
A Star is Born

Properties of “Typical” Giant Molecular Clouds

Mass	1-2x10^5 M_{Sun}
Mean diameter	45 pc
Projected surface area	2.1x10^3 pc^2
Volume	9.6x10^4 pc^3
Volume averaged $n(H_2)$	~50 cm^{-3}
Mean N(column density)	3-6x10^{21} cm^{-2}
Local surface density (galactic disk)	~4 kpc^{-2}
Mean separation	~500 pc

Cloud Collapse

For a cloud of uniform density ρ_0 and temperature T, it will collapse due to self-gravity if it mass M is large enough:

$$M \geq M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

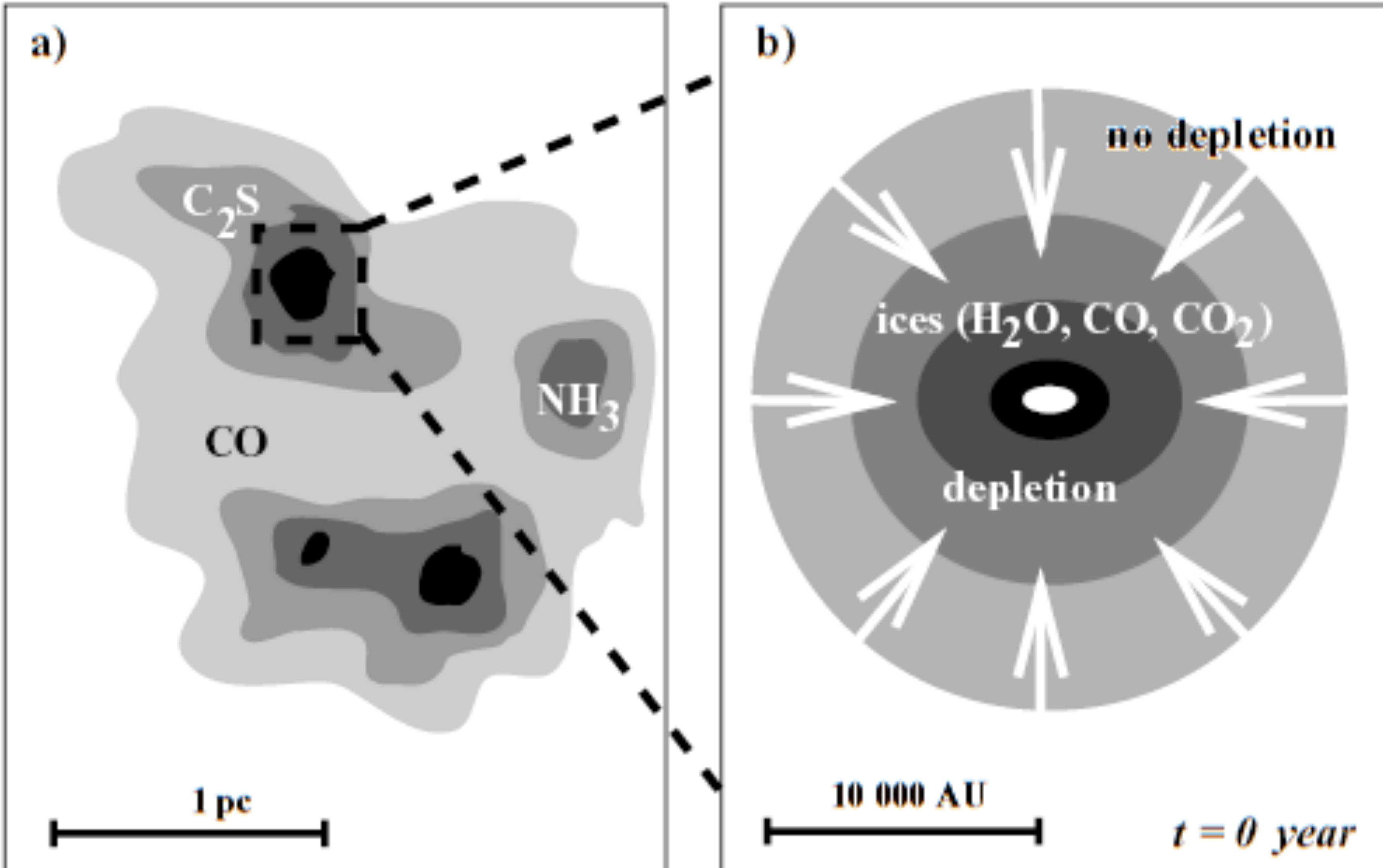
$$M_J = \text{"}Jeans\ Mass\text{"}$$

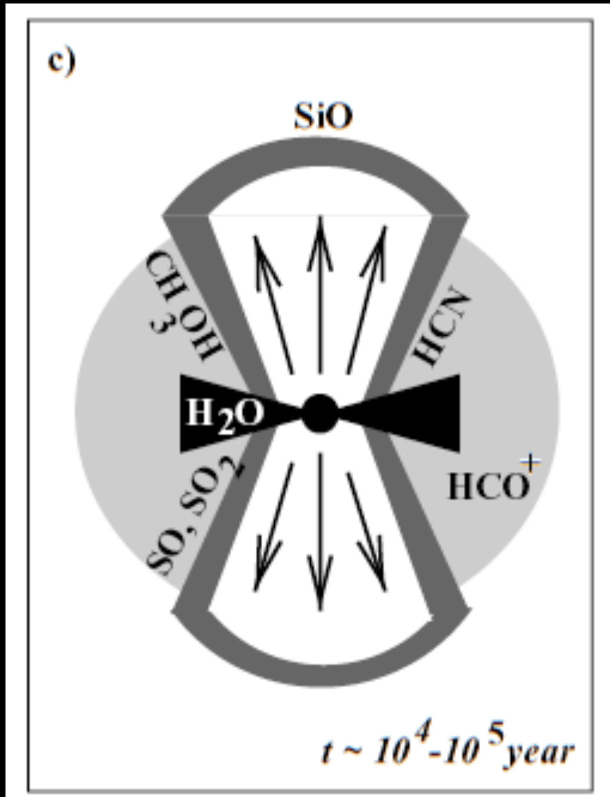
If the collapse is nearly "free-fall" then the timescale for the collapse is:

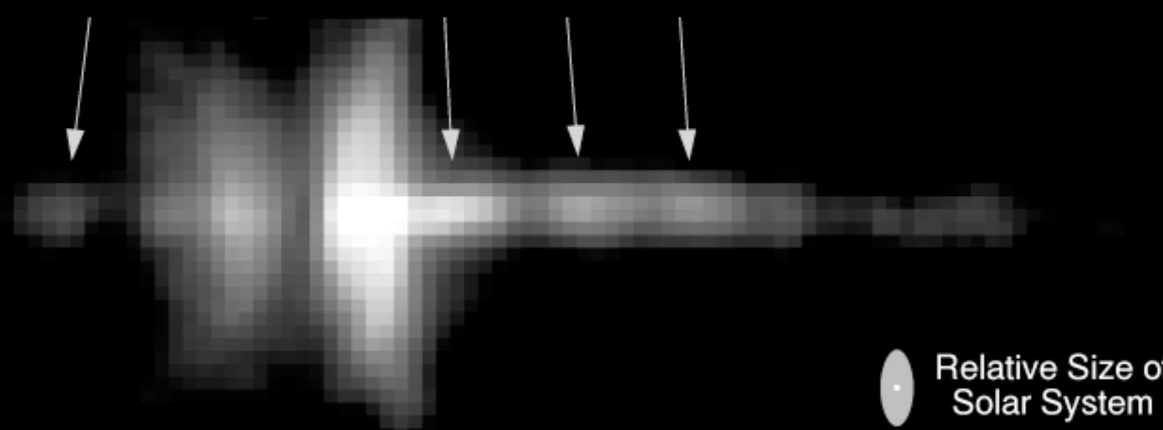
$$t_{ff} \sim \left(\frac{R^3}{GM}\right)^{1/2} = \left(\frac{\frac{3M}{4\pi\rho_0}}{GM}\right)^{1/2} = \left(\frac{3}{4\pi G\rho_0}\right)^{1/2}$$

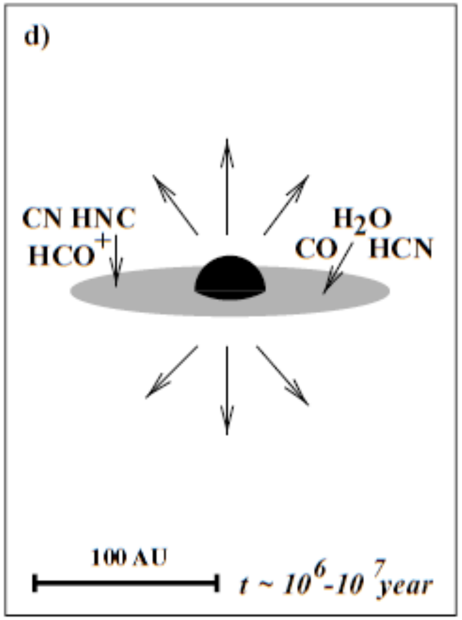
Note: there are many ways to approach this problem, but most are the same to within 10% or so. Don't let this bother you....

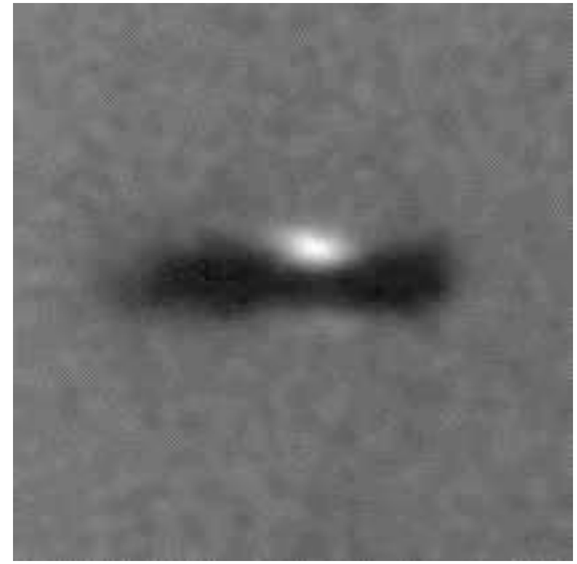
* Caveat: On the largest scales, however, the pressure may be dominated by *magnetic turbulence* (e.g.Franco & Alves 2015, arXiv:1504.08222)

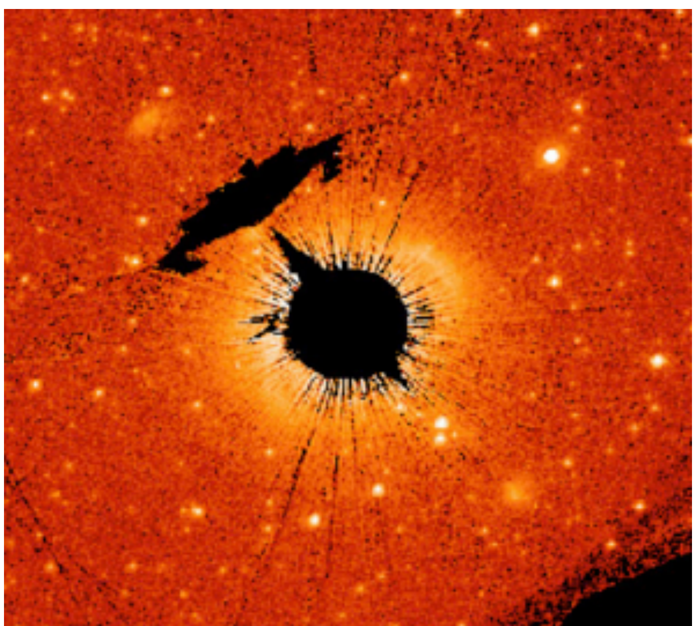

a)
C2S
CO
NH3
1 pc
b)
no depletion
ices (H2O, CO, CO2)
depletion
10 000 AU
t = 0 year

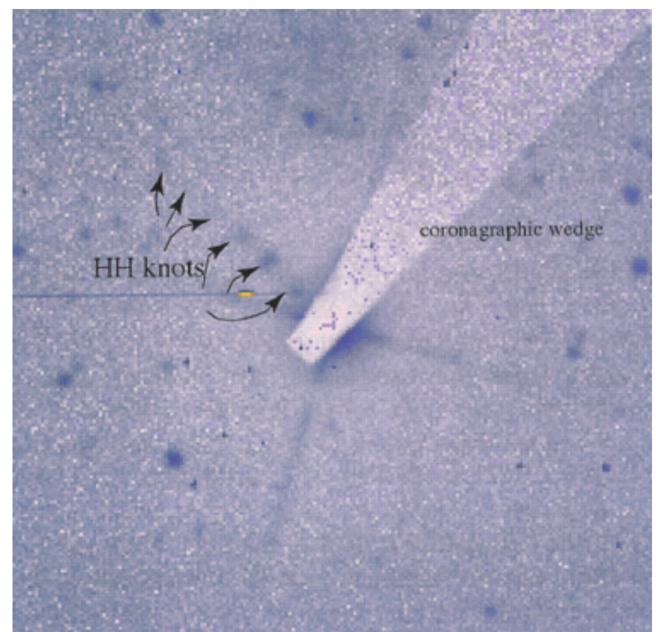

c)
SiO
CH_3OH
HCN
H_2O
SO, SO_2
HCO^+
$t \sim 10^4$-10^5 year


Relative Size of Solar System


d)
CN HNC
HCO^+
H_2O
CO
HCN
100 AU
$t \sim 10^6$-10^7 year






HH knots
coronagraphic wedge

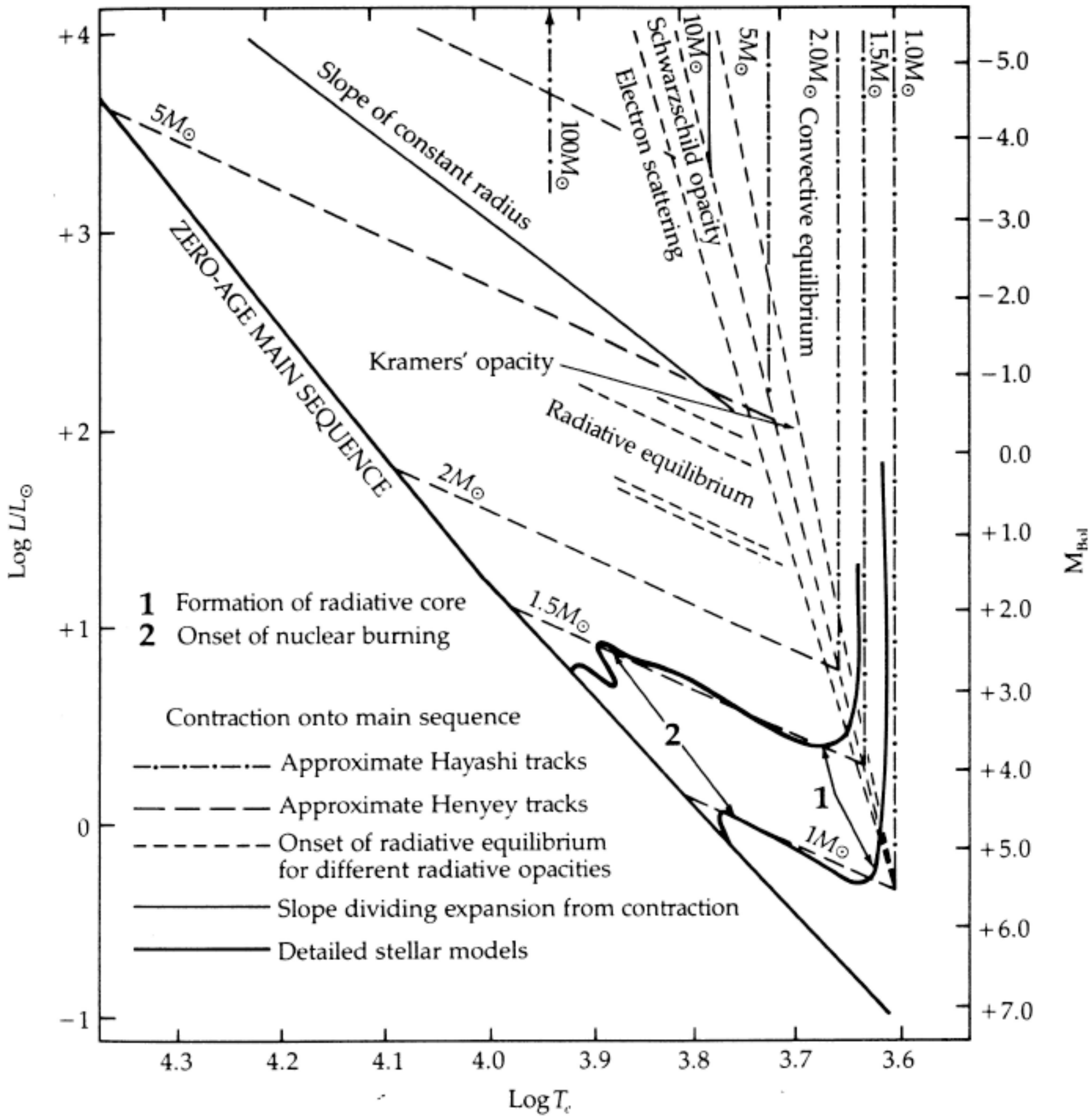
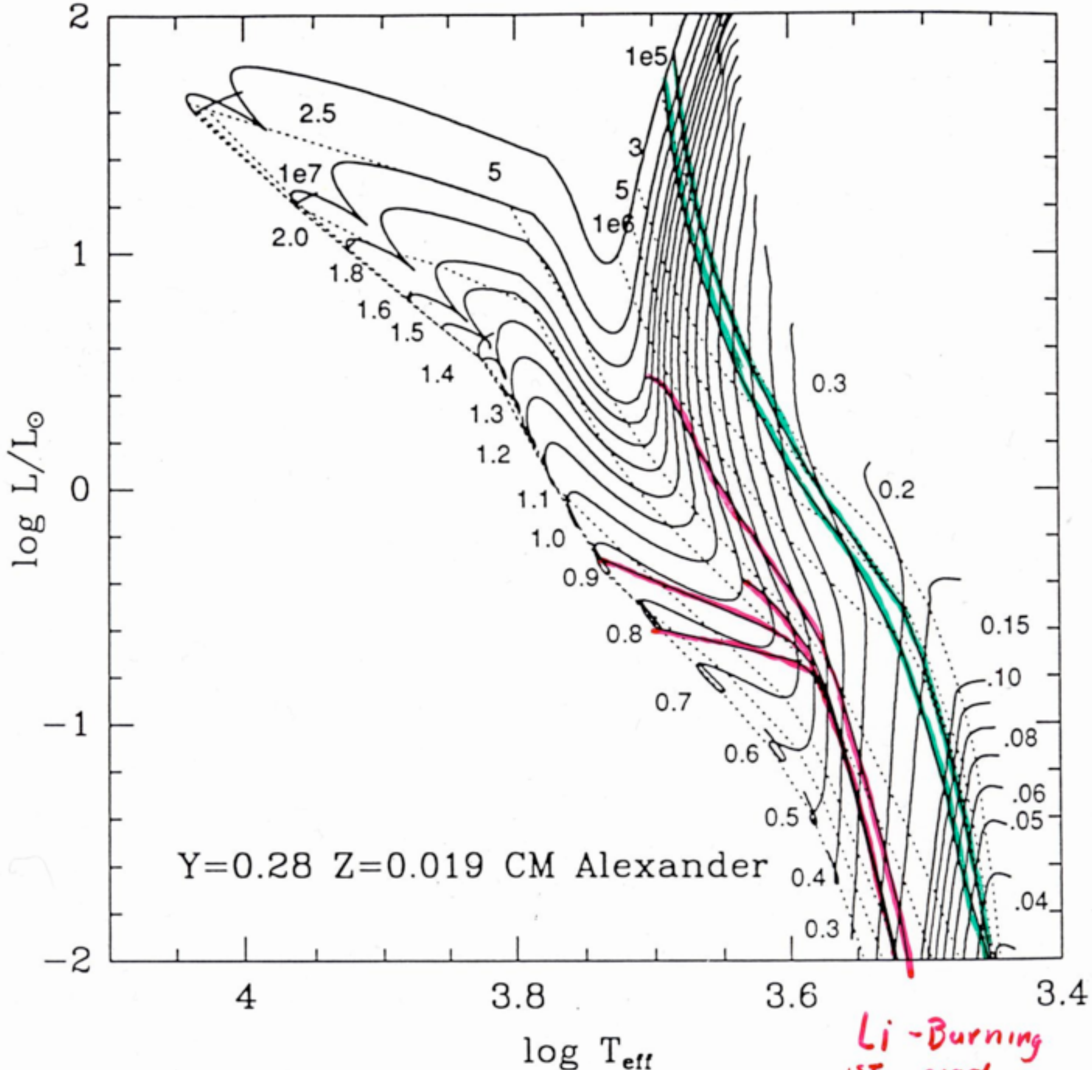


Figure 5.1 shows the schematic tracks for fully convective stars and radiative stars on their way to the main sequence. The low dependence of the convective tracks on mass implies that most contracting stars will occupy a rather narrow band on the right hand side of the H-R diagram. The line of constant radius clearly indicates that stars on the Henyey tracks continue to contract. The dashed lines indicate the transition from convective to radiative equilibrium for differing opacity laws. The solid curves represent the computed evolutionary tracks for two stars of differing mass.[5]

^{2}H burning
$X = 10^{-5} \rightarrow 10^{-8}$

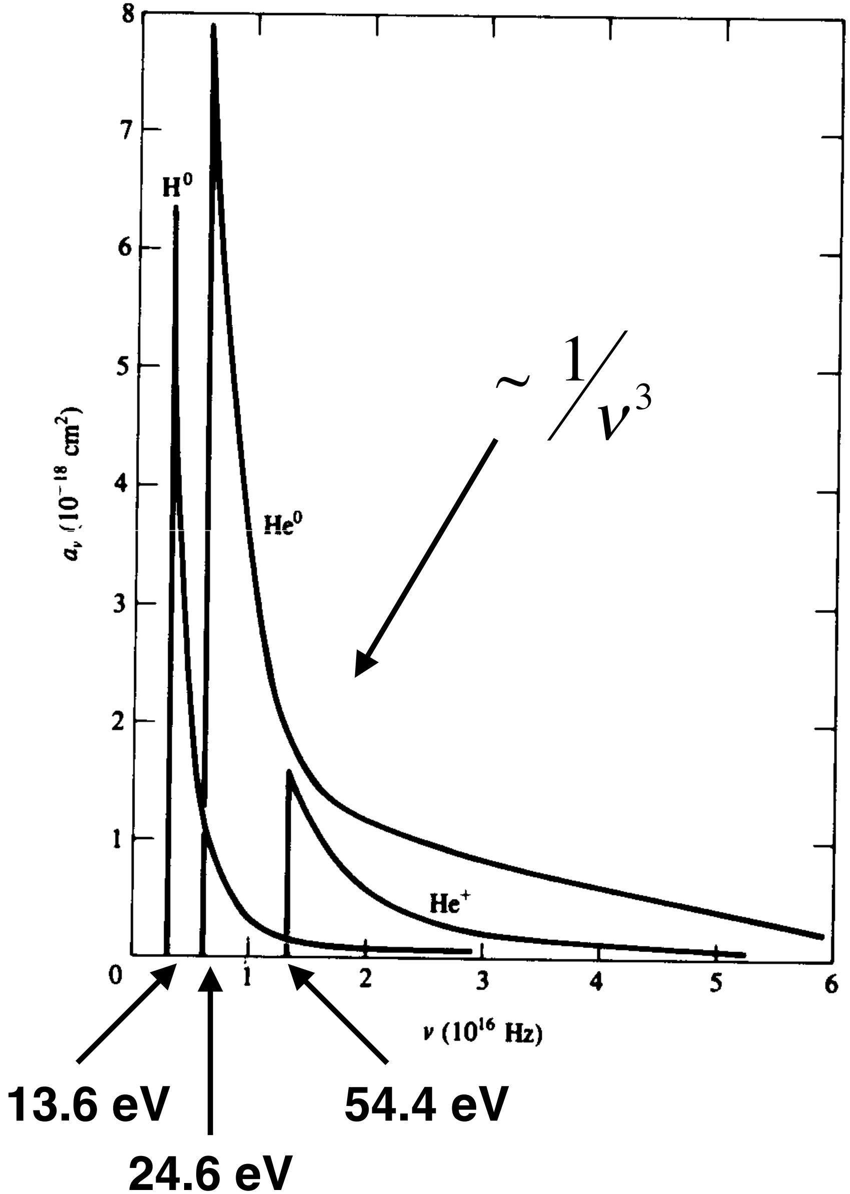
$$p + {}^{2}H \rightarrow \gamma + {}^{3}He$$



Li - Burning
1st - start
2nd - $\frac{1}{10}$
3rd - $\frac{1}{100}$
4th - $\frac{1}{1000}$

$$p + {}^{7}Li \rightarrow 2\,{}^{4}He$$
$$p + {}^{6}Li \rightarrow {}^{4}He + {}^{3}He$$

Ionized Gas Clouds



Ionization cross sections of H^0, He^0 and He$^+$ from Osterbrock's AGN[2]

Interactions

Particle-Particle $x_m = \dfrac{1}{\sigma n}$ $t_m = \dfrac{1}{\sigma n v}$

Photon-Particle $x_r = \dfrac{1}{a n}$ $t_r = \dfrac{1}{a n c}$

Example – H II Region
electron-ion collisions

$$\sigma = \frac{4\pi e^4}{9k^2T^2} = \frac{3.9x10^{-6}}{T^2}\, cm^2$$

Typical n and T: n~10 and T~10^4:

x_m=$2x10^{10}$ cm versus sizes ~ $3x10^{18}$ cm

t_m=400 s versus ages ~ $3x10^{13}$ s

So: electron-ion (and electron-electron) interactions:

- mechanical equilibrium
- maxwellian velocity distribution

How big can this nebula be? If we equate the rate of ionizing photons produced by the star to the recombination rate in the nebula (assuming steady state), we get

$$\int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} \equiv \underbrace{Q\left(H^0\right)}_{\substack{\#\ photons/\mathrm{sec} \\ able\ to\ ionize\ H}} = \overbrace{\frac{4\pi}{3} R^3}^{volume} n^2 \alpha_B$$

$$where\ \alpha_B = recombinations\ that\ do\ NOT\ lead\ to\ more\ ionizations$$

For hydrogen, α_B would include only recombinations to the *n=2 quantum level and higher*. Recombinations to n=1 will produce a photon which will ionize some neutral H atom elsewhere, so cannot be counted in the net recombination rate.

In a typical nebula, a typical recombination rate is:

$$n_e \alpha \sim n_{H^+} \alpha \sim 10^{-11} s^{-1}$$

Approximate idealized H II region – "Strömgren* Sphere"

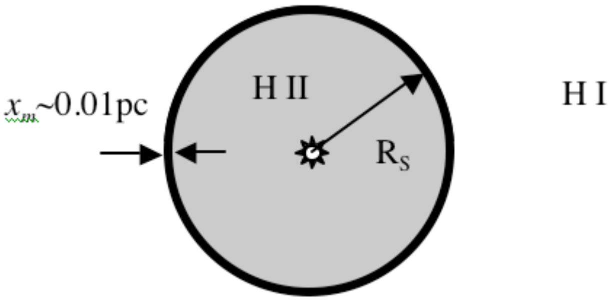


TABLE 2.3
Calculated radii of Strömgren spheres

Spectral type	M_v	$T_*(°K)$	Log $Q(H^0)$ (photons/sec)	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})
O5	– 5.6	48,000	49.67	6.07	108
O6	– 5.5	40,000	49.23	5.63	74
O7	– 5.4	35,000	48.84	5.24	56
O8	– 5.2	33,500	48.60	5.00	51
O9	– 4.8	32,000	48.24	4.64	34
O9.5	– 4.6	31,000	47.95	4.35	29
B0	– 4.4	30,000	47.67	4.07	23
B0.5	– 4.2	26,200	46.83	3.23	12

NOTE: $T = 7500°$ K assumed for calculating α_B.

*(after Bengt Strömgren)

$$transition\ zone \sim 1\ m.f.p. \sim \frac{1}{na_\nu} \sim 10^{16}\,cm \sim 0.01\,pc$$

After recombination, the radiative rate downward by deexcitation cascades goes as $A_{ul} \sim 10^8\ s^{-1}$. So once recombination occurs, *almost all H^0 is in the ground (n=1) electronic state*.

In a more realistic nebula, H^+ *and* He^+ regions will exist, and may not have their outer radii coincide.

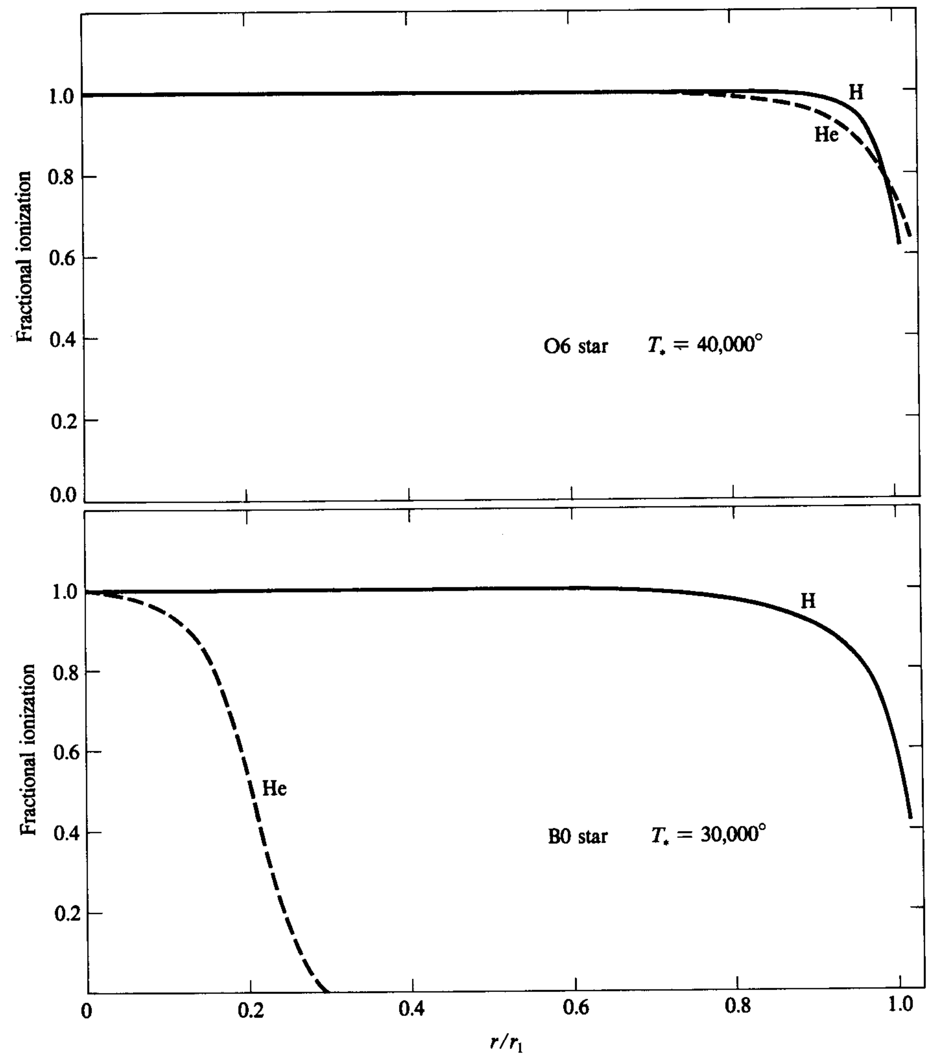


FIGURE 2.4
Ionization structure of two homogeneous H + He model H II regions.

Similarly, the metal ions may have numerous ionization zones.

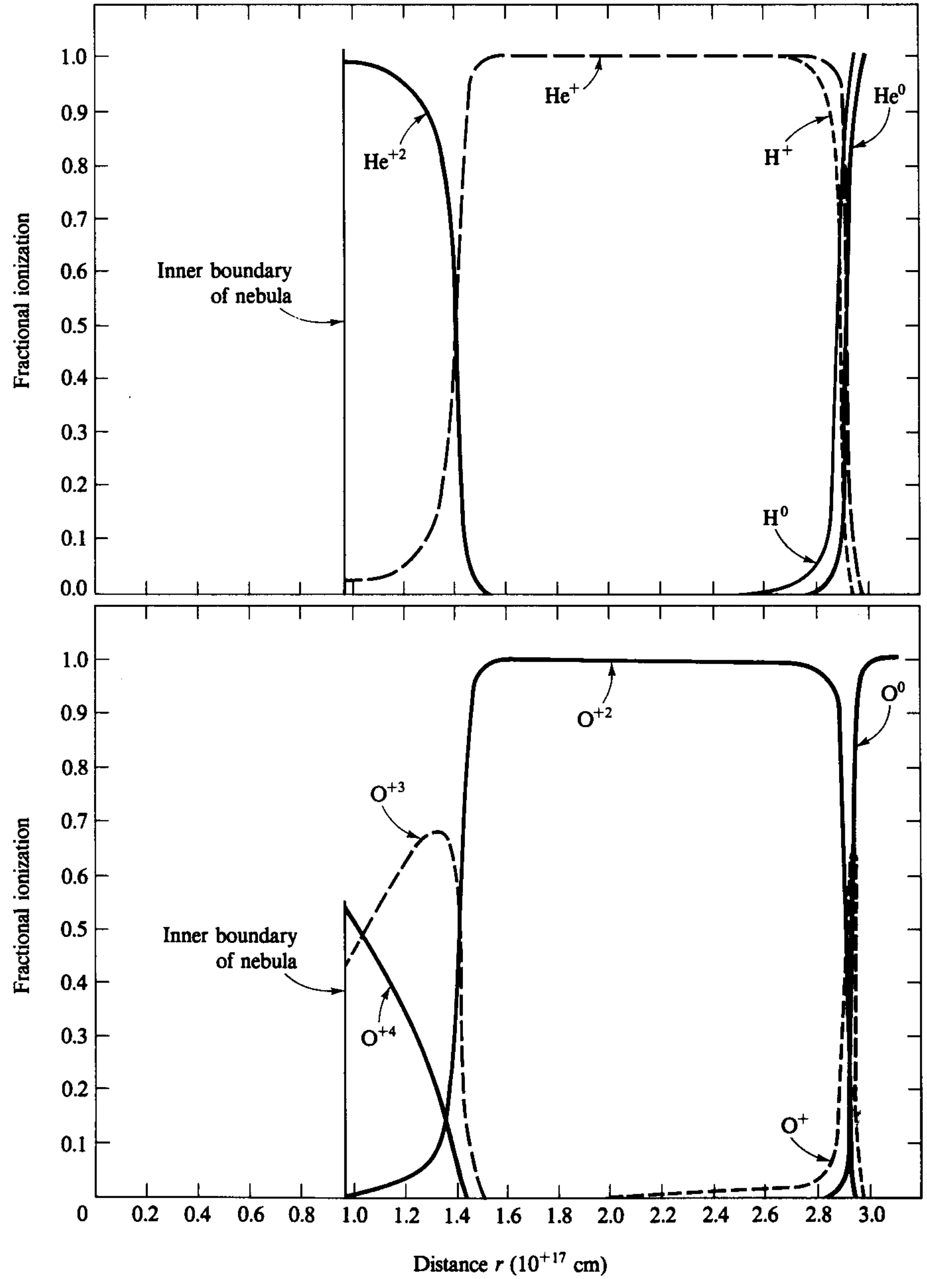


FIGURE 2.6
Ionization structure of H, He (*top*), and O (*bottom*) for a model planetary nebula.

Fractional Ionization – Inside a Typical H II Region

Near a "typical" hot ionizing star, T_*~4x10^4 K and n_{neb}~10 cm^{-3},

$$\begin{cases} \int_{\nu_0}^{\infty} \frac{L_\nu}{h\nu} d\nu \approx 5x10^{48} ionizing\ photons\ s^{-1} \\ \left(\nu_0 = \frac{13.6eV}{h}\ for\ hydrogen \right) \\ a_\nu\left(H^0\right) \sim 6x10^{-18}\ cm^2 \\ \Rightarrow ionization\ rate / H^0 \approx 10^{-8} s^{-1} \quad for\ r \sim 5pc \end{cases}$$

Now, $\alpha\left(H^0, T\right) \sim 4x10^{-13} cm^3 s$ so in stead state

$$10^{-8} n\left(H^0\right) = n_e n\left(H^+\right) \cdot 4x10^{-13}$$

or $\frac{n_e n_{H^+}}{n_{H^0}} \sim \frac{1}{4} x10^5$ For nearly pure H, $n_e \sim n_{H^+}$

DEFINE $\xi = \frac{n_{H^0}}{n_H} \Rightarrow \left\{ \begin{array}{l} n_{H^0} = \xi n_H \\ n_{H^+} = (1-\xi) n_H \end{array} \right\}$ then, $\frac{(1-\xi)^2 n_H^2}{\xi n_H} = \frac{(1-\xi)^2}{\xi} n_H \sim \frac{10^5}{4}$

$For\ n_H \sim 10 cm^{-3} \rightarrow \xi \sim 4x10^{-4}$

H is almost totally ionized!

TABLE 2.2
Calculated ionization distributions for model H II regions

r(pc)	$T_* = 4 \times 10^4$ ° K Blackbody model $\frac{N_p}{N_p + N_{H^0}}$	$T_* = 4 \times 10^4$ ° K Blackbody model $\frac{N_{H^0}}{N_p + N_{H^0}}$	$T_* = 3.74 \times 10^4$ ° K Model stellar atmosphere $\frac{N_p}{N_p + N_{H^0}}$	$T_* = 3.74 \times 10^4$ ° K Model stellar atmosphere $\frac{N_{H^0}}{N_p + N_{H^0}}$
0.1	1.0	4.5×10^{-7}	1.0	4.5×10^{-7}
1.2	1.0	2.8×10^{-5}	1.0	2.9×10^{-5}
2.2	0.9999	1.0×10^{-4}	0.9999	1.0×10^{-4}
3.3	0.9997	2.5×10^{-4}	0.9997	2.5×10^{-4}
4.4	0.9995	4.4×10^{-4}	0.9994	4.5×10^{-4}
5.5	0.9992	8.0×10^{-4}	0.9992	8.1×10^{-4}
6.7	0.9985	1.5×10^{-3}	0.9985	1.5×10^{-3}
7.7	0.9973	2.7×10^{-3}	0.9973	2.7×10^{-3}
8.8	0.9921	7.9×10^{-3}	0.9924	7.6×10^{-3}
9.4	0.977	2.3×10^{-2}	0.979	2.1×10^{-2}
9.7	0.935	6.5×10^{-2}	0.940	6.0×10^{-2}
9.9	0.838	1.6×10^{-1}	0.842	1.6×10^{-1}
10.0	0.000	1.0	0.000	1.0

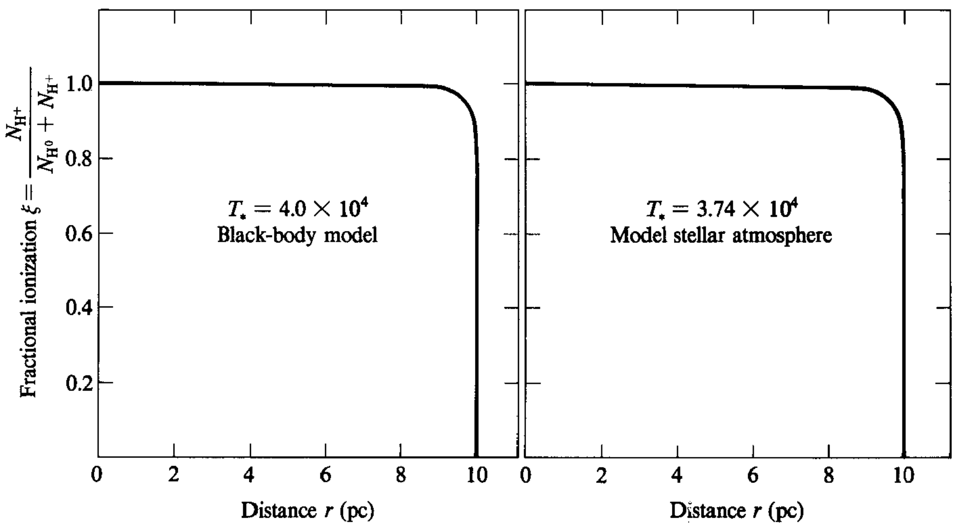
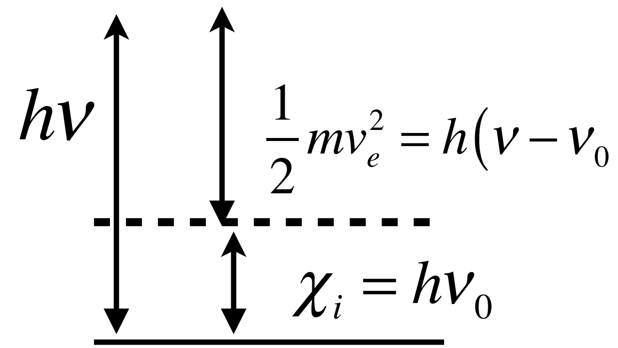


FIGURE 2.3
Ionization structure of two homogeneous pure-H model H II regions.

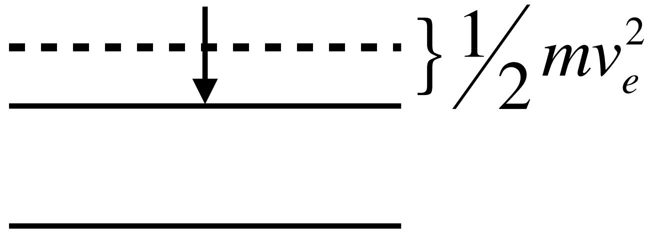
Heating & Cooling

Heating - Photoionization
Cooling - Recombination
- Bremsstrahlung (free-free)
- Collisional



$$\underbrace{G}_{\substack{energy\ input\\ rate\ per\ vol}} = \underbrace{n_e n_p \alpha_A}_{\substack{recomb\\ rate\ per\ vol}} \overbrace{\left(\frac{3}{2}kT_i\right)}^{\substack{energy\ input\ per\ recomb\\ (actually\ per\ ionization)}} \qquad (\alpha_B\ to\ correct\ for\ diffuse\ field)$$

$$For\ blackbody\ stars\ T_i \approx \frac{2}{3}T_{star}$$



L(rad)

$$L_R = n_p n_e \sum_n \sum_L \int_0^\infty v \sigma_{nL} \left(\tfrac{1}{2} m v^2 \right) f(v)\, dv$$

$$= n_p n_e \sum_n \beta_n kT$$

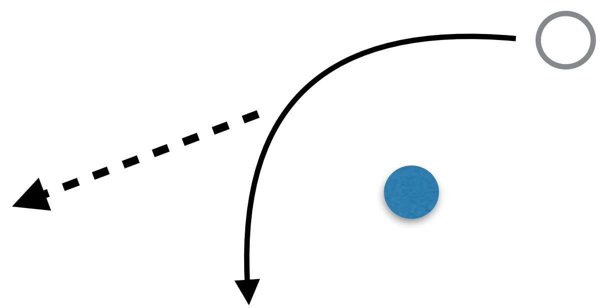
$$= n_p n_e \beta_B kT \qquad \beta_B = \sum_{n=2}^{\infty} \beta_n \quad (\textit{correct for diffuse field})$$

L(ff)

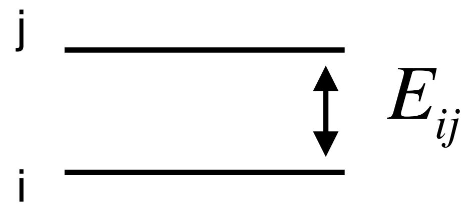
$$L_{FF} = \frac{2^5 \pi e Z^2}{3^{3/2} h m c^3} \left(\frac{2\pi kT}{m} \right)^{1/2} g_{ff} n_p n_e$$

$$= 1.42 x 10^{-27} Z^2 T^{1/2} g_{ff} n_p n_e$$

$$\sim L_R / 3$$



L(collisional)



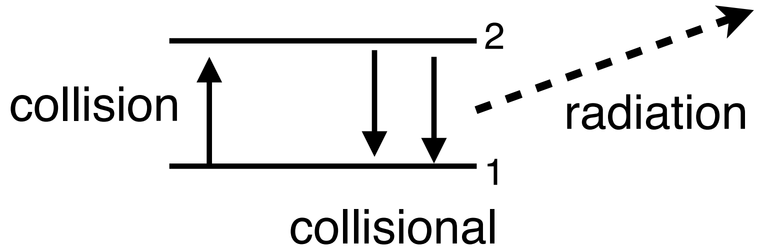
$$L_C = n_a n_e q_{ij} E_{ij}$$

$$q_{ij} = \frac{8.63x10^{-6}}{T^{1/2}} \frac{\Omega_{ij}}{\omega_i} e^{-E_{ij}/kt} \ upward$$

$$q_{ji} = \frac{8.63x10^{-6}}{T^{1/2}} \frac{\Omega_{ji}}{\omega_j} \ downward\left(no\ energy\ threshold\right)$$

ω *statistical weight of level*

Ω "*collision strength*"

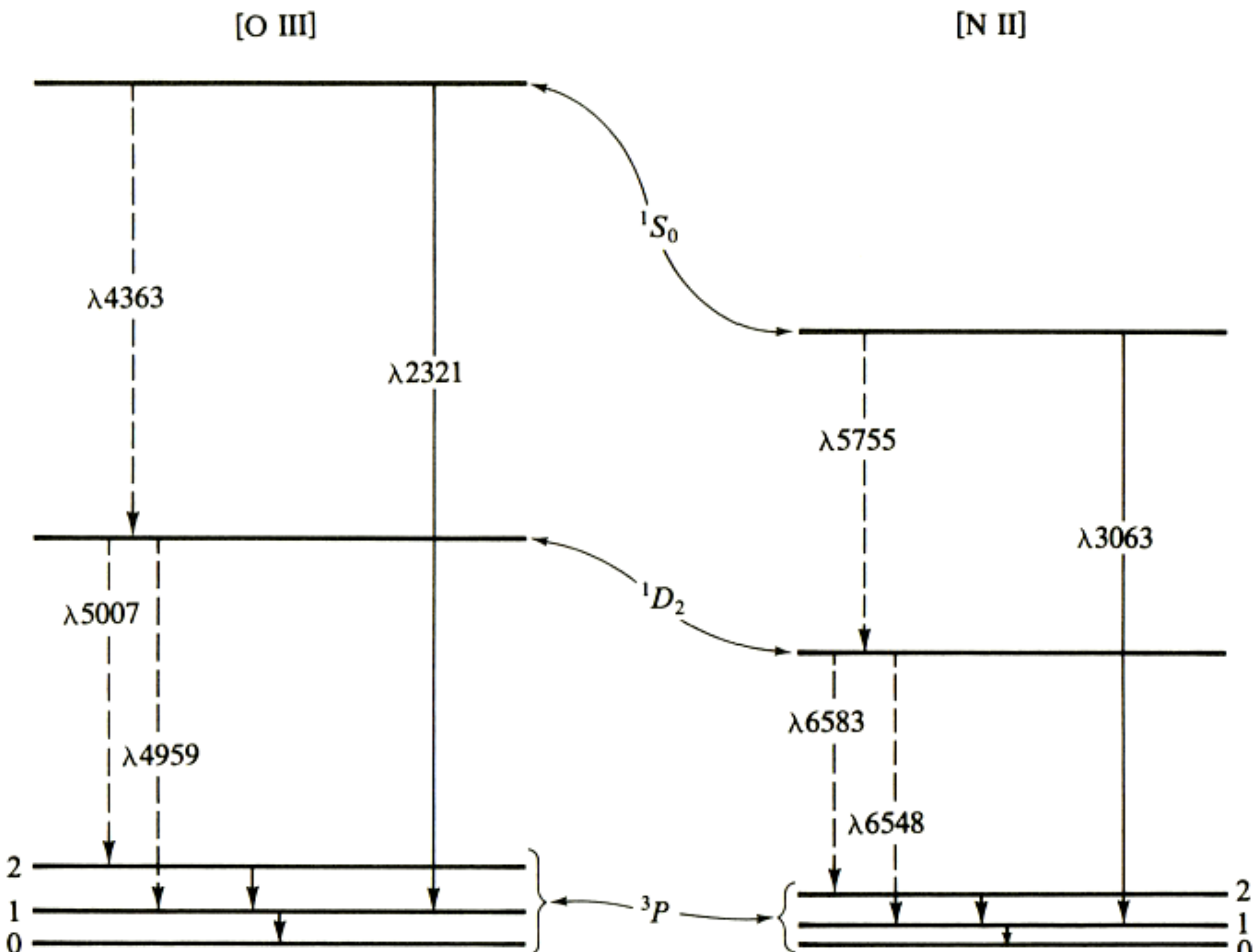


$$n_1 n_e q_{12} = n_2 \left(n_e q_{21} + A_{21} \right)$$

$$\frac{n_2}{n_1} = \frac{n_e q_{12}}{A_{21}} \left[\frac{1}{1 + \frac{n_e q_{21}}{A_{21}}} \right]$$

$$L_C = n_2 A_{21} E_{21} = n_1 n_e q_1 \frac{E_{21}}{1 + \frac{n_e q_{21}}{A_{21}}}$$

$$n \rightarrow \infty \quad L_C \rightarrow n_1 \frac{\omega_2}{\omega_1} e^{E/kT} A_{21} E_{21} \ \textit{Boltzmann Rate}$$


[O III]
[N II]
$^1S_0$
$^1D_2$
^3P
λ4363
λ2321
λ5007
λ4959
λ5755
λ3063
λ6583
λ6548
2
1
0
2
1
0

Other Processes

Dielectric Recombination

Capture of e^- excites a second e^- $\Rightarrow$ 2 EXCITED ELECTRONS

This dominates the $C^{++} + e^- \Rightarrow C^+$ reaction.

Charge-Exchange Reaction

$$Example: \quad O^+\left({}^4S\right) + H^0\left({}^2S\right) \rightarrow O^0\left({}^3P\right) + H^+$$

Inside an H II region, $\left(\frac{n_{H^0}}{n_e} \approx \frac{n_{H^0}}{n_{H^+}} \sim 10^{-4}\right)$ $\quad \frac{C.E.R.}{Rad.Recomb.} \sim 0.05$

At the edge of an H II region, $\left(\frac{n_{H^0}}{n_e} \sim \frac{1}{2}\right)$ $\quad \frac{C.E.R.}{Rad.Recomb.} \sim 10^2$!