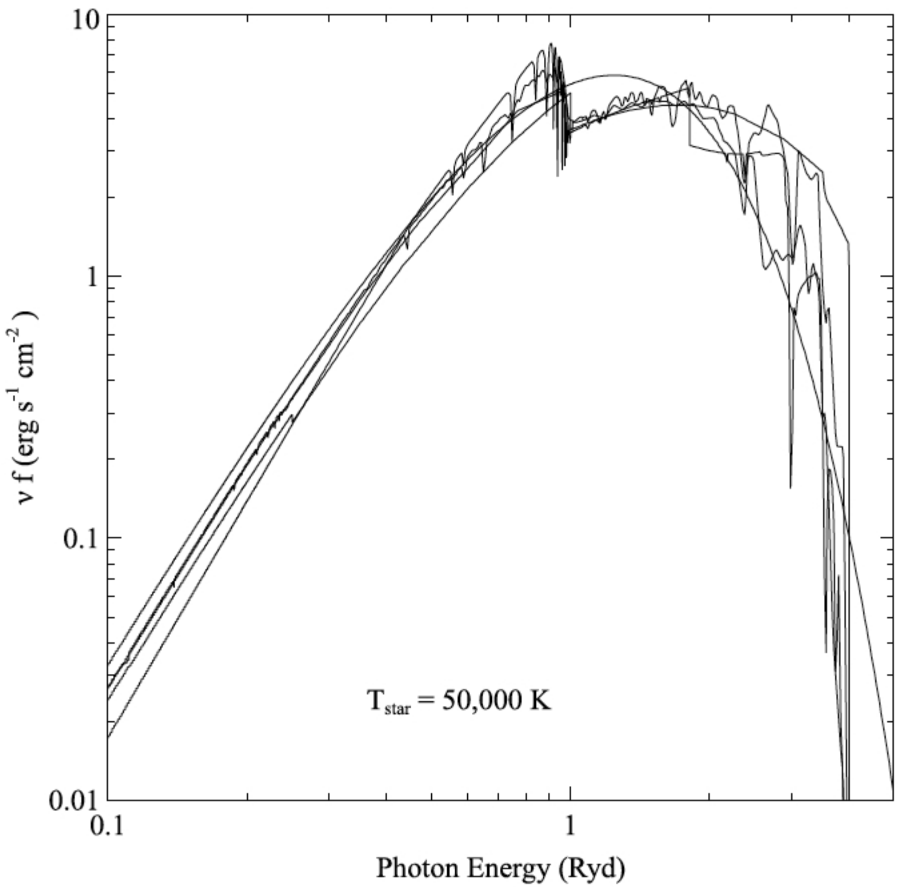
Minimum to run Cloudy

- **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

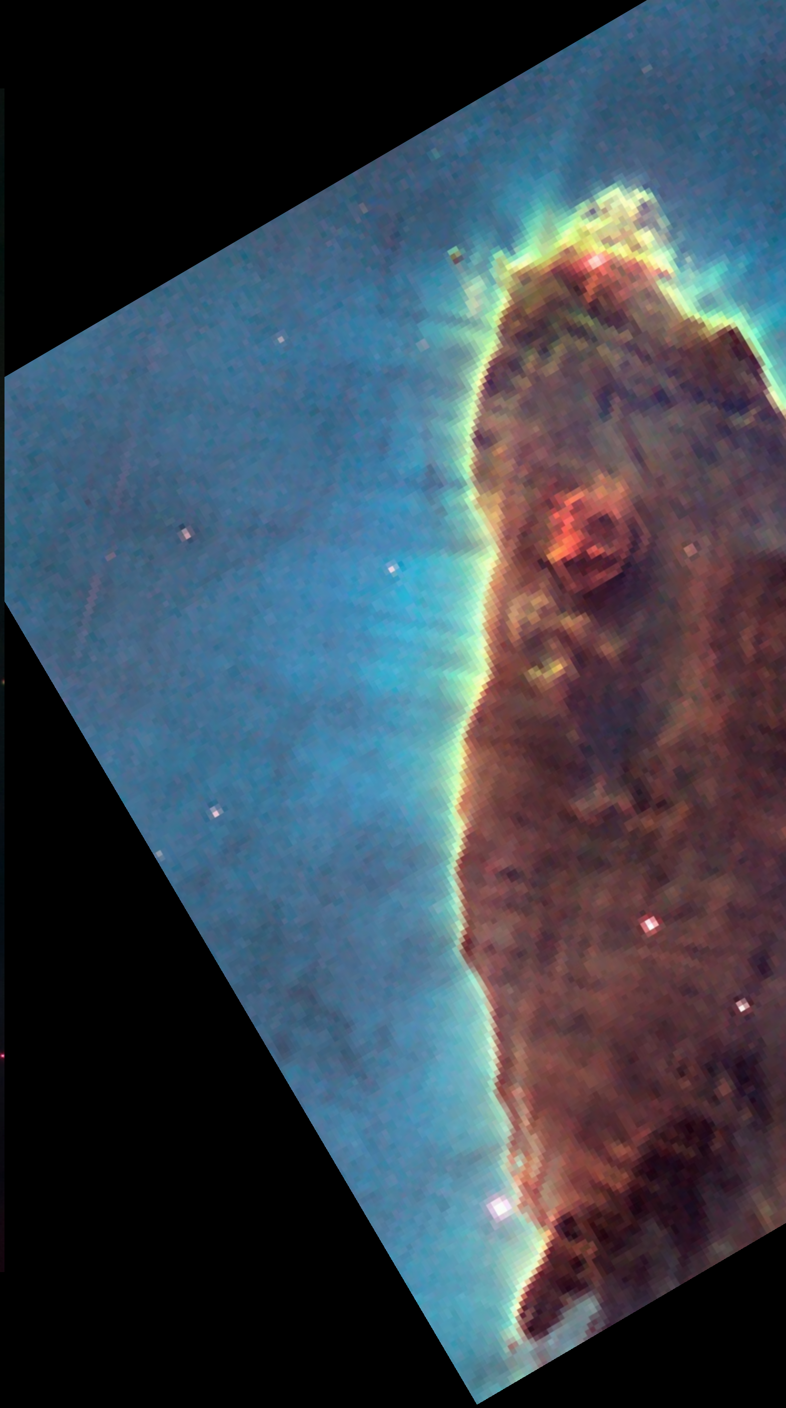
Parameters – the SED shape

- 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



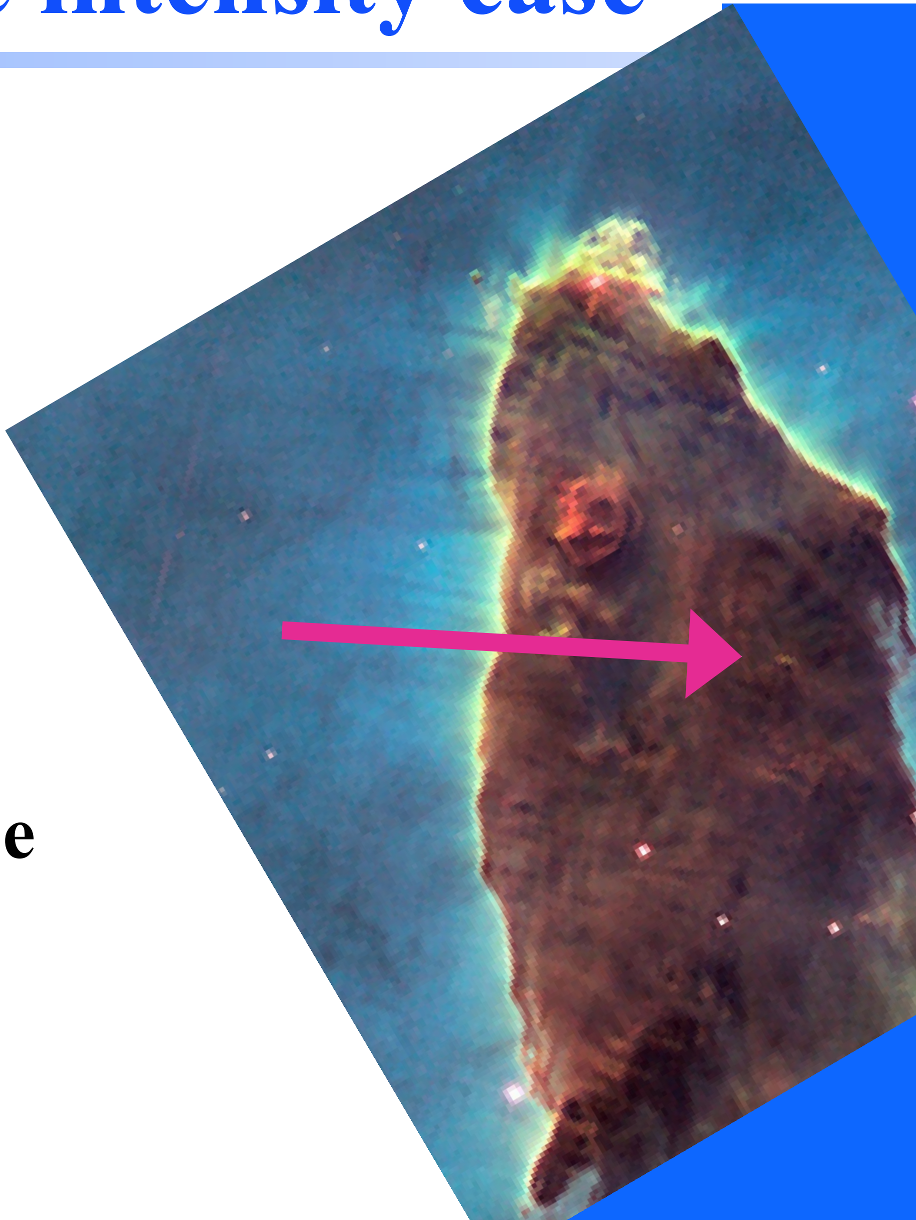
SED brightness – the luminosity case

- **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}



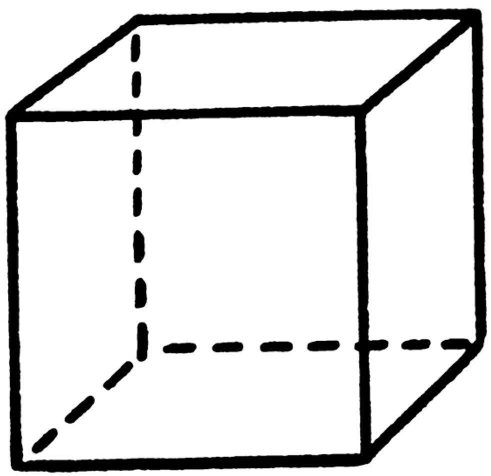
SED brightness – the intensity case

- **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)**

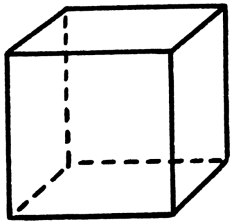


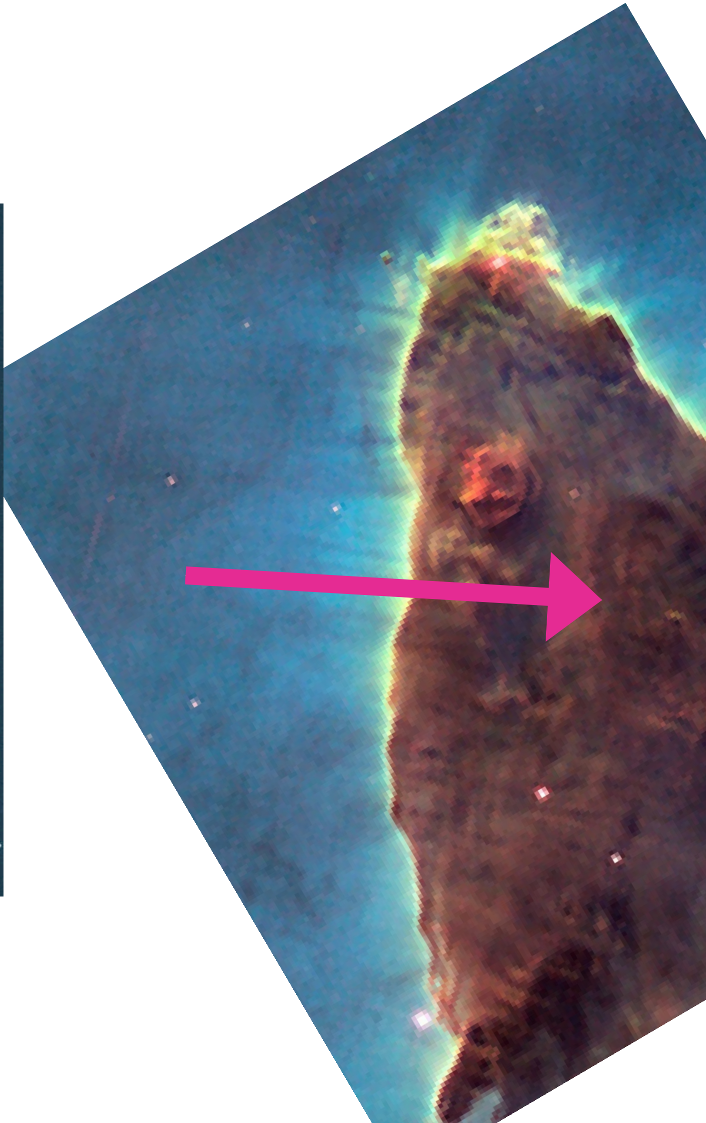
A “unit cell”

- **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

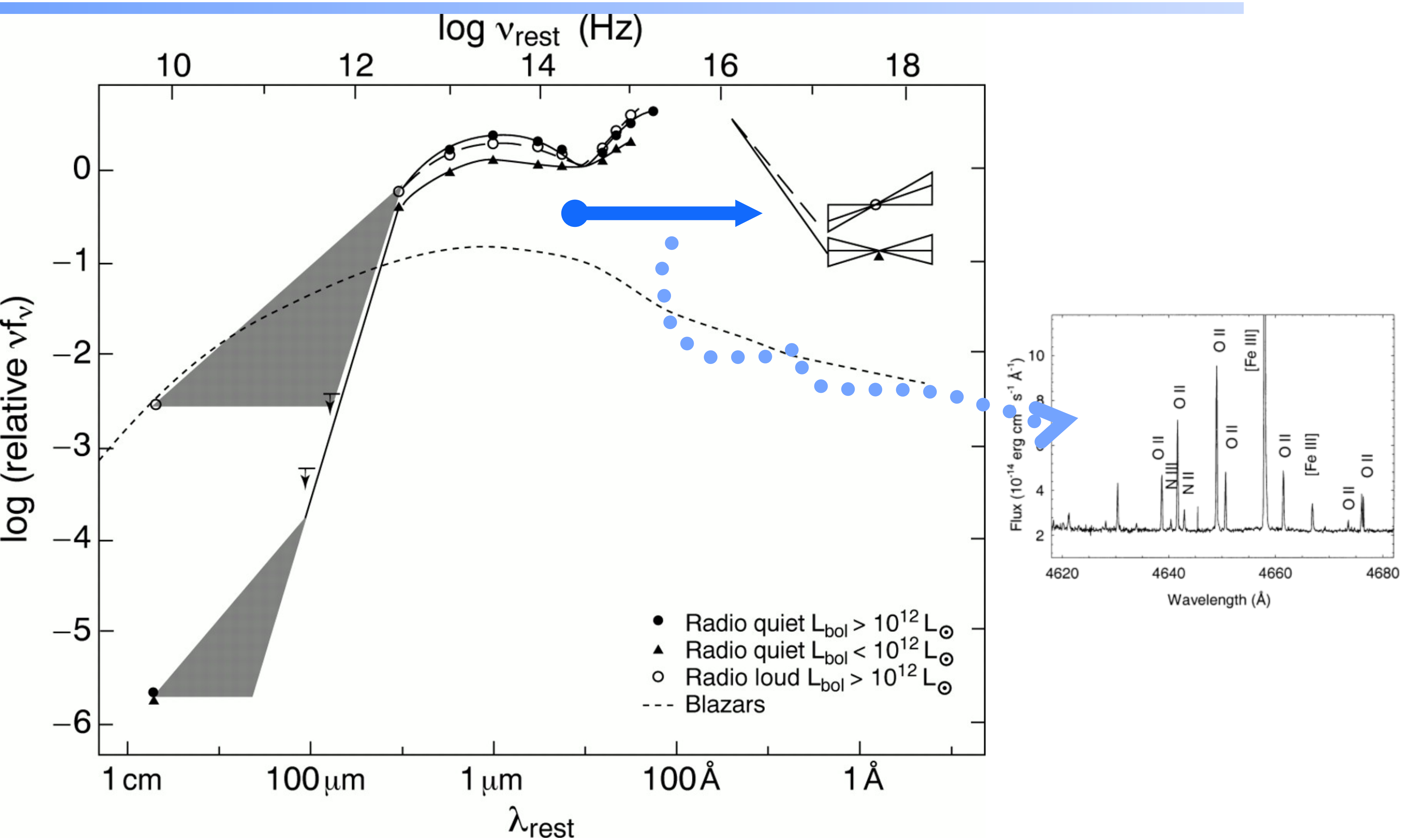
- **"hden" command set H density cm^{-3}**
- **Constant density by default**
  - the H density is the same across the cloud
- **Other equations of state possible**
  - Constant pressure, flows, power-laws

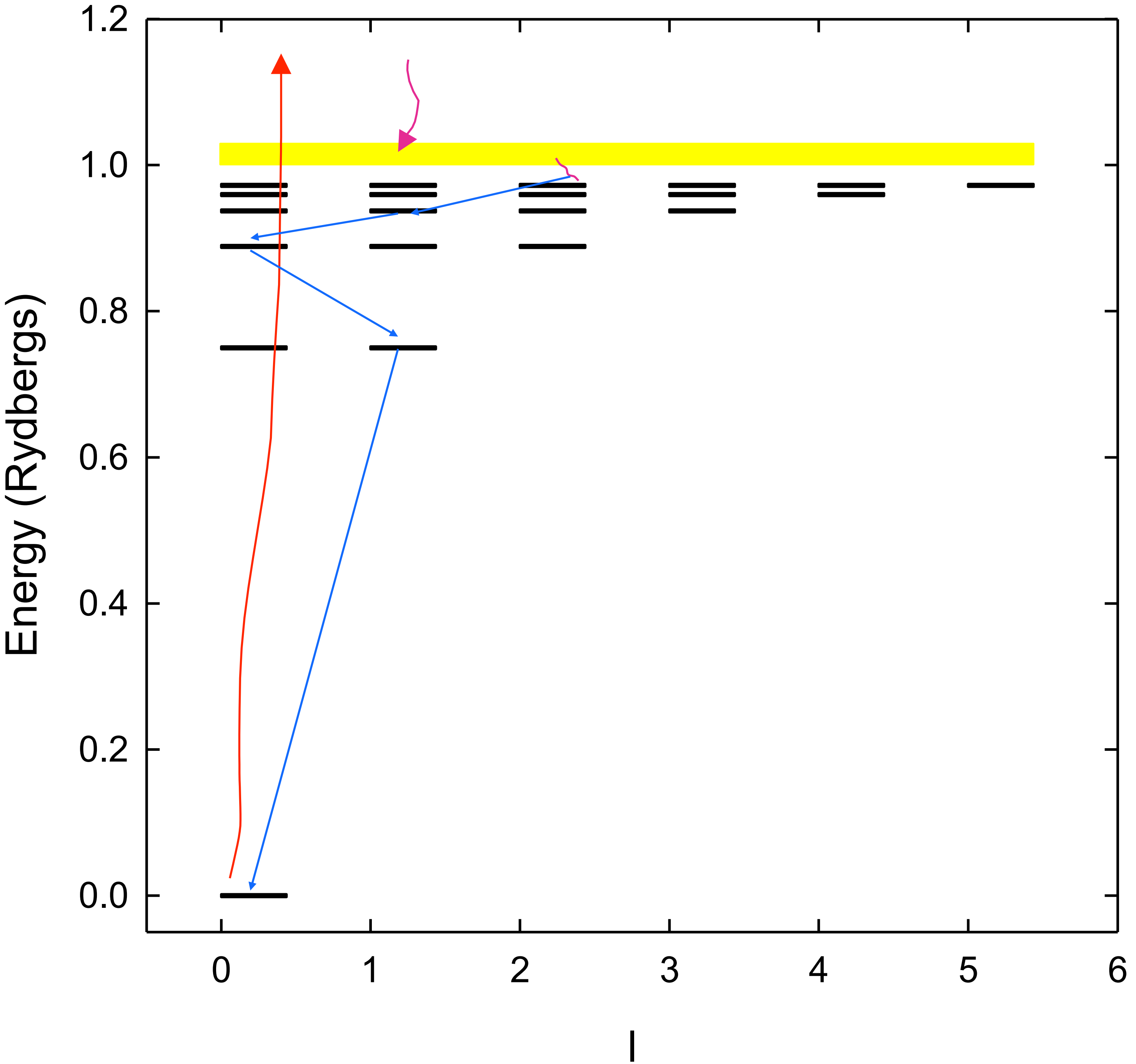
Composition, Hazy 1 Chap 7

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

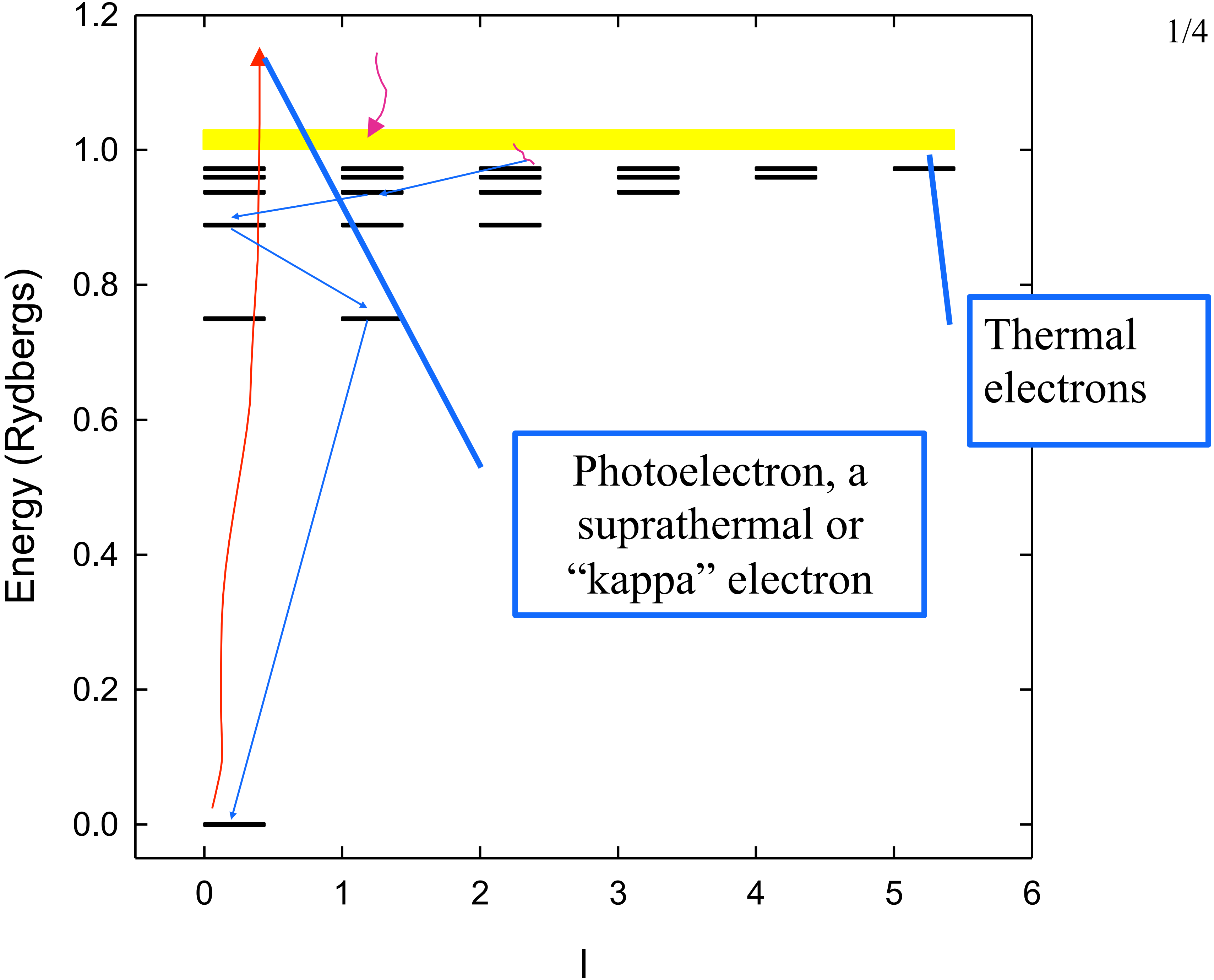
- **We will often use “abundances ISM” to get ISM grains plus depleted ISM abundances**

The “primary mechanism” Continuum → emission lines



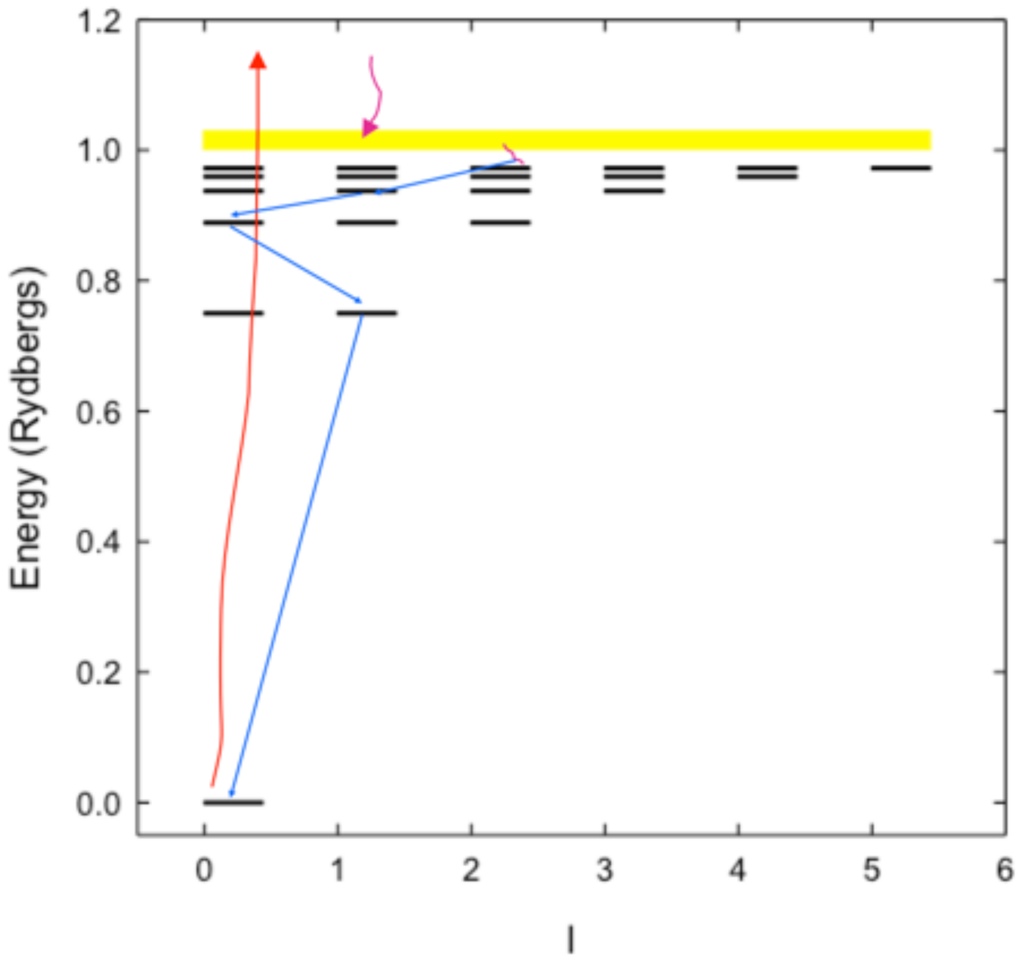


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Energy (Rydbergs)
0
1
2
3
4
5
6
l


1.2
1.0
0.8
0.6
0.4
0.2
0.0
Energy (Rydbergs)
0
1
2
3
4
5
6
l
Thermal electrons
Photoelectron, a suprathermal or “kappa” electron

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

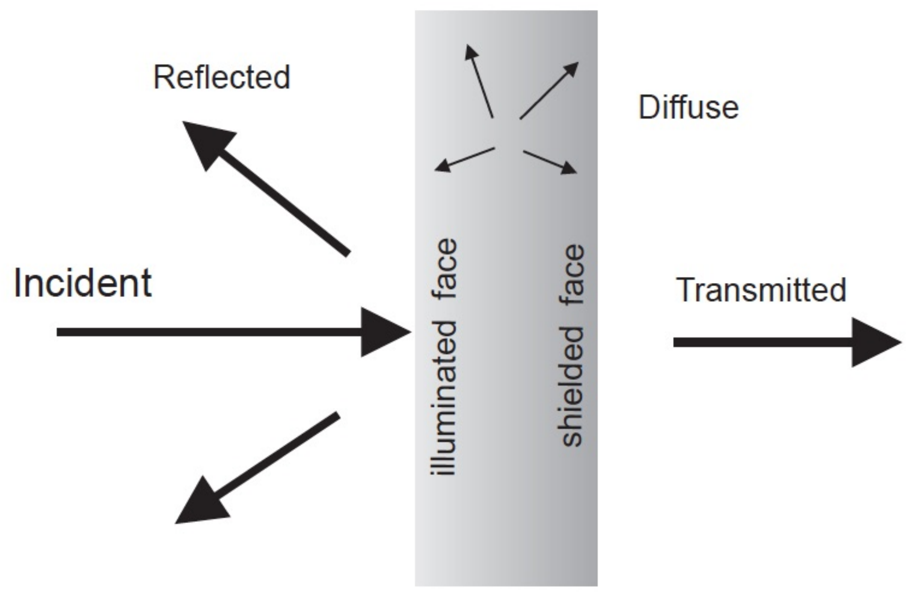


Figure 2.1: Several of the radiation fields that enter in the calculations.

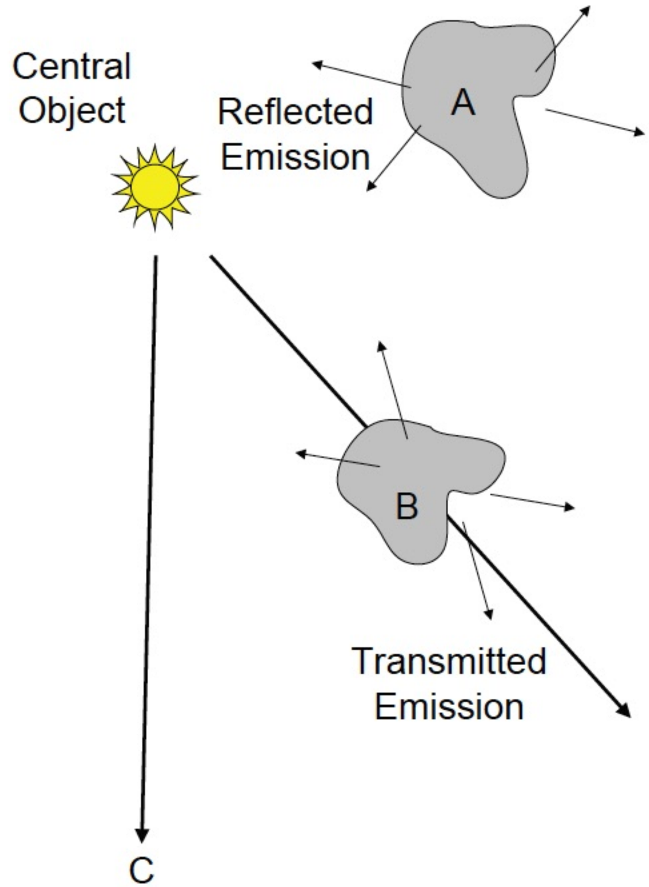
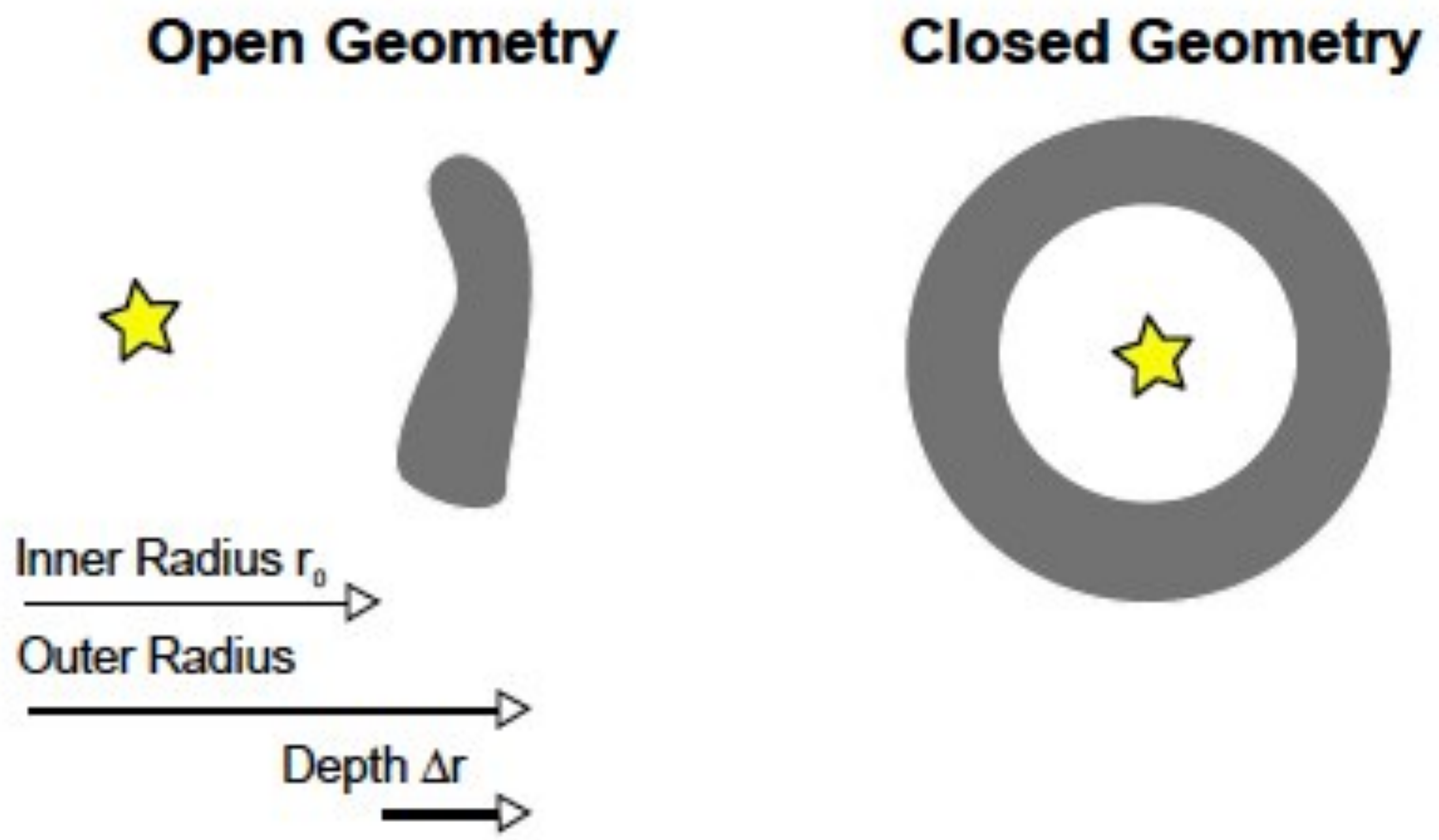


Figure 16.2: This figure illustrates several components of the radiation field that enter in the calculations.

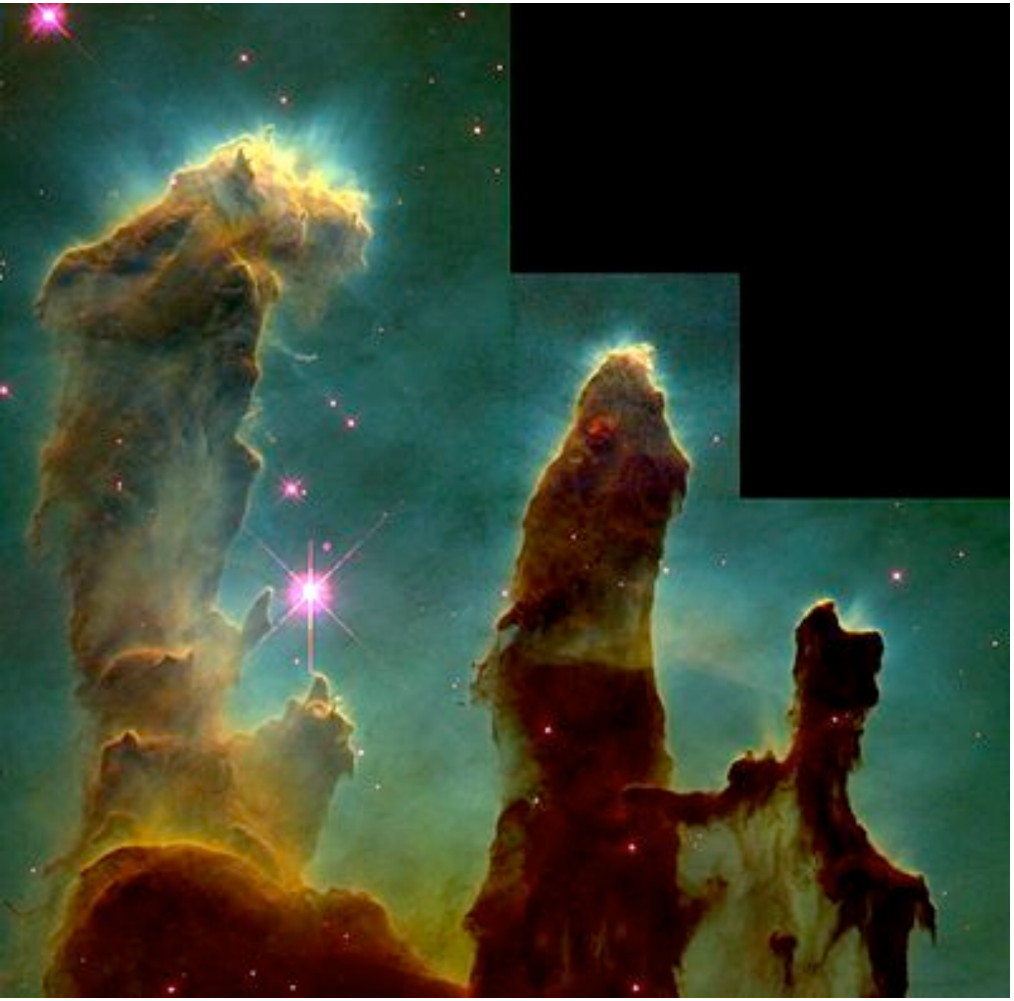
Open vs closed geometry Hazy 2.3



Plot components of radiation field

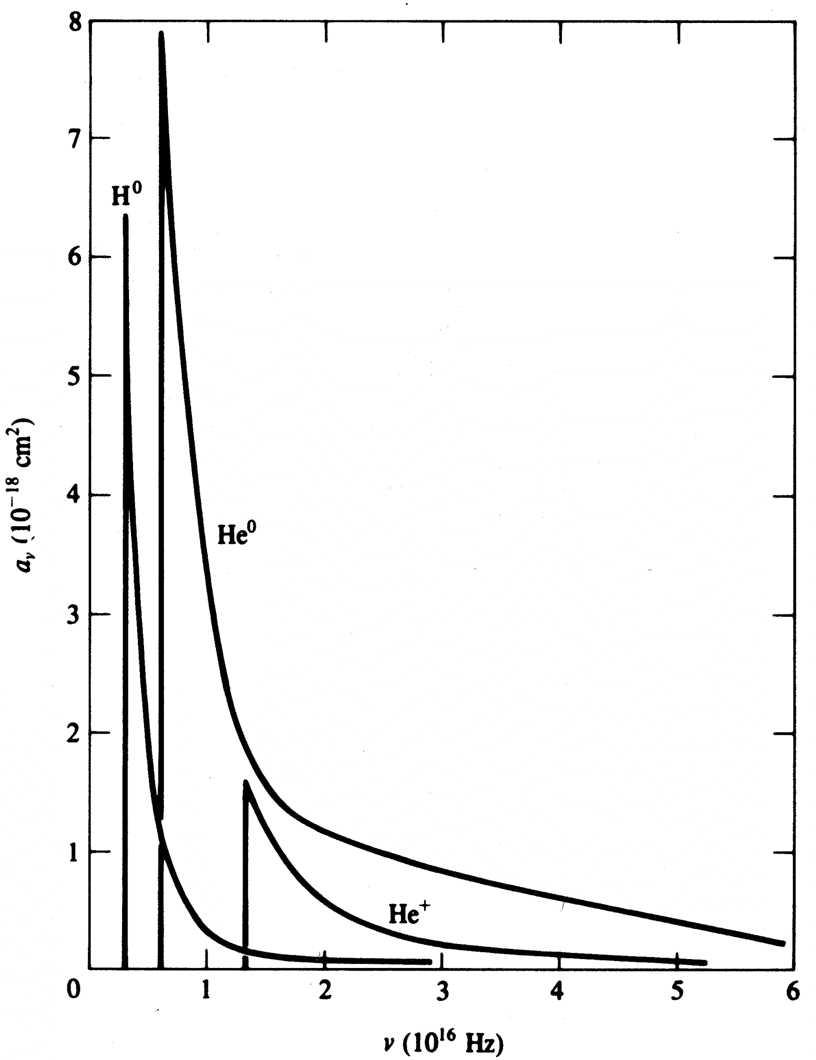
- Incident stellar continuum
- Total continuum produced
- Reflected continuum

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

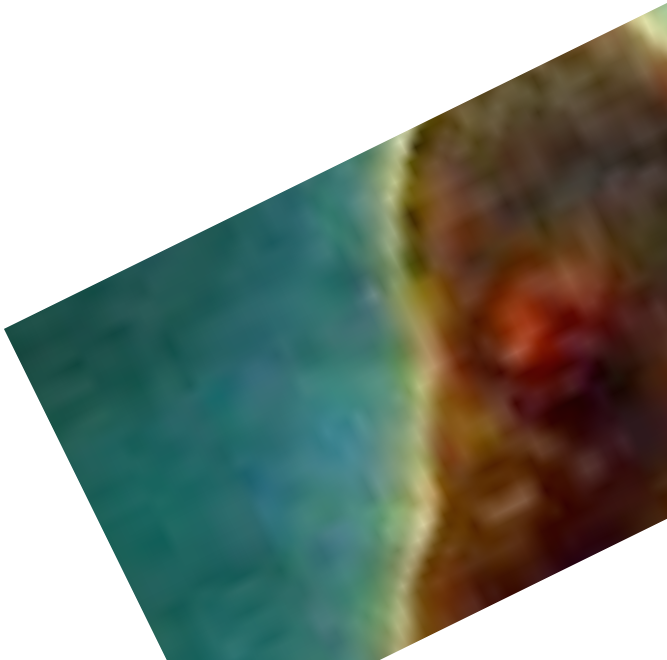
	T				
	1,250 K	2,500 K	5,000 K	10,000 K	20,000 K
$\alpha_A = \sum_1^\infty \alpha_n$	1.74×10^{-12}	1.10×10^{-12}	6.82×10^{-13}	4.18×10^{-13}	2.51×10^{-13}
$\alpha_B = \sum_2^\infty \alpha_n$	1.28×10^{-12}	7.72×10^{-13}	4.54×10^{-13}	2.59×10^{-13}	1.43×10^{-13}
$\alpha_C = \sum_3^\infty \alpha_n$	1.03×10^{-12}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

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 $4\pi j$ [erg cm^{-3} s^{-1}]**
  - Emission per unit volume, per second
- **Optical depth τ**
  - Number of mean free paths through a medium
- **Opacity κ – 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