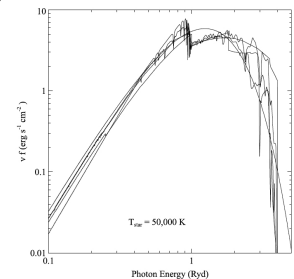


## Minimum to run Cloudy

- ◆ **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

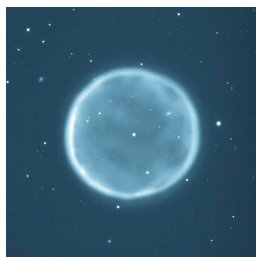
## Parameters – the SED shape

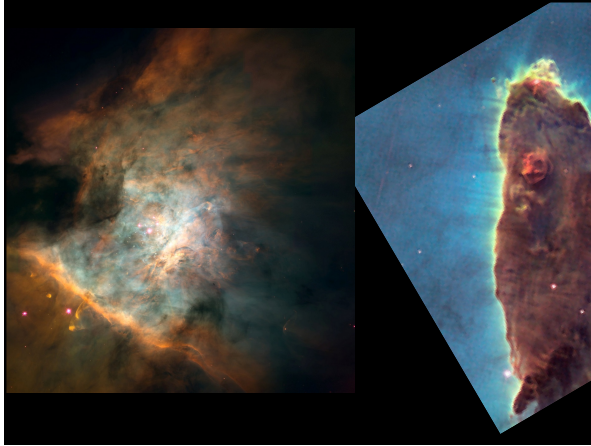
- ◆ Quick start guide Chapter 5
- ◆ Hazy 1, Chapters 4, 6
- ◆ Can be specified as a fundamental shape such as a blackbody
- ◆ Generally entered as table of points



## SED brightness – the luminosity case

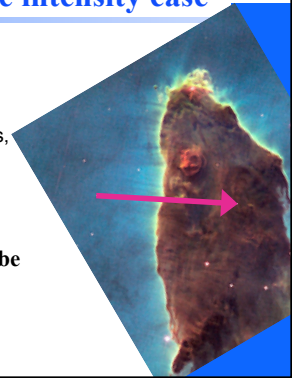
- ◆ **Specify  $Q(H)$  – photon luminosity**
  - Inner radius of cloud must be specified, since  $\phi(H) = Q(H) / 4\pi r^2$
  - predicts emission line luminosities  $\text{erg s}^{-1}$





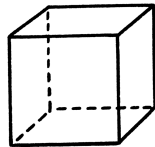
### SED brightness – the intensity case

- ◆ Specify  $\phi(H)$  – flux of photons per unit area
  - The “intensity case”
  - predicts surface brightness, emission per unit area  $\text{erg cm}^{-2} \text{s}^{-1}$
  - Inner radius of cloud does not need to be specified
- ◆ Ionization parameter can be used to set  $\phi(H)$

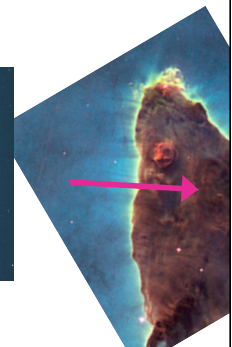


### A “unit cell”

- ◆ We will model a cubic cm of matter in many of the atomic calculations
- ◆ A “unit cell”,  $1 \text{ cm}^3$
- ◆ Intensity case plus commands
  - Stop zone 1
  - Set dr 0



### The three geometries



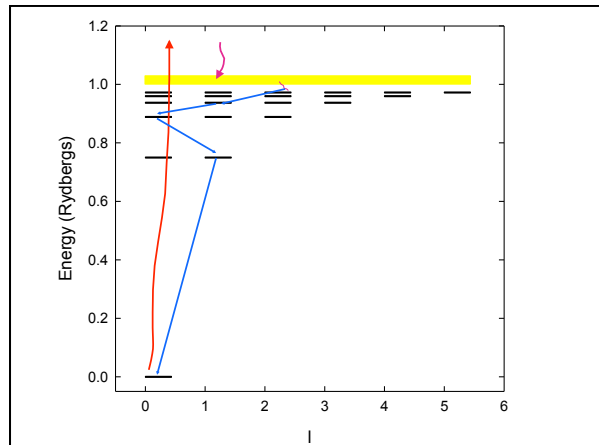
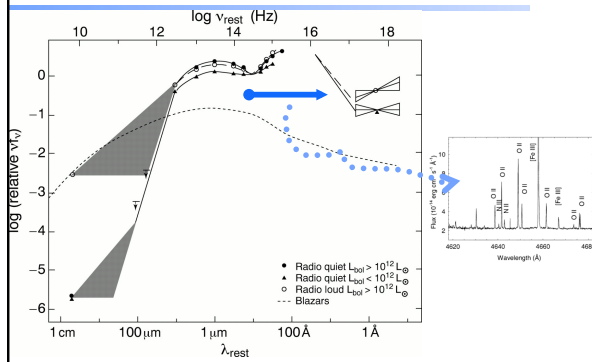
### Cloud density, Hazy 1 Chap 8

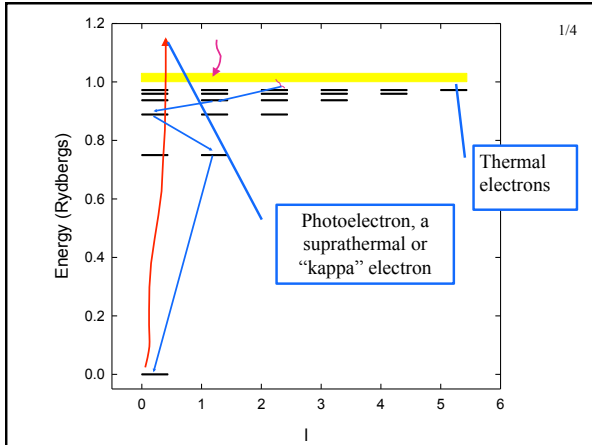
- ◆ “hden” command set H density  $\text{cm}^{-3}$
- ◆ Constant density by default
  - the H density is the same across the cloud
- ◆ Other equations of state possible
  - Constant pressure, flows, power-laws

### Composition, Hazy 1 Chap 7

- ◆ Solar, no grains, by default
- ◆ Other standard mixtures possible,
- ◆ Stored in data / abundances
  
- ◆ We will often use “abundances ISM” to get ISM grains plus depleted ISM abundances

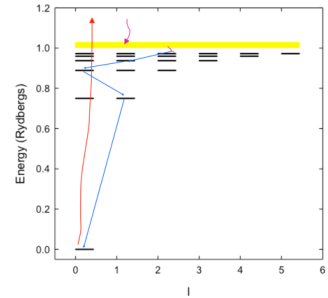
### The “primary mechanism” Continuum → emission lines





### Life history of an Orion electron

- ◆ **H<sup>0</sup> ground state**  
– 1 day
- ◆ **Suprathermal**  
– 1 second
- ◆ **Thermal**  
– 1 yr
- ◆ **H<sup>0</sup> excited states**  
– 10<sup>-7</sup> s
- ◆ **H<sup>0</sup> ground state**



### Let's model a ...

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

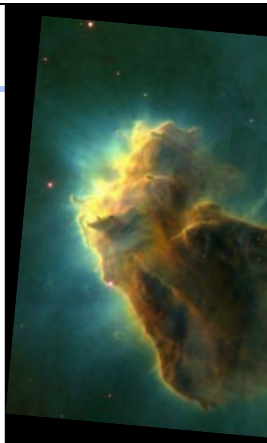


Table 2.3  
Calculated Strömgren radii as function of spectral types spheres

AGN3

Spectral type	$T_e$ (K)	$M_V$	$\log Q(\text{H}^0)$ (photons/s)	$\log n_e n_p r_1^3$ $n$ in $\text{cm}^{-3}$ , $r_1$ in pc	$\log n_e n_p r_1^3$ $n$ in $\text{cm}^{-3}$ , $r_1$ in pc	$r_1$ (pc) $n_e = n_p$ $= 1 \text{ cm}^{-3}$
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:  $T = 7,500 \text{ K}$  assumed for calculating  $\sigma_B$ .

**definitions**

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

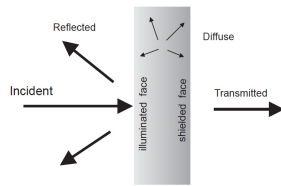


Figure 2.1: Several of the radiation fields that enter in the calculations.

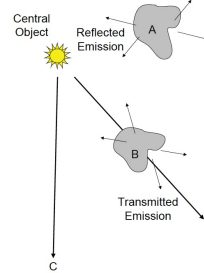
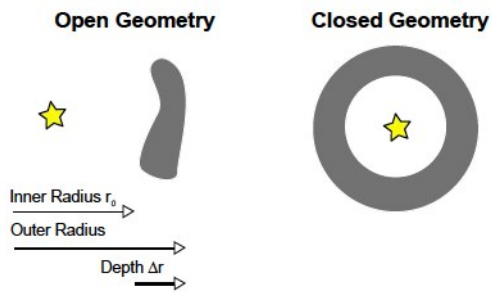


Figure 16.2: This figure illustrates several components of the radiation field that enter in the calculations.

**Open vs closed geometry Hazy 2.3**

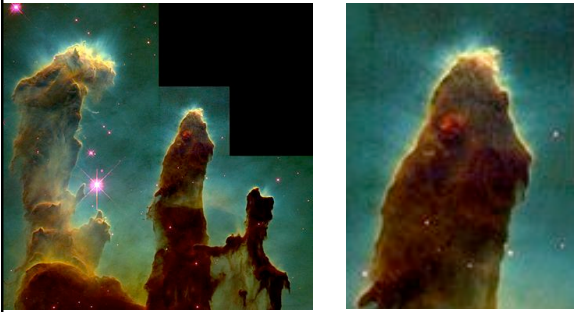


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**Plot components of radiation field**

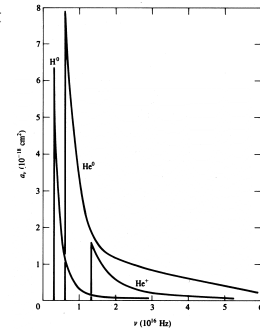
- ◆ **Incident stellar continuum**
- ◆ **Total continuum produced**
- ◆ **Reflected continuum**

### Strömgren length



### Photoionization

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



### Make plot of total opacity and emissivity for zone 1

### 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  $\text{cm}^3 \text{s}^{-1}$ ) for H-like ions

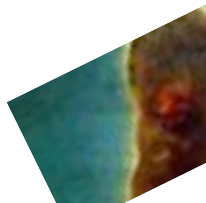
	$T$				
	1,250 K	2,500 K	5,000 K	10,000 K	20,000 K
$\alpha_A = \sum_1^{\infty} \alpha_n$	$1.74 \times 10^{-12}$	$1.10 \times 10^{-12}$	$6.82 \times 10^{-13}$	$4.18 \times 10^{-13}$	$2.51 \times 10^{-13}$
$\alpha_B = \sum_2^{\infty} \alpha_n$	$1.28 \times 10^{-12}$	$7.72 \times 10^{-13}$	$4.54 \times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

## Strömgren length

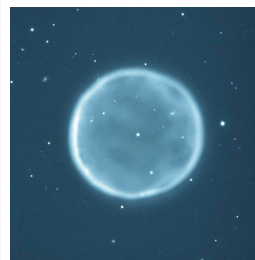
- ◆ Number of ionizing photons entering layer is balance by number of recombinations along it

$$\varphi(H) = n_e n_p \propto L$$

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



## Matter vs radiation bounded



## Beyond the H<sup>+</sup> layer

- ◆ Little H<sup>+</sup> ionizing radiation gets past the H<sup>+</sup> 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<sup>+</sup> 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<sup>+</sup> - H<sup>0</sup> ionization front.
  - But is this what you want?

## Definitions – AGN3 Appendix 1

- ◆ **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  $4\pi j$  [ $\text{erg cm}^{-3} \text{s}^{-1}$ ]**
  - Emission per unit volume, per second
- ◆ **Optical depth  $\tau$** 
  - Number of mean free paths through a medium
- ◆ **Opacity  $\kappa$  –  $\text{cm}^2$  – atomic property of material**
  - $\tau = \kappa n$
- ◆ **Planck function  $B = j/\kappa$**
- ◆ **Rob Rutten's course notes describe this and more**
  - [http://www.staff.science.uu.nl/~rutte101/Radiative\\_Transfer.html](http://www.staff.science.uu.nl/~rutte101/Radiative_Transfer.html)