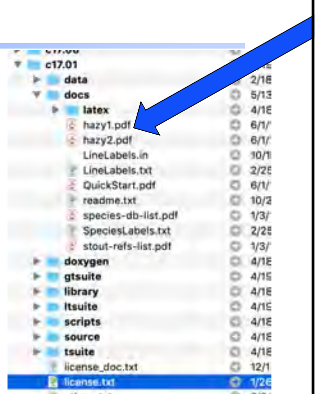
The Cloudy download

- 527 MB uncompressed
- 468 MB of this is data, 9.4 MB is source
- 88.8% atomic & molecular data



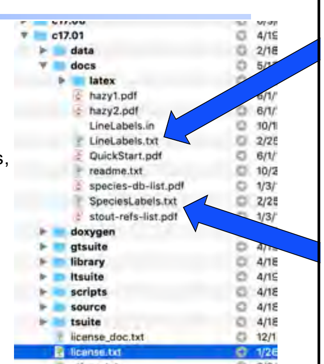
Documentation

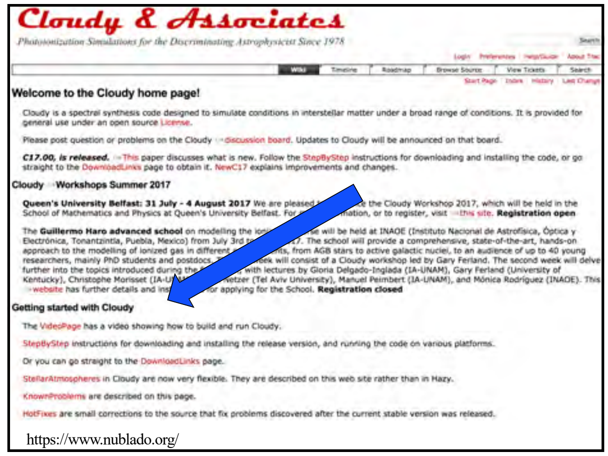
- QSG Quick Start Guide
- Hazy 1, all commands
- Hazy 2, description of output, comparison with observations



Documentation

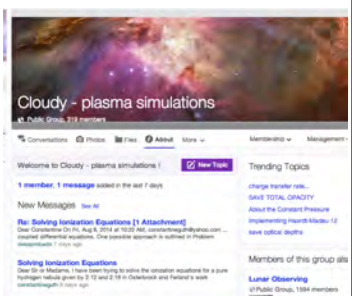
- LineLabels.txt
  - List of all lines known to the code
- SpeciesLabels.txt
  - List of all species (atoms, ions, and molecules) known to the code
- Can be recreated by running LineLables.in

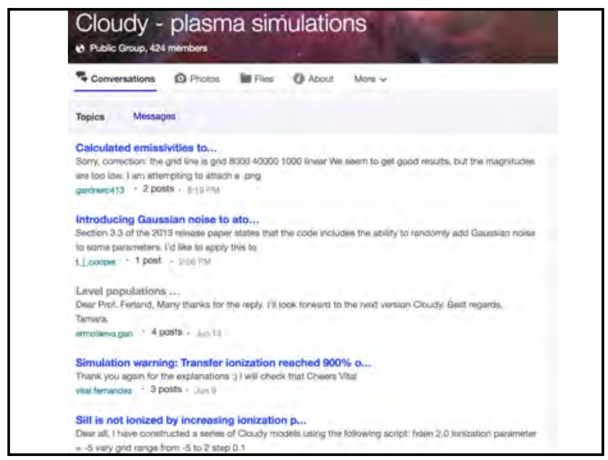




Where to go for help

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



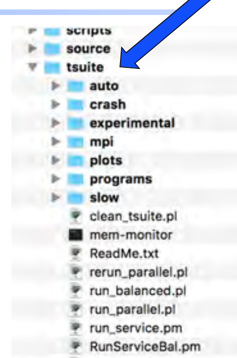


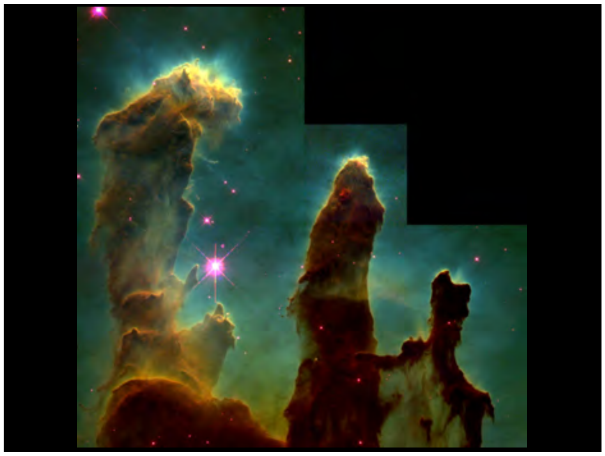
Running cloudy

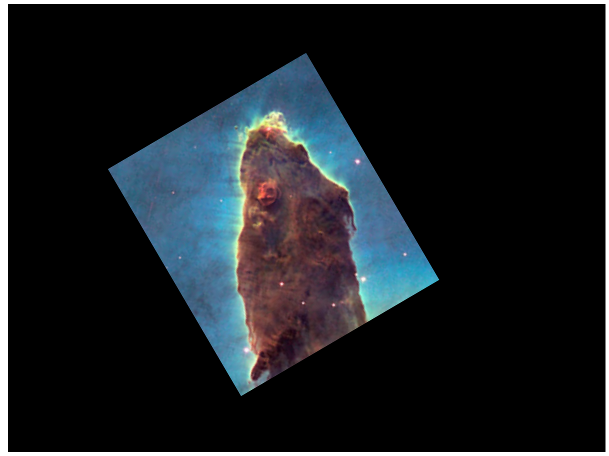
- "run" file contains /Users/gary/cloudy/trunk/source/sys_llvm/cloudy.exe -r $1 2> $1.err
- If file "model.in" contains input, then
  - run model &
  - Produces output "model.out"
  - The model will run in the "background" when the line ends with &

The test suite

- Fully tests the code after any change
  - "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







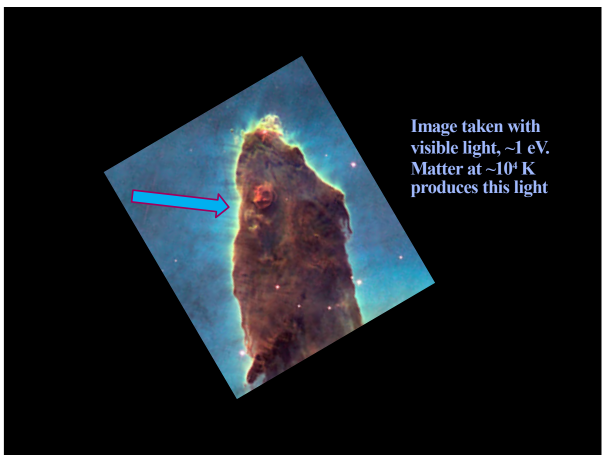
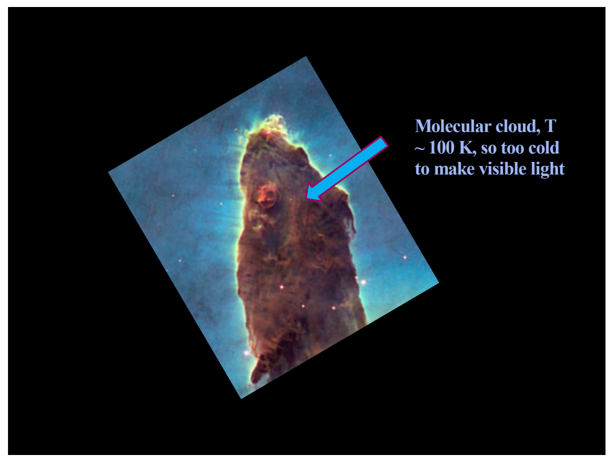
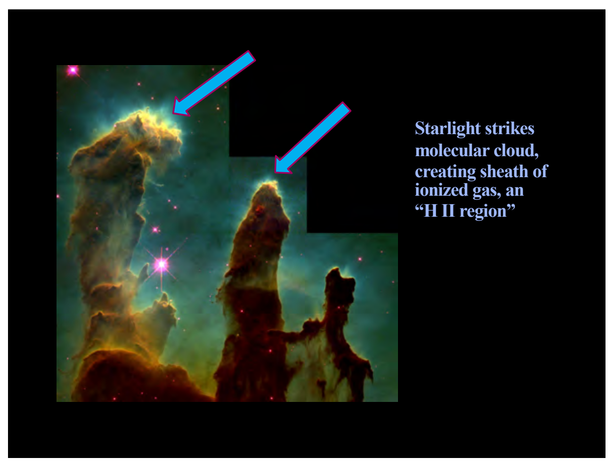


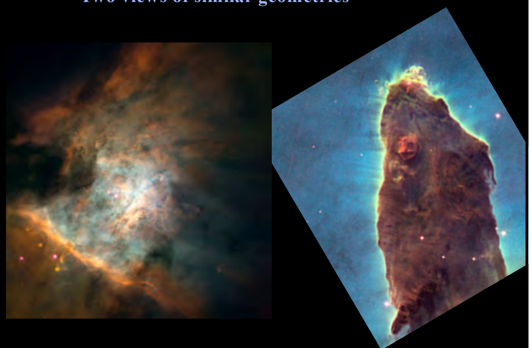
Image taken with
visible light, ~1 eV.
Matter at ~10^4 K
produces this light


Molecular cloud, T
~ 100 K, so too cold
to make visible light


The emission from
the surface is
mostly powered by
starlight


Starlight strikes
molecular cloud,
creating sheath of
ionized gas, an
"H II region"

Two views of similar geometries



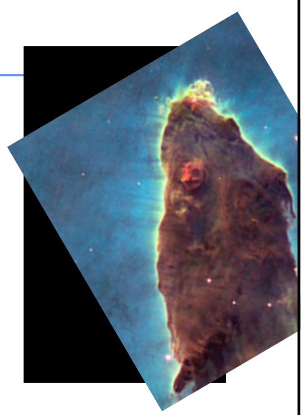
The Orion Nebula face-on

M 16 edge-on

Minimum to run Cloudy

- Hazy 1 Section 1.2
- Must specify
  - Gas density
  - SED – shape of the radiation field striking the cloud
  - The flux of photons striking cloud, photons cm^{-2} s^{-1} since atomic physics depends on this

Let's model a …



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

Commands – Hazy1 Chap 3

- Free format keywords and numbers
- Input deck ends with empty line or *****
- Many numbers are logs, check Hazy1 carefully

Incident radiation field, Hazy 1, Chap 4

- Often the only energy source for the cloud
- SED – shape of radiation field
- Brightness, how intense it is
- These are specified separately

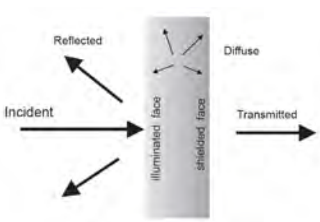
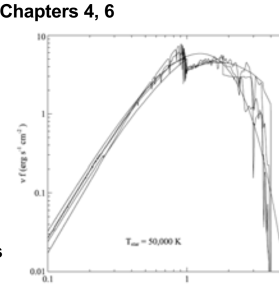


Figure 2.1: Several of the radiation fields that enter in the calculations.

Parameters – the SED shape

- Can be specified as a fundamental shape such as a blackbody
  - QSG Chapter 5, Hazy 1, Chapters 4, 6
- Or by interpolation on a table of points
  - Plot shows BB & 4 available stellar SEDs
- Rydberg
  - approximately the ionization potential of hydrogen
  - The natural unit for atomic physics
  - Internally, Cloudy works with Rydbergs



SED shape

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 3.040×10^{-9} Ryd ($\lambda \approx 29.98$ m) and 100 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, 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.

blackbody

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  ,
```

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.

Table 2.3
Calculated Strömgren radii as function of spectral types spheres

AGN3

From absorption line spectrum

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		55	49.70	48.99	6.09	107
O4.5 V		44	49.61	48.90	6.00	100
O5 V		33	49.53	48.81	5.92	94
O5.5 V		22	49.43	48.72	5.82	87
O6 V		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
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Note: $T = 7{,}500$ K assumed for calculating α_B.

```
# <== this is a comment
#
# the cloud is ionized by a nearby star cluster, NGC 6611.  The brightest
# star is  the O3 - O5 V star W205 which is about 2kpc distant
# McLeod+15 http://adsabs.harvard.edu/abs/2015MNRAS.450.1057M
#
# 50 000 K blackbody, roughly an O3 - O5 V star
blackbody, T=4.87e4 K # the AGN3 Table 2.3 entry for O4 V
```

SED brightness, Hazy 1, Chap 5

- **Luminosity case**
  - Specify total photon luminosity
  - Q(H) or L into 4π per second
  - Must specify radius to get flux
  - 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 area
  - Radius not needed

Luminosity of the star

- Can specify as M_V, or $L_{bolometric}$
- But number of hydrogen-ionizing photons Q(H) is more meaningful
- $Q(\mathrm{H}) = \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu}\, d\nu$ photons s^{-1}
  – AGN3 section 2.3
  – Hazy 1 section 5.14

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) $n_e = n_p = 1\ cm^{-3}$
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O4.5 V	47,400	[illegible]	61	48.90	6.00	100
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Note: $T = 7{,}500$ K assumed for calculating α_B.

Models of stellar atmosphere

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) $n_e = n_p = 1\ cm^{-3}$
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O4 V	48,700	−5.55	49.70	[illegible]	[illegible]	107
O4.5 V	47,400	−5.44	49.61	[illegible]	[illegible]	100
O5 V	46,100	−5.33	49.53	[illegible]	[illegible]	94
O5.5 V	44,800	−5.22	49.43	[illegible]	[illegible]	87
O6 V	43,600	−5.11	49.34	[illegible]	[illegible]	81
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O9.5 Ia	31,200	−6.5	49.17	47.17	5.56	71

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

Radio observations of brems emission of H II regions

```
# <== this is a comment
#
# the cloud is ionized by a nearby star cluster, NGC 6611.  The brightest
# star is  the O3 - O5 V star W205 which is about 2kpc distant
# McLeod+15 http://adsabs.harvard.edu/abs/2015MNRAS.450.1057M
#
# 50 000 K blackbody, roughly an O3 - O5 V star
blackbody, T=4.87e4 K # the AGN3 Table 2.3 entry for O4 V
Q(H)  49.70
#
```

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 to derive flux of photons on cloud surface
- Radius command
  – log radius in cm by default
  – Linear, or parsecs, can be used by setting optional keywords
- Let's put our cloud 10^{19} cm from the star, a bit over 2 parsec

```
# RADIUS gives the separation between the star and the cloud.
# units are log cm.  The projected separation between star
# and nebula is about 2 pm according to McLeod.  This is
# slightly more than 2 pc (log 2 pc 18.78 cm)
radius 19
```

```
# <== this is a comment
#
# the cloud is ionized by a nearby star cluster, NGC 6611.  The brightest
# star is  the O3 - O5 V star W205 which is about 2kpc distant
# McLeod+15 http://adsabs.harvard.edu/abs/2015MNRAS.450.1057M
#
# 50 000 K blackbody, roughly an O3 - O5 V star
blackbody, T=4.87e4 K # the AGN3 Table 2.3 entry for O4 V
Q(H)  49.70
#
# RADIUS gives the separation between the star and the cloud.
# units are log cm.  The projected separation between star
# and nebula is about 2 pc according to McLeod.  This is
# slightly more than 2 pc (log 2 pc 18.78 cm)
radius 19
#
```

Gas density

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 [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

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

where Δr is the cloud thickness and c_s is the sound speed (AGN3 eq 6.25)

Cloud density, Hazy 1 Chap 8

- **"hden" command, Chapt 8.8, sets log of total hydrogen density, cm^{-3}**
- **sets hydrogen density, molecular, atomic, and ionized**
- **Density is kept constant by default**
  - the H density is the same across the cloud
- **Other equations of state possible**
  - Constant pressure, dynamical flows, power-laws
- **typical H II region density, $n_H = 10^3$ cm^{-3}**

HDEN command

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

$$n(H) = n(H^0) + n(H^+) + 2n(H_2) + \sum_{other} n(H_{other}) \; [cm^{-3}]. \qquad (8.13)$$

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., $n(H) \leq 10^{15}$ cm^{-3} and $T \leq 10^4$ 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.

```
Q(H)  49.70
#
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radius 19
#
# this is the log of the hydrogen density, cm-3
hden 3
#
```

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 thicknes**

Let's model a …

- **H II region abundances**
- **And grains**

```
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#
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# slightly more than 2 pc (log 2 pc 18.78 cm)
radius 19
#
# this is the log of the hydrogen density, cm-3
hden 3
#
# use a standard set of H II region abundances, including grains
abundances HII region
#
```
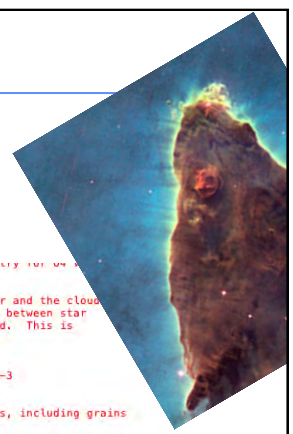



Include some backgrounds

```
abundances HII region
#
# not important in the H II region,
# but will be critical when we
# extend it to the PDR
cosmic ray background
#
# cosmic microwave background at z=0
CMB
#
```

Background cosmic rays

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

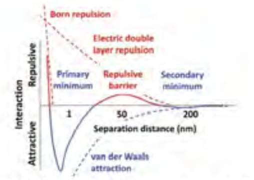


Fig. 2 Colloid-surface interactions emanating from van der Waals attraction, electric double layer repulsion, and Born repulsion producing the repulsive energy barrier, primary minimum attraction, and secondary minimum attraction

Did Cloudy end OK?

- Check the last line of the output. It should say "Cloudy exited OK"

[Stop in cdMain at ../maincl.cpp:470, Cloudy exited OK]

What Cloudy did

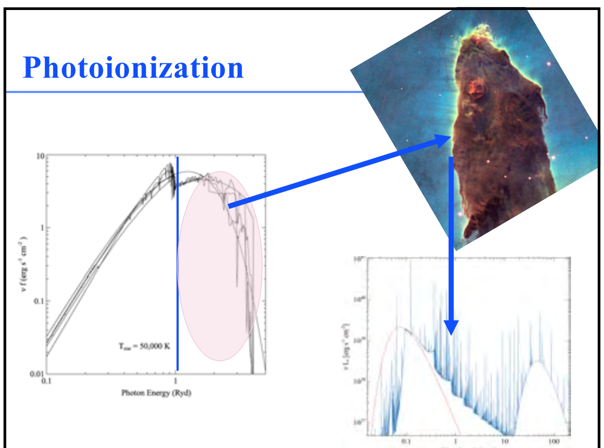
- Transfer the beam of light into the cloud
  - Attenuate starlight by gas and dust opacity
- Determine the level of ionization at every depth point
- Determine the chemistry too
- Solve for the gas kinetic temperature
- Determine the populations of thousands of levels within hundreds of ions and molecules
- Predict spectrum of thousands of lines
- All self-consistently, with few free parameters

"Save" files

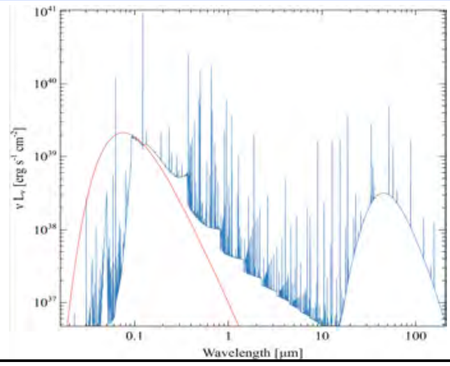
- The input contains a number of "save commands"
  - These are how we access part of the vast amount of information Cloudy computes
- Keywords specify what to save
- "Filename" to say where to save it

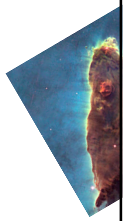
```
#
# save the spectrum
save continuum "M16.con" units microns last
#
```

Photoionization



save continuum "M16.con" units microns last





Notes on save files

- The command must include a filename between double quotes
  - Office products will put “smart quotes” in our examples
  - C++ requires straight quotes

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

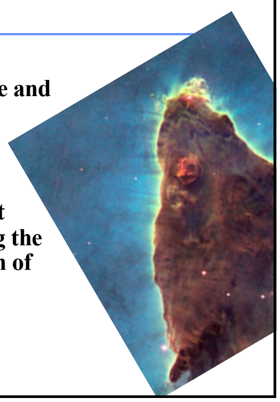
- Data in save files are tab, not space, delimited

Cloud structure

this will save the temperature and
ionization of the cloud

save overview "M16.ovr" last

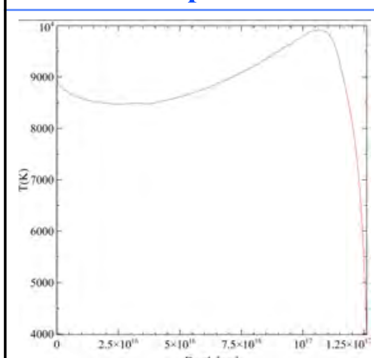
The overview file contains a lot of useful information including the gas temperature and ionization of some abundant elements

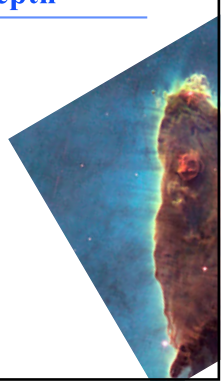


Kinetic temperature

- How hot the gas is.
  - Grains present but have a different set of temperatures
- The electron temperature or kinetic temperature is the only well defined temperature in the system

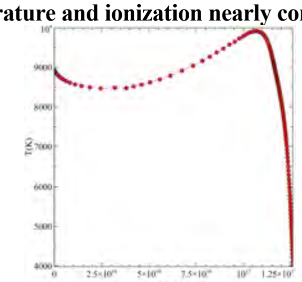
Kinetic temperature vs depth

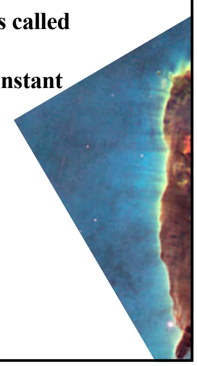




“zones”

- Cloudy divides a cloud into thin layers called “zones”
- Temperature and ionization nearly constant within each zone



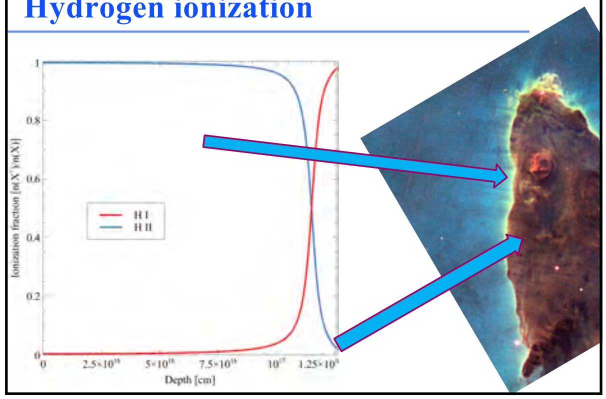


Ionization fractions

- The fraction of an element present in a particular ionization stage
- More useful than the density of ions
- $0 \le IF \le 1$

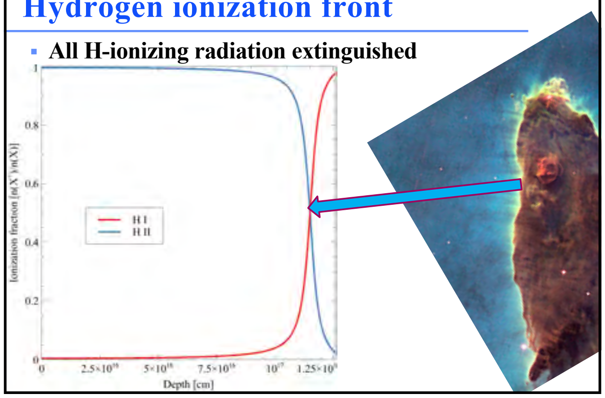
	Spectrum	Baryon
Atomic hydrogen	H I	H^0
Ionized hydrogen	H II	H^+
Doubly ionized C	C III	C^{2+}
Molecular H	H_2	H_2

Hydrogen ionization



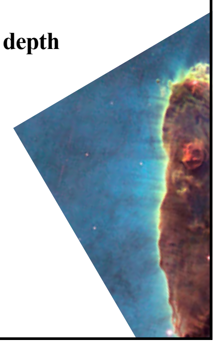
Hydrogen ionization front

- All H-ionizing radiation extinguished

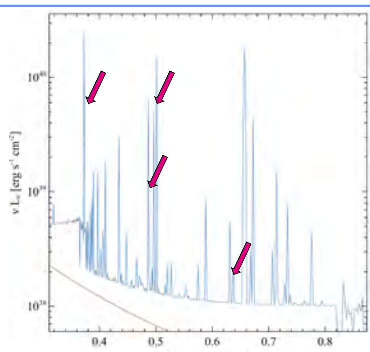


Save some line brightness vs depth

\# save line emissivity as a function of depth
save line emissivity ".ems" last
H 1 4861.33A
O 1 6300.30A
Blnd 3727.00A
O 3 5006.84A
end of lines



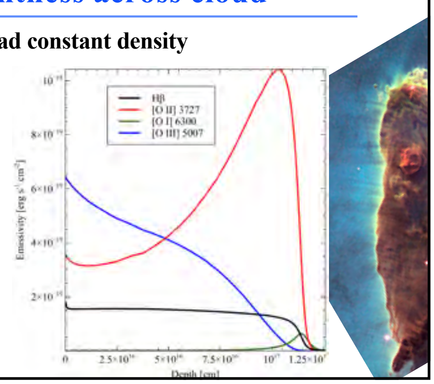
The predicted optical spectrum



We are saving the brightness of these lines vs depth

Lines brightness across cloud

- Our model had constant density
- It predicts a ~2x increase in brightness in total line emission
- Appearances can be deceiving!



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Nick Abel's H^+-H^0-H_2 region animation