Ionized Gas

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Ionization

- Photoionization

$$\sigma_{\mathrm{pe}}(\nu) \approx \sigma_0 \left(\frac{h\nu}{Z^2 I_{\mathrm{H}}}\right)^{-3} \quad \text{for } Z^2 I_{\mathrm{H}} < h\nu \lesssim 10^2 Z^2 I_{\mathrm{H}}$$

Ionization

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$$\sigma_{\mathrm{pe}} \to \frac{2^8}{3Z^2} \alpha \pi a_0^2 \left(\frac{h\nu}{Z^2 I_{\mathrm{H}}}\right)^{-3.5} \quad \text{for } h\nu \gg Z^2 I_{\mathrm{H}}$$

Ionization

- Photoionization

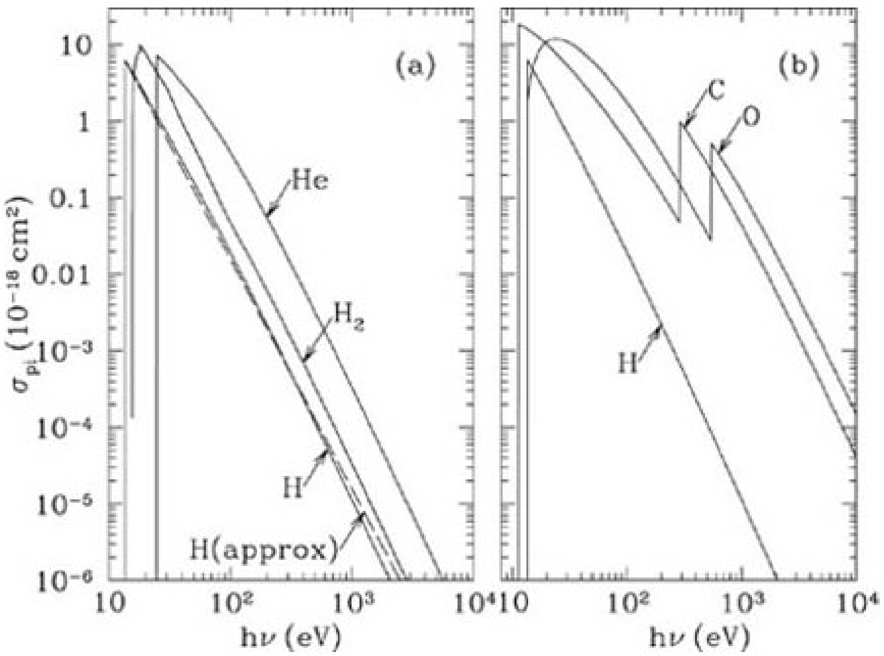


Figure 13.1 Photoionization cross sections for H, H_2, He, C, and O. The dashed line in (a) shows the power-law approximation (13.3) for H.

Ionization

- Photoionization

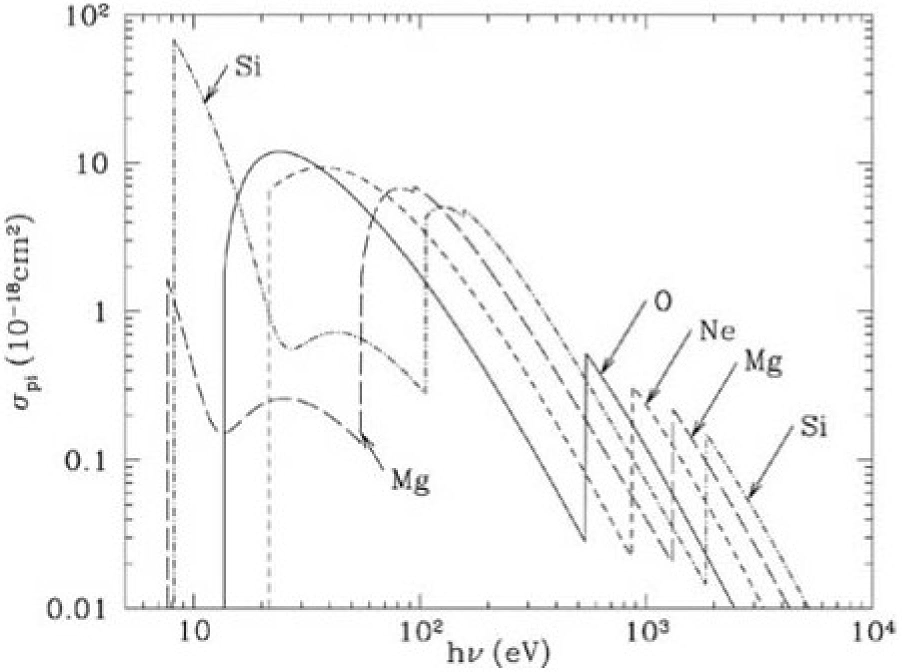


Figure 13.2 Photoionization cross sections for O, Ne, Mg, Si.

Ionization

- Photoionization

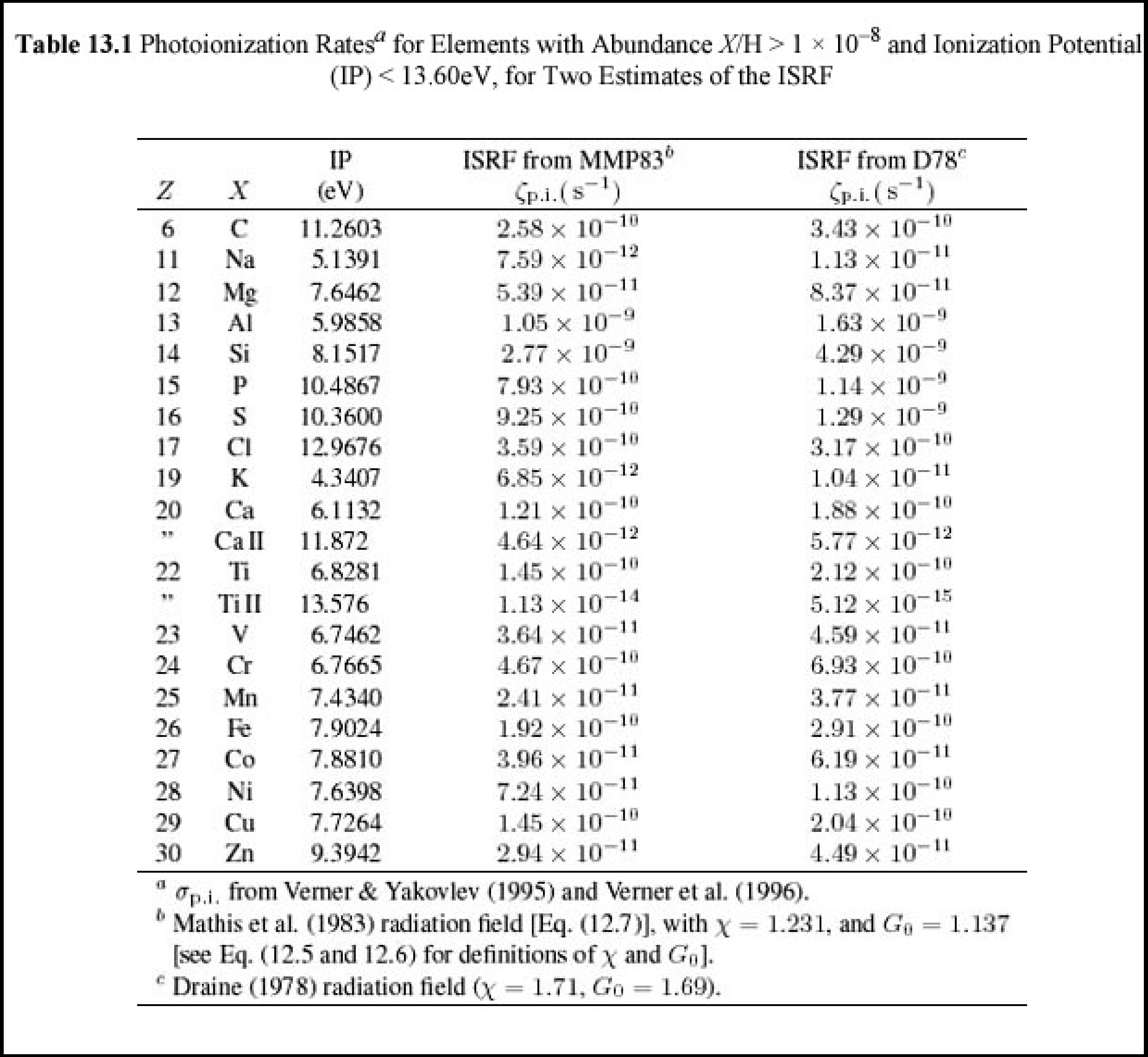


Table 13.1 Photoionization Rates[a] for Elements with Abundance X/H > 1 × 10^{-8} and Ionization Potential (IP) < 13.60eV, for Two Estimates of the ISRF

Z	X	IP (eV)	ISRF from MMP83[b] $\zeta_{\rm p.i.}({\rm s}^{-1})$	ISRF from D78[c] $\zeta_{\rm p.i.}({\rm s}^{-1})$
6	C	11.2603	2.58×10^{-10}	3.43×10^{-10}
11	Na	5.1391	7.59×10^{-12}	1.13×10^{-11}
12	Mg	7.6462	5.39×10^{-11}	8.37×10^{-11}
13	Al	5.9858	1.05×10^{-9}	1.63×10^{-9}
14	Si	8.1517	2.77×10^{-9}	4.29×10^{-9}
15	P	10.4867	7.93×10^{-10}	1.14×10^{-9}
16	S	10.3600	9.25×10^{-10}	1.29×10^{-9}
17	Cl	12.9676	3.59×10^{-10}	3.17×10^{-10}
19	K	4.3407	6.85×10^{-12}	1.04×10^{-11}
20	Ca	6.1132	1.21×10^{-10}	1.88×10^{-10}
"	Ca II	11.872	4.64×10^{-12}	5.77×10^{-12}
22	Ti	6.8281	1.45×10^{-10}	2.12×10^{-10}
"	Ti II	13.576	1.13×10^{-14}	5.12×10^{-15}
23	V	6.7462	3.64×10^{-11}	4.59×10^{-11}
24	Cr	6.7665	4.67×10^{-10}	6.93×10^{-10}
25	Mn	7.4340	2.41×10^{-11}	3.77×10^{-11}
26	Fe	7.9024	1.92×10^{-10}	2.91×10^{-10}
27	Co	7.8810	3.96×10^{-11}	6.19×10^{-11}
28	Ni	7.6398	7.24×10^{-11}	1.13×10^{-10}
29	Cu	7.7264	1.45×10^{-10}	2.04×10^{-10}
30	Zn	9.3942	2.94×10^{-11}	4.49×10^{-11}

[a] $\sigma_{\rm p.i.}$ from Verner & Yakovlev (1995) and Verner et al. (1996).

[b] Mathis et al. (1983) radiation field [Eq. (12.7)], with $\chi = 1.231$, and $G_0 = 1.137$ [see Eq. (12.5 and 12.6) for definitions of χ and G_0].

[c] Draine (1978) radiation field ($\chi = 1.71$, $G_0 = 1.69$).

Ionization

- Photoionization

$$\sigma_{\rm pe}(\nu) \approx \sigma_0 \left(\frac{h\nu}{Z^2 I_{\rm H}}\right)^{-3} \quad \text{for } Z^2 I_{\rm H} < h\nu \lesssim 10^2 Z^2 I_{\rm H}$$

- Auger effect in X-rays.

$$\sigma_{\rm pe} \rightarrow \frac{2^8}{3Z^2}\alpha\pi a_0^2 \left(\frac{h\nu}{Z^2 I_{\rm H}}\right)^{-3.5} \quad \text{for } h\nu \gg Z^2 I_{\rm H}$$

    - Secondary ionization.
- Collisional ionization.

$$\begin{aligned} k_{\rm c.i.} &= \int_I^\infty \sigma_{\rm c.i.}(E)\, v f_E dE \\ &= \left(\frac{8kT}{\pi m_e}\right)^{1/2} \int_I^\infty \sigma_{\rm c.i.}(E) \frac{E}{kT} {\rm e}^{-E/kT} \frac{dE}{kT} \end{aligned}$$

    - for thermal electrons.
- For energies close to threshold energy (I) $\sigma = C\pi a_0^2 (1 - I/E)$

$$\begin{aligned} k_{\rm c.i.} &= C\pi a_0^2 \left(\frac{8kT}{\pi m_e}\right)^{1/2} {\rm e}^{-I/kT} \\ &= 5.466 \times 10^{-9} C T_4^{1/2} {\rm e}^{-I/kT}\ {\rm cm^3\ s^{-1}} \end{aligned}$$

Ionization

- Photoionization
- Auger effect in X-rays.
    - Secondary ionization.
- Collisional ionization.
- Cosmic ray ionization.

Recombination

- Radiative recombination
  - Thermal distribution.

- $X^+ + e^- \rightarrow X + h\nu$

$$\alpha_{n\ell}(T) = \left(\frac{8kT}{\pi m_e}\right)^{1/2} \int_0^\infty \sigma_{\mathrm{rr},n\ell}(E) \frac{E}{kT} \mathrm{e}^{-E/kT} \frac{dE}{kT}$$

Recombination

- In the case of hydrogen:
  - rate coefficients have been calculated
  - Optically thin in which case ionizing radiation escapes.
  - radiative capture rate is the sum of all α_{nl}

- $\alpha(T) = \Sigma_{nl}\alpha_{nl}(T)$
- $\sim 4.13x10^{-13}(T_4)^y$ where
- $y = -.7131-0.0115\ln(T_4)$

Recombination

- In the case of hydrogen:
  - rate coefficients have been calculated
  - Optically thin in which case ionizing radiation escapes.
  - radiative capture rate is the sum of all α_{nl}

- $\alpha_A(T) = \Sigma_{nl}\alpha_{nl}(T)$
- $\sim 4.13x10^{-13}(T_4)^y$ where
- $y = -.7131-0.0115\ln(T_4)$

Recombination

- Optically thick when ionizing photons are immediately absorbed.
    - Subtract photons to ground state because they don't escape.

- $\alpha(T) = \Sigma_{nl}\alpha(T) = \alpha_A - \alpha_{1s}$
- $\sim 2.54 \times 10^{-13}(T_4)^y$ where y $= -0.8163 - 0.0208\ln(T_4)$

Ionization Balance

- Steady state balance between ionization and recombination. Taking only collisional ionization:

- $n_e <\sigma v>_{ci} n(X^{n+}) =$

  $n_e <\sigma v>_{rr} n(X^{(n+1)+})$

$$\frac{\langle \sigma v \rangle_{\rm rr}}{\langle \sigma v \rangle_{\rm ci}} \approx 4\pi\alpha^3 \frac{f_{\rm pi}}{C} \frac{I}{kT} {\rm e}^{I/kT}$$

- where α is the fine structure constant.
- I is the threshold energy.

Collisional Ionization

- Steady state balance between ionization and recombination. Taking only collisional ionization:

- $n_e <\sigma v>_{ci} n(X^{n+}) =$
  $n_e <\sigma v>_{rr} n(X^{(n+1)+})$
- $$\frac{\langle \sigma v \rangle_{\rm rr}}{\langle \sigma v \rangle_{\rm ci}} \approx 4\pi\alpha^3 \frac{f_{\rm pi}}{C} \frac{I}{kT} \, {\rm e}^{I/kT}$$
- where α is the fine structure constant.
- I is the threshold energy.

Strömgren Sphere

- Optically thick to ionized radiation.
- Fully ionized inside sphere.
- Transition over distance short compared to R_s.

- $Q = 4/3\pi R^3\alpha n_p n_e$

Strömgren Sphere

Time scale:	$Q = 4/3\pi R^3 \alpha n_p n_e$
For ionization	$4/3\pi R3\ n/Q = 1/\ \alpha n$
For recombination	$1/\alpha n$
Time taken:	~1000 years

Heating and Cooling

- Temperature determined by balance between heating and cooling.

Heating and Cooling

- Dominant heating is by photoionization.
- Probability of photoionization per unit time:
- Heating rate:

- X + hν → X+ + e- + K. E.

$$\zeta(X^{+r}) = \int_{\nu_0}^{\infty} \sigma_{\rm pe}(\nu) c \left[\frac{u_\nu}{h\nu}\right] d\nu$$

$$\Gamma_{\rm pe} = n(X^{+r}) \int_{\nu_0}^{\infty} \sigma_{\rm pe}(\nu) c \left[\frac{u_\nu}{h\nu}\right] (h\nu - h\nu_0)\, d\nu$$

Heating and Cooling

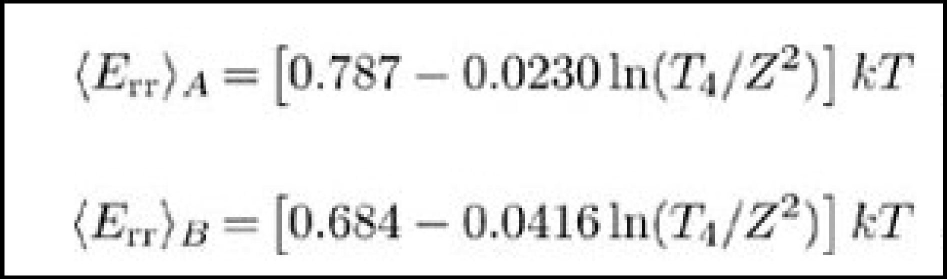
- Dominant heating is by photoionization.
- Photoionization of dust.
  - Important for light not hard enough to ionize HI
  - If dust competes with HI for E > 13.6 eV
- Cosmic rays.
- Shock heating.

- $X + h\nu \rightarrow X+ + e- + K.\ E.$

Heating and Cooling

- Cooling from recombination radiation.
  - With approximations:

- $\Lambda_{rr} = \alpha n_e n_H <E_{rr}>$

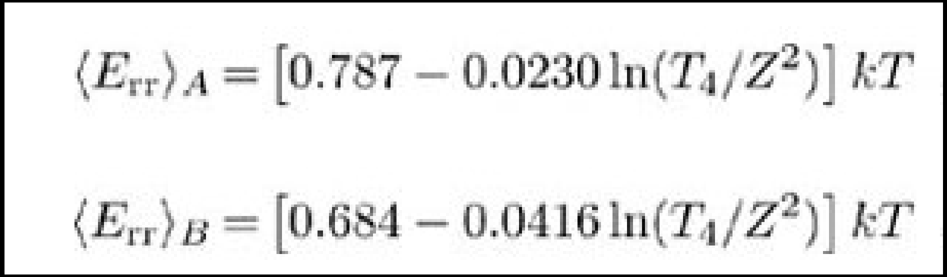


$$\langle E_{\rm rr}\rangle_A = \left[0.787 - 0.0230 \ln(T_4/Z^2)\right] kT$$

$$\langle E_{\rm rr}\rangle_B = \left[0.684 - 0.0416 \ln(T_4/Z^2)\right] kT$$

Heating and Cooling

- Cooling from recombination radiation.
- $\Lambda_{rr} = \alpha n_e n_H <E_{rr}>$
  - With approximations:



$$\langle E_{rr}\rangle_A = \left[0.787 - 0.0230\ln(T_4/Z^2)\right] kT$$

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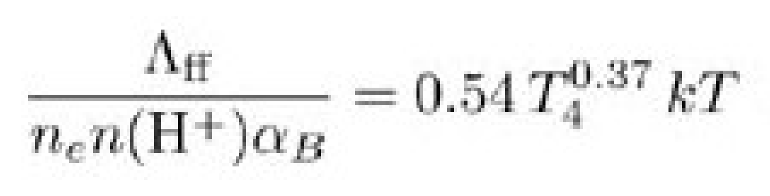
  - Free-Free Emission



$$\frac{\Lambda_{ff}}{n_e n(\mathrm{H}^+)\alpha_B} = 0.54\, T_4^{0.37}\, kT$$

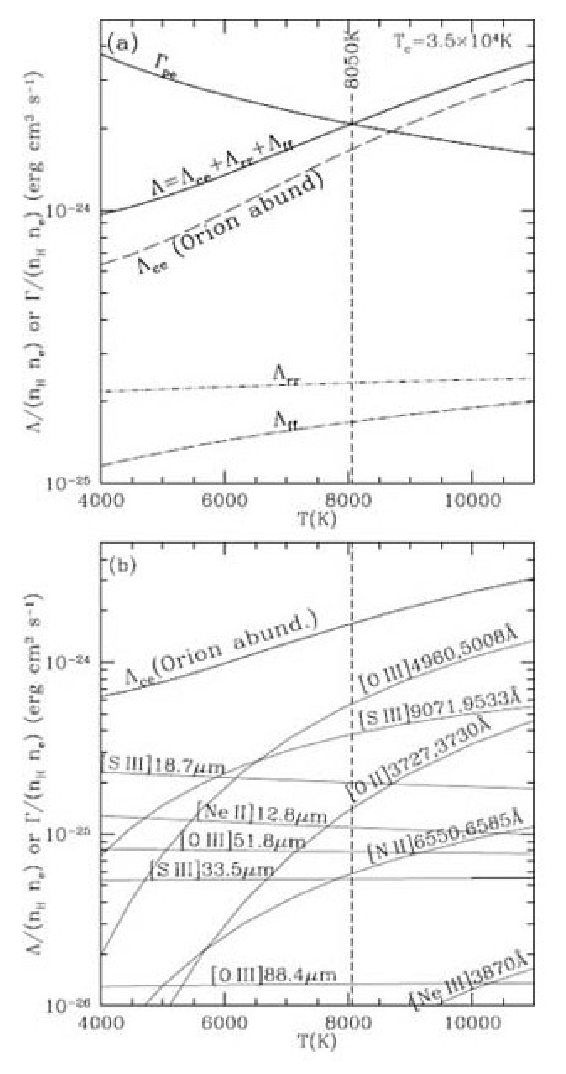
- If T ~ 10,000 K then the plasma loses 1.22kT of energy per recombination.

Heating and Cooling

- Collisionally excited lines.
  - Excited to upper level followed by sum over downward transitions.

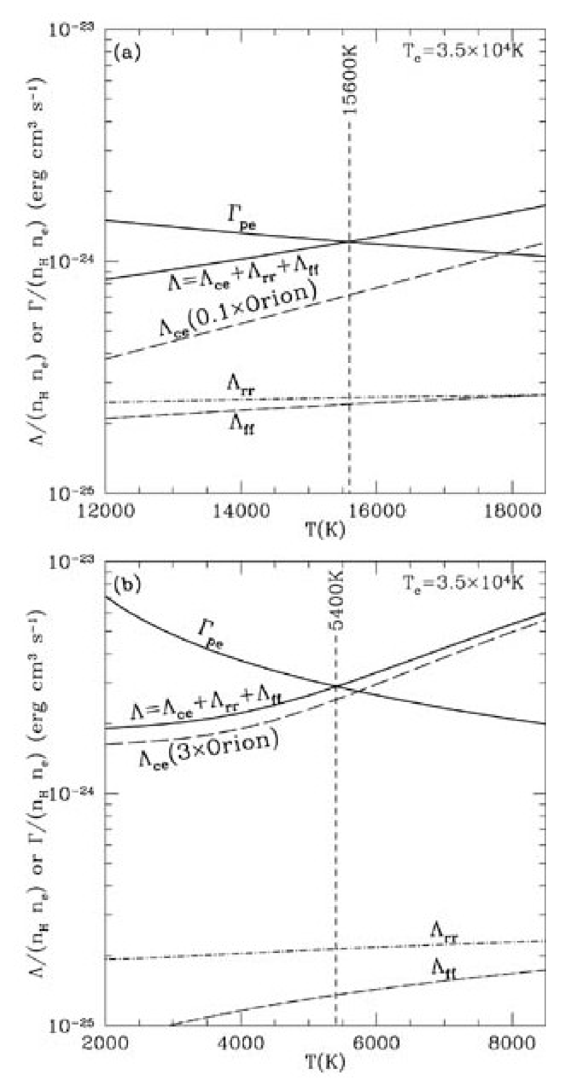
$$\Lambda_{ce} = \sum_{X} \sum_{i} n(X,i) \sum_{j<i} A_{ij}(E_i - E_j)$$

Cooling



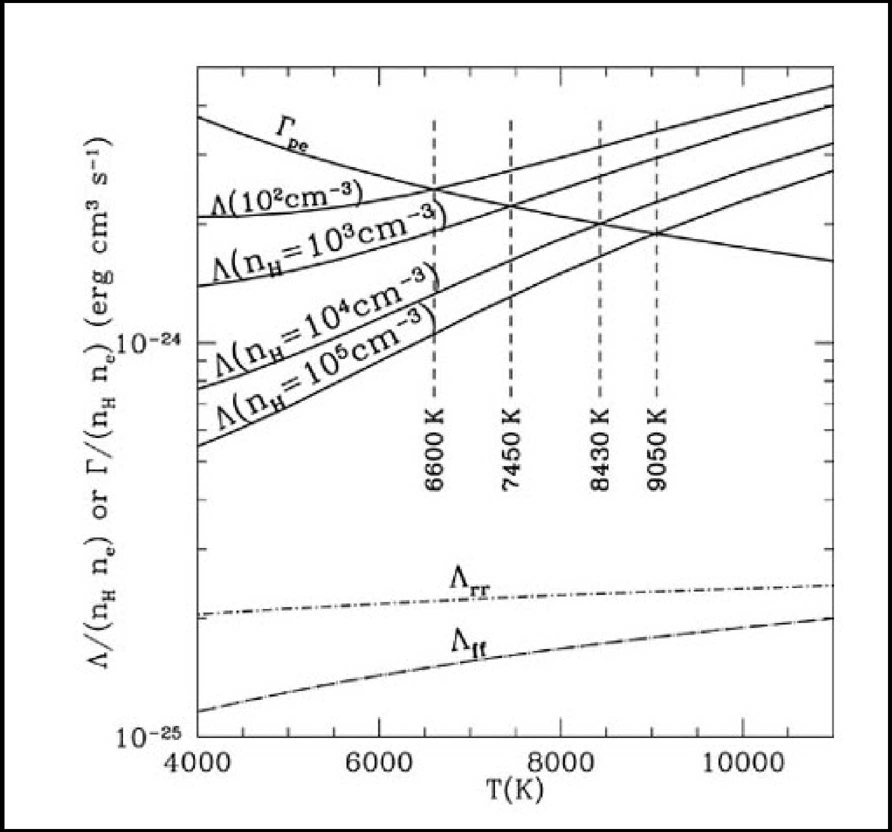
- Thermal equilibrium when heating balances cooling.
- 8500 K in this example (Orion).

Cooling



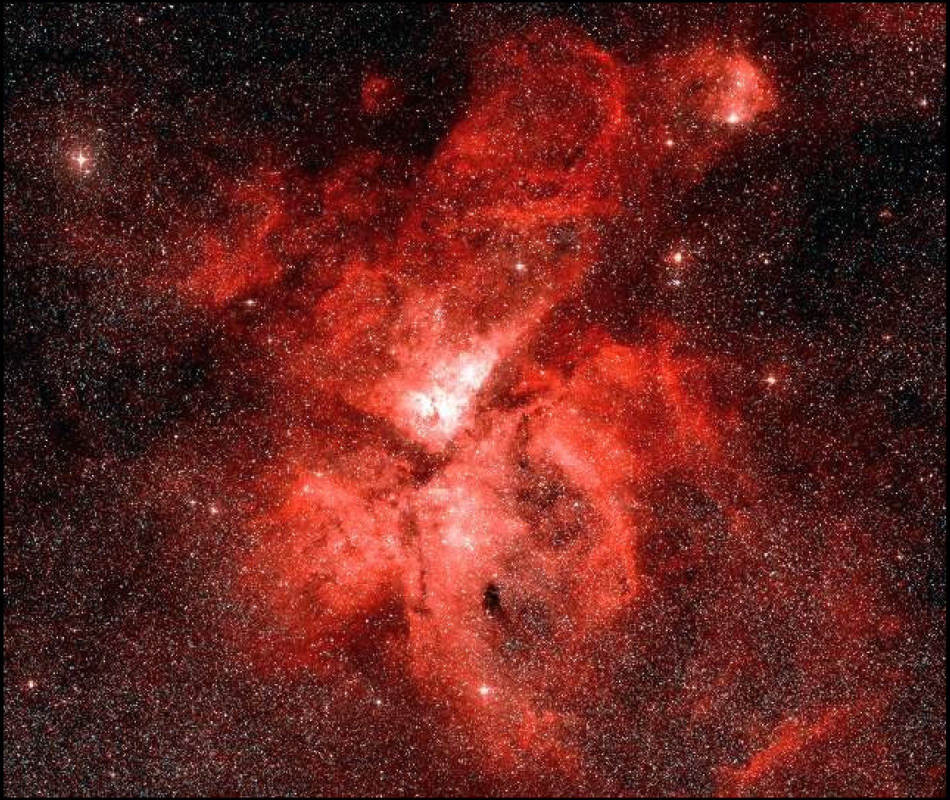
- Thermal equilibrium when heating balances cooling.
- 8500 K in this example (Orion).
- Lower metallicity => higher temperature.
- Higher metallicity => lower temperature.

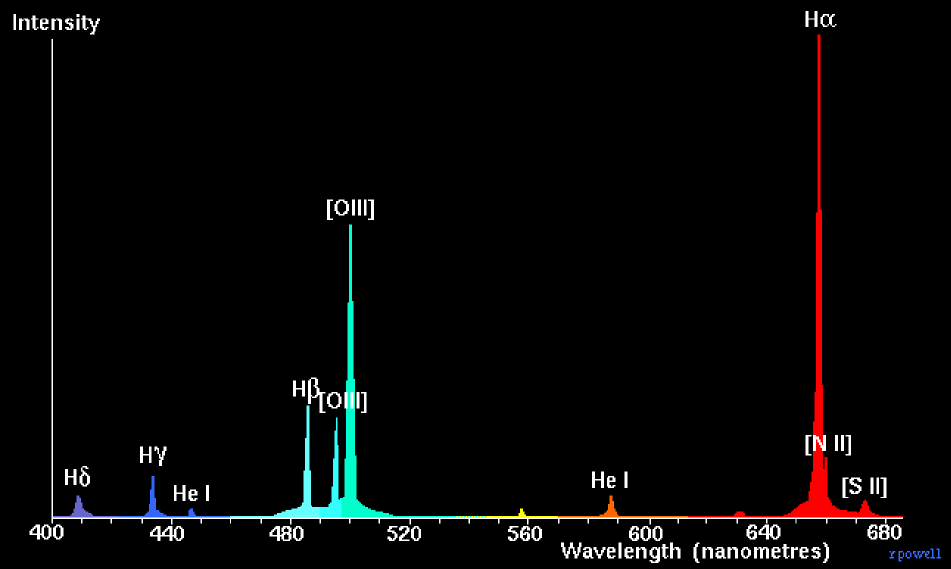
Cooling



- Thermal equilibrium when heating balances cooling.
- 8500 K in this example (Orion).
- Lower density => lower temperature.
- Higher density => higher temperature.

Eta Car




Intensity
Hα
[OIII]
Hβ
[OIII]
[N II]
Hγ
Hδ
He I
He I
[S II]
400
440
480
520
560
600
640
680
Wavelength (nanometres)
rpowell

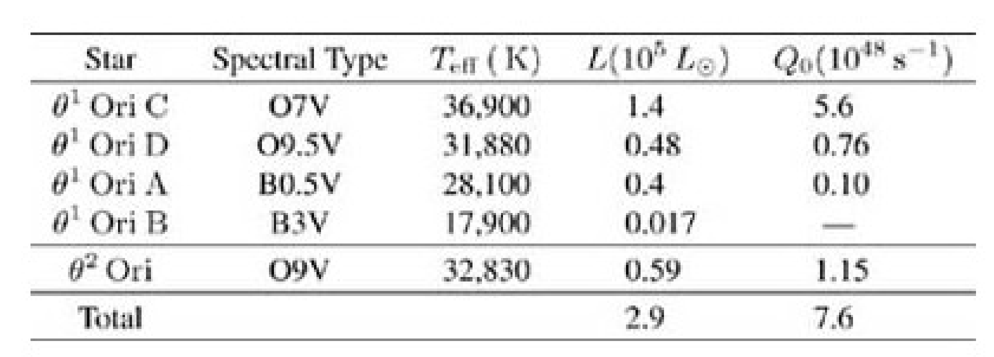
Special Case: Orion Nebula

http://www.spacetelescope.org/images/heic0601a/

Special Case: Orion Nebula

Orion Nebula

- Luminous HII region.
    - M42 = NGC 1976
    - d = 414 ± 7 pc
- Contains cluster of stars: Orion Nebula Cluster.
    - Core radius: 0.2 pc.
    - 2300 stars within radius of 2 pc.
- θ1 Ori C (O7 V) produces 80% ionizing photons.



Star	Spectral Type	$T_{\rm eff}$ (K)	$L(10^5 L_\odot)$	$Q_0(10^{48}\,{\rm s}^{-1})$
θ^1 Ori C	O7V	36,900	1.4	5.6
θ^1 Ori D	O9.5V	31,880	0.48	0.76
θ^1 Ori A	B0.5V	28,100	0.4	0.10
θ^1 Ori B	B3V	17,900	0.017	—
θ^2 Ori	O9V	32,830	0.59	1.15
Total			2.9	7.6

Orion Nebula

- Trapezium stars ionize HII region.
- HII regions expand and create blister.
- Gas breaks out of blister.
  - Velocities at Mach 2.
- Herbig-Haro objects:
  - Shocked gas where material in jets stopped by ambient medium.
- Propylds: Young stellar objects with dusty disks.