Coronal equilibrium

- Coronal equilibrium occurs when heat or mechanical energy sets a kinetic temperature
- Besides the sun, this occurs in …
- Accretion disks
  - Gas "viscosity" converted into heat
- Shocks
  - Collision between two parcels of gas,
  - Energy of motion converted into heat

Shock in an ideal gas

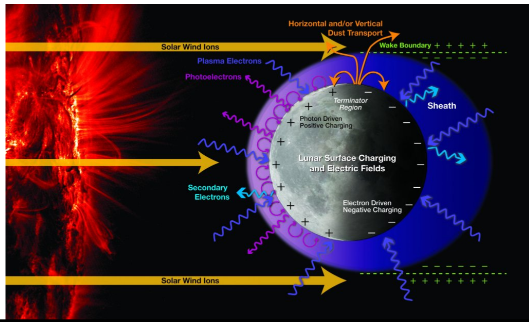
- Energy of motion $\frac{1}{2} \rho v^2$
- Thermal energy 3/2 nkT
- $T(\text{shock}) = \rho v^2 / 3nk = v^2 / 3k\ \rho/n = v^2 \mu / 3k$
- If the gas is ionized then $n \approx 2n(H)$ so $\mu \approx m_p / 2$

All stars have winds

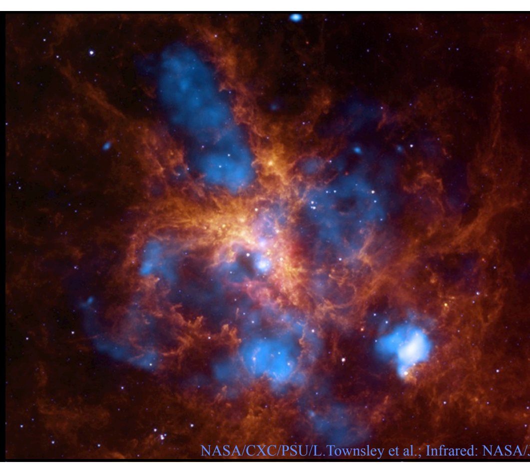
- Wind speed roughly escape velocity from surface of star
- Wind strikes surrounding clouds creating shocks
- visible in x-ray for moderate to high speed shocks, in the optical / UV for slow shocks

Earth within solar wind

- Solar wind speed ≈400 km/s at Earth's orbit



ESO

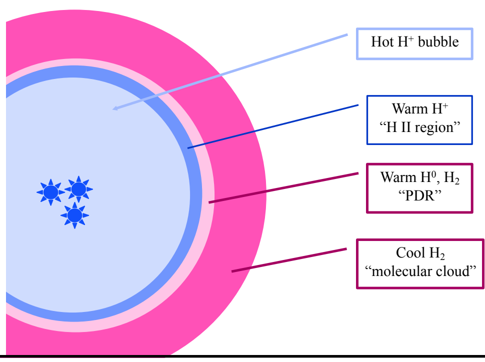


NASA/CXC/PSU/L.Townsley et al.; Infrared: NASA/JPL

H II regions

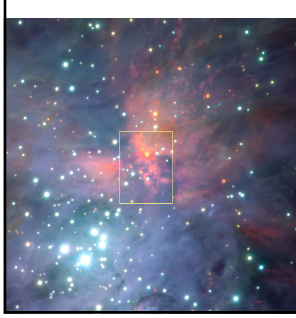
- Wind speed ≈500 km/s

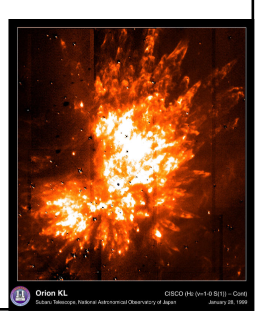
Idealized structure of an H II region

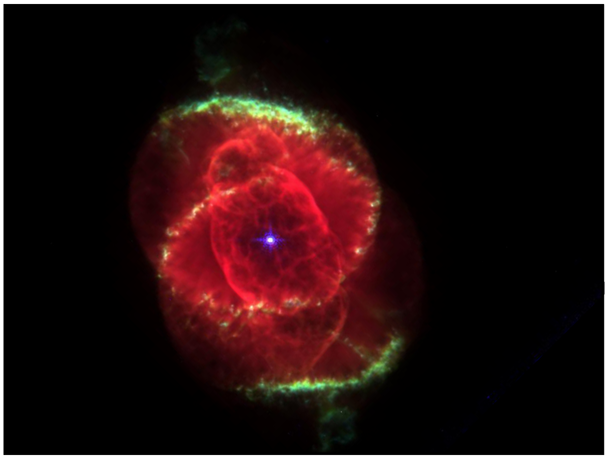


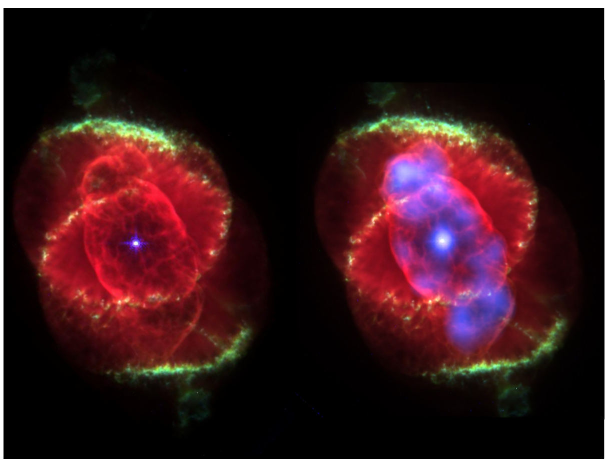
BN – KL in Orion

- 10 km/s









Planetary nebula

- Wind~10^3 km/s

T Tauri jets

- ≈ 50 km/s

AGN

- Wind = 1e4 km/s

Homework

- Choose one of these objects and compute its shock spectrum
- Plot the ionization distribution and the spectrum

What our calculation included

- Coronal equilibrium
- Lightest 30 elements
- All stages of ionization
- About 100 molecules
- Fully self consistent
- Time steady

- Ionization caused by thermal collisions
- Light was not considered

Mon. Not. R. astr. Soc. (1969) **142,** 501–521.

THE IONIZATION EQUILIBRIUM OF ELEMENTS BETWEEN CARBON AND NICKEL

Carole Jordan

(Received 1968 July 31)

SUMMARY

The ionization equilibrium N(ion)/N(Element), for ions of elements abundant in the Sun, has been calculated as a function of temperature between $T_e \sim 10^4$ °K and $\sim 10^8$ °K. Two sets of results are given. The first includes the processes of collisional ionization, collisional excitation followed by auto-ionization, direct radiative recombination, radiative recombination via bound levels, and di-electronic recombination, reduced by a density dependent term. As the variation of the electron density with electron temperature in the solar atmosphere enters into the calculations these results are applicable only to the solar corona and chromosphere. The second set includes collisional ionization, collisional excitation followed by auto-ionization, direct radiative recombination, and the full di-electronic recombination rate. These results are applicable to any low density plasma where the radiation field is negligible.

http://adsabs.harvard.edu/abs/1969MNRAS.142..501J

- log N(i)/N(E) for O ions

$\log_{10}T_e$	Ion	OI	II	III	IV	V	VI	VII	VIII	IX
3.7		0.00	-	-	-	-	-	-	-	-
3.8		0.00	6.15	-	-	-	-	-	-	-
3.9		0.00	3.68	-	-	-	-	-	-	-
4.0		0.01	1.71	-	-	-	-	-	-	-
4.1		0.20	0.44	-	-	-	-	-	-	-
4.2		1.04	0.04	-	-	-	-	-	-	-
4.3		2.01	0.00	-	-	-	-	-	-	-
4.4		2.79	0.00	3.08	-	-	-	-	-	-
4.5		3.48	0.01	1.58	-	-	-	-	-	-
4.6		-	0.14	0.55	4.30	-	-	-	-	-
4.7		-	0.59	0.13	2.55	-	-	-	-	-
4.8		-	1.15	0.04	1.43	5.33	-	-	-	-
4.9		-	1.78	0.13	0.60	3.35	-	-	-	-
5.0		-	2.47	0.38	0.25	1.90	-	-	-	-
5.1		-	3.29	0.83	0.12	1.04	4.13	-	-	-
5.2		-	4.17	1.39	0.21	0.46	2.51	-	-	-
5.3		-	-	2.11	0.52	0.19	1.27	2.56	-	-
5.4		-	-	3.12	1.11	0.21	0.66	1.03	-	-
5.5		-	-	4.34	2.01	0.79	0.60	0.25	-	-
5.6		-	-	5.89	3.26	1.66	1.01	0.05	-	-
5.7		-	-	-	4.42	2.49	1.41	0.02	-	-
5.8		-	-	-	5.56	3.32	1.85	0.00	-	-
5.9		-	-	-	-	4.03	2.23	0.00	3.22	-
6.0		-	-	-	-	4.63	2.56	0.00	2.10	5.49
6.1		-	-	-	-	-	2.78	0.03	1.21	3.61
6.2		-	-	-	-	-	-	0.12	0.63	2.12
6.3		-	-	-	-	-	-	0.34	0.32	1.13
6.4		-	-	-	-	-	-	0.74	0.29	0.50
6.5		-	-	-	-	-	-	1.28	0.51	0.19
6.6		-	-	-	-	-	-	1.89	0.82	0.08
6.7		-	-	-	-	-	-	2.47	1.14	0.03
6.8		-	-	-	-	-	-	3.04	1.46	0.02
6.9		-	-	-	-	-	-	3.55	1.75	0.01
7.0		-	-	-	-	-	-	4.01	2.00	0.00

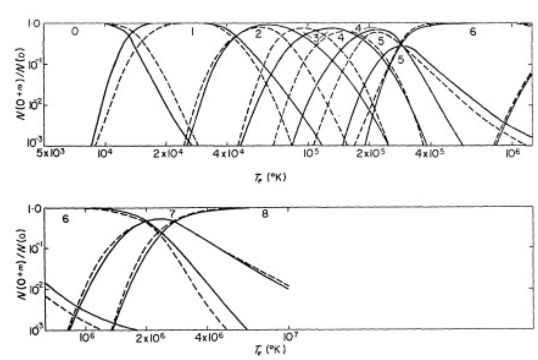


FIG. 1. *The ionization equilibrium of O ions. The full lines illustrate the present calculations which are applicable to the Sun. The dashed lines show the results of House (1964).*

Today's version

- **In cloudy / tsuite / programs / collion**

#Te	0	0+1	0+2	0+3	0+4	0+5	0+6	0+7	0+8
3.00	-5.95	--	--	--	--	--	--	--	--
3.10	-5.30	--	--	--	--	--	--	--	--
3.20	-2.53	--	--	--	--	--	--	--	--
3.30	-1.39	--	--	--	--	--	--	--	--
3.40	-0.84	--	--	--	--	--	--	--	--
3.50	-0.48	--	--	--	--	--	--	--	--
3.60	-0.46	--	--	--	--	--	--	--	--
3.70	-0.48	--	--	--	--	--	--	--	--
3.80	-0.49	--	--	--	--	--	--	--	--
3.90	-0.40	-8.41	--	--	--	--	--	--	--
4.00	-0.09	-3.55	--	--	--	--	--	--	--
4.10	-0.02	-1.42	--	--	--	--	--	--	--
4.20	-0.26	-0.35	--	--	--	--	--	--	--
4.30	-0.99	-0.05	-7.21	--	--	--	--	--	--
4.40	-1.79	-0.01	-4.90	--	--	--	--	--	--
4.50	-2.46	-0.00	-2.96	--	--	--	--	--	--
4.60	-2.93	-0.02	-1.33	-5.77	--	--	--	--	--
4.70	-3.28	-0.18	-0.47	-3.41	--	--	--	--	--
4.80	-3.70	-0.53	-0.16	-2.02	-6.65	--	--	--	--
4.90	-4.21	-0.97	-0.09	-1.11	-4.45	--	--	--	--
5.00	-4.84	-1.49	-0.18	-0.51	-2.82	-7.27	--	--	--
5.10	-5.62	-2.13	-0.45	-0.21	-1.66	-4.85	-8.35	--	--
5.20	-6.52	-2.87	-0.86	-0.14	-0.88	-3.03	-5.27	--	--
5.30	-7.52	-3.71	-1.40	-0.27	-0.40	-1.70	-2.91	--	--
5.40	-8.70	-4.71	-2.13	-0.64	-0.25	-0.84	-1.21	--	--
5.50	--	-6.11	-3.29	-1.47	-0.64	-0.62	-0.31	--	--
5.60	--	-7.87	-4.81	-2.71	-1.48	-0.95	-0.07	-8.37	--
5.70	--	--	-6.29	-3.93	-2.35	-1.38	-0.02	-6.26	--
5.80	--	--	-7.61	-5.02	-3.12	-1.77	-0.01	-4.59	--
5.90	--	--	-8.77	-5.95	-3.77	-2.10	-0.00	-3.23	-7.76
6.00	--	--	--	-6.74	-4.30	-2.33	-0.01	-2.15	-5.43
6.10	--	--	--	-7.39	-4.71	-2.48	-0.02	-1.30	-3.56
6.20	--	--	--	-7.96	-5.06	-2.60	-0.10	-0.71	-2.14
6.30	--	--	--	-8.55	-5.46	-2.80	-0.28	-0.39	-1.13
6.40	--	--	--	--	-5.99	-3.15	-0.63	-0.34	-0.51
6.50	--	--	--	--	-6.67	-3.67	-1.13	-0.51	-0.21
6.60	--	--	--	--	-7.41	-4.28	-1.69	-0.79	-0.09
6.70	--	--	--	--	-8.15	-4.88	-2.24	-1.08	-0.04
6.80	--	--	--	--	-8.85	-5.45	-2.75	-1.36	-0.02
6.90	--	--	--	--	--	-5.99	-3.22	-1.61	-0.01
7.00	--	--	--	--	--	-6.50	-3.64	-1.83	-0.01

Shock in an ideal gas

- Energy of motion $\frac{1}{2} \rho v^2$
- Thermal energy 3/2 nkT
- $T(\text{shock}) = \rho v^2 / 3nk = v^2 / 3k\ \rho/n = v^2 \mu / 3k$
- If the gas is ionized then $n \approx 2n(H)$ so $\mu \approx m_p / 2$
- $T(\text{shock}) = 20\ v(\text{km/s})^2$ K

Watch for these correlations

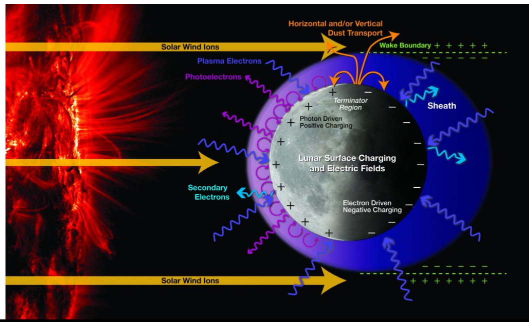
- $T_{shock} \sim = 20\ v(\text{km/s})^2$ [K]
- Ionization potential Z^2 Ryd
  - $\approx 1.5\times10^5 Z^2$ [K] (from energy match)
  - $\approx 10^4 Z^2$ [K] (thermal distribution of energies)
- 100 km/s -> 200 000 [K]
- From 200 000 K = $10^4 Z^2$ -> $Z \approx 4$

Watch for these correlations

- $T_{shock} \sim = 20\ v(\text{km/s})^2$ K
- E(level above ground) = $Z^2 (1-n^{-2})$
- Rydberg formula
  - E(photon) = $E_u - E_l = Z^2 (n_l^{-2} - n_u^{-2})$
- High Z, lines have higher energy, shorter wavelength

Earth within solar wind

- Solar wind speed ≈400 km/s at Earth's orbit



T Tauri jets

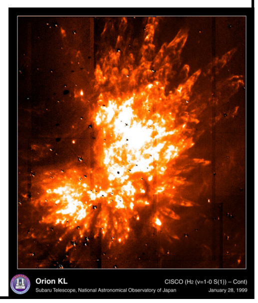
- ≈ 50 km/s

H II regions

- Wind speed ≈500 km/s

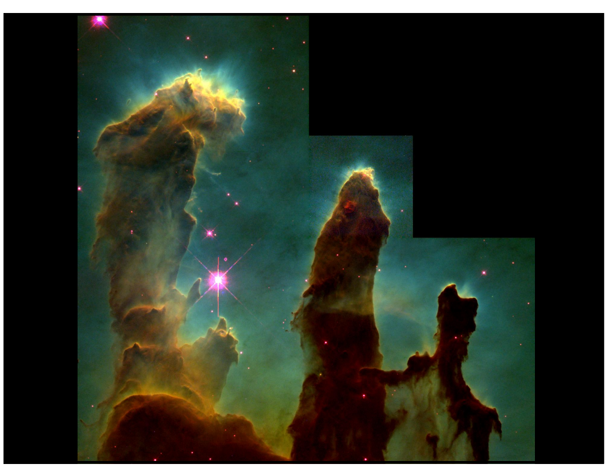
BN – KL in Orion

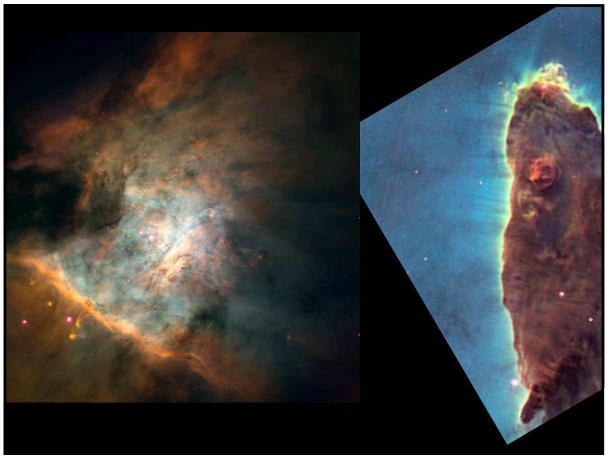
- 10 km/s



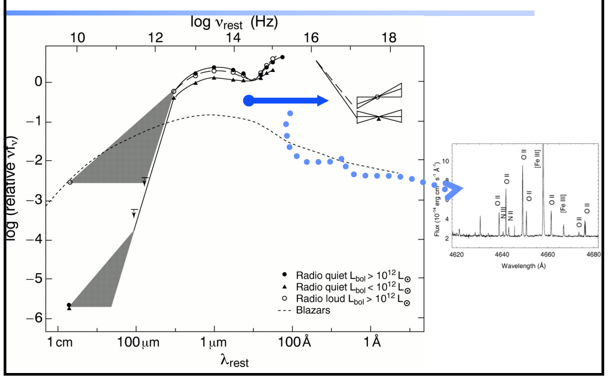
Planetary nebula

- Wind~10^3 km/s



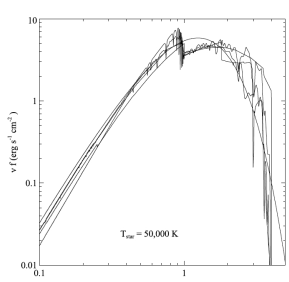


Photoionization
Continuum → emission lines

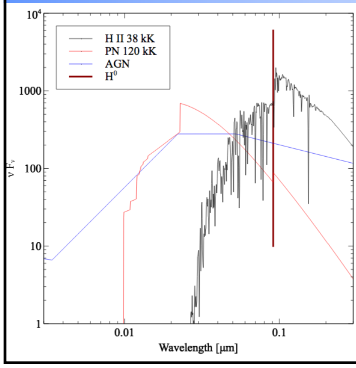


Stellar SEDs

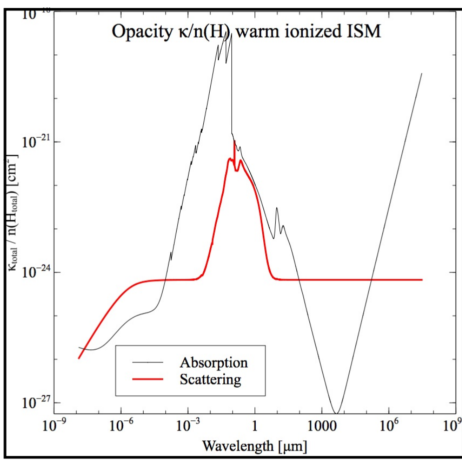
- Models of 50k K O stars



SED, H^0 ion limit, photoelectron energy



SED	<hϖ-13.6eV>
H II	52.7 kK
PN	266 kK
AGN	321 kK
Thermal	10 – 20 kK

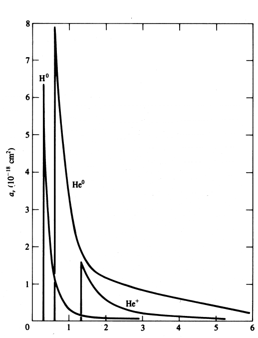


Total opacity per hydrogen

Photoionization

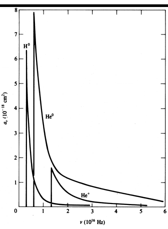
- **Highest cross section at lowest photon energies**
- **AGN3 Fig 2.2**

$$a\left(H^0\right) \approx 6.30\times10^{-18}\left(\frac{\nu}{\nu_0}\right)^{-3}\ [\mathrm{cm}^2]$$



Photoionization

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



$$a_\nu(Z) = \frac{A_0}{Z^2}\left(\frac{\nu_1}{\nu}\right)^4 \frac{\exp\left\{4 - \left[\left(4\tan^{-1}\varepsilon\right)/\varepsilon\right]\right\}}{1-\exp\left(-2\pi/\varepsilon\right)} \ [\mathrm{cm}^2] \text{ for } \nu \geq \nu_1 \qquad (2.4)$$

where

$$A_0 = \frac{2^9\pi}{3e^4}\left(\frac{1}{137.0}\right)\pi a_0^2 = 6.30\times10^{-18}\ [\mathrm{cm}^2],$$

$$\varepsilon = \sqrt{\frac{\nu}{\nu_1} - 1},$$

Photoionization rate [s^{-1}]

- Flux of ionizing photons × photoionization cross section

$$\int_{\nu_0}^{\infty} \frac{4\pi J_\nu}{h\nu} a_\nu(\mathrm{H}^0)\, d\nu = \int_{\nu_0}^{\infty} \phi_\nu a_\nu(\mathrm{H}^0)\ d\nu = \Gamma(\mathrm{H}^0) \qquad (2.1)$$

Hydrogen collisional ionization

$\mathrm{H} + e^- \xrightarrow{k_8} \mathrm{H}^+ + e^- + e^- \ \ldots \quad k_8 = 5.8\times10^{-11} T^{1/2} \exp(-158{,}000/T)\ \mathrm{cm}^3\ \mathrm{s}^{-1}$ Lotz 1967

$\mathrm{H} + \mathrm{H} \xrightarrow{k_9} \mathrm{H}^+ + e^- + \mathrm{H} \ldots\ldots \quad k_9 = 1.7\times10^{-4} k_8$ Drawin 1969

- Electron collisional ionization rate
  - $c = k_8 n_e$
- Hydrogen atom collisional rate
  - $c = k_9 n(H^0)$
- Palla+1983

Radiative recombination

- Brems is produced by distant collisions between electrons and charges
  - Photon energy taken from kinetic energy of free electron
- A very close collision can cause an electron to lose so much energy that it becomes bound to the ion
- Ion + electron => atom + photon
- Rate coefficient α $cm^3\ s^{-1}$
- Rate = α n_e

Radiative recombination

$$\alpha_B(T_e) = \begin{cases} 2.90 \times 10^{-10}\, T_e^{-0.77}, & T_e \leq 2.6 \times 10^4\ \mathrm{K} \\ 1.31 \times 10^{-8}\, T_e^{-1.13}, & T_e > 2.6 \times 10^4\ \mathrm{K} \end{cases} \ \mathrm{cm^3\ s^{-1}} \quad . \tag{6}$$

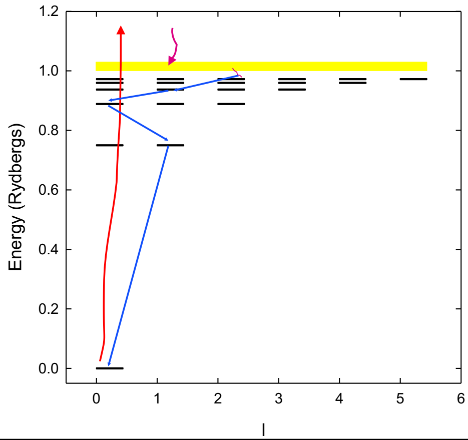
- Ferland 1980

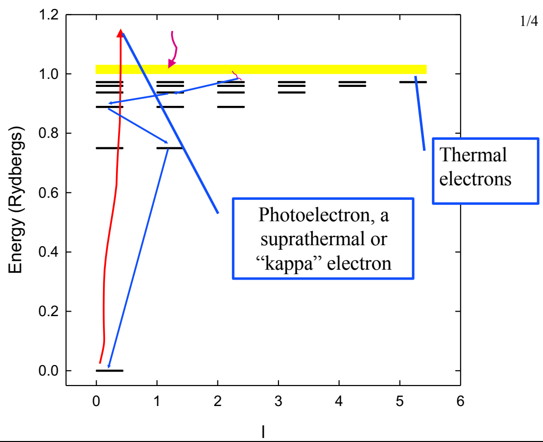
Recombination AGN3 Chap 2

- 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

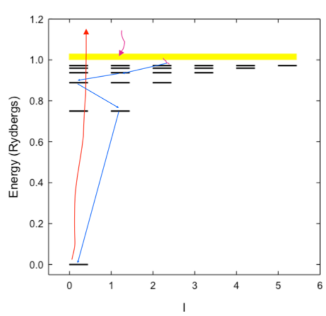
	T				
	1,250 K	2,500 K	5,000 K	10,000 K	20,000 K
$\alpha_A = \sum_1^\infty \alpha_n$	1.74×10^{-12}	1.10×10^{-12}	6.82×10^{-13}	4.18×10^{-13}	2.51×10^{-13}
$\alpha_B = \sum_2^\infty \alpha_n$	1.28×10^{-12}	7.72×10^{-13}	4.54×10^{-13}	2.59×10^{-13}	1.43×10^{-13}
$\alpha_C = \sum_3^\infty \alpha_n$	1.03×10^{-12}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





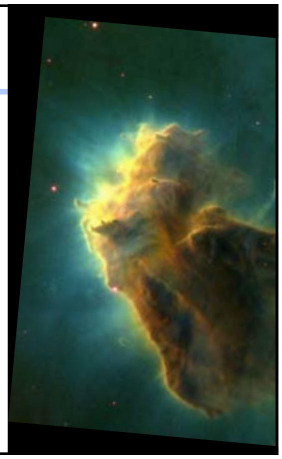
Life history of an Orion electron

- **H^0 ground state**
  - 1 day
- **Suprathermal**
  - 1 second
- **Thermal**
  - 1 yr
- **H^0 excited states**
  - 10^{-7} s
- **H^0 ground state**

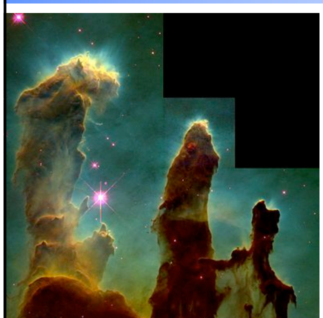


Let’s model a …

- Relatively dense, $n_H = 10^4$ cm^{-3}
- ISM cloud
- O6 star, but all light at 2 Ryd
- $Q(H)=10^{48}$ s^{-1}
- 1 pc = 3×10^{18} cm away



Strömgren length

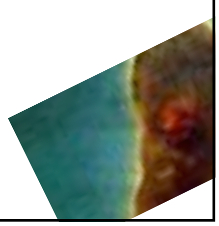


Strömgren length

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

$$\varphi(H) = n_e n_p \alpha \quad L$$

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



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