Heating and Cooling of the ISM

Most of the IS gas in the MW is neutral, and 78% of the neutral hydrogen is atomic.

References

Draine, Sec. 24.1 for dust; Chap 30 for H I; Chap 27 for H II
Spitzer, Chap. 6; p. 131

Scheffler & Elsasser, p. 285

Bowers & Deeming, p. 357

Heating

- Photoionization (by x rays)
- Ionization by cosmic rays
- Photoelectric effect on grain surface
- H_2 formation on grains
- Shock heating and other MHD phenomena

Cooling

- Collisional excitation followed by radiation (molecular rotation, vibration, atomic fine structure)
- Free-free emission of electrons
- Dust emission --- Collisions between gas and dust

Adopting a typical diffuse cloud (H I) parameters,

$T \approx 50 - 150$ K, mean = 80 K,

$n_H \approx 10 - 1000$ cm^{-3}, mean = 20 cm^{-3},

$n_e \approx 10^{-4}\, n_H$,

$M = 400\, M_\odot$,

$R = 5$ pc

Total gravitational energy $E_G \approx (3GM^2/5R) \approx 2 \times 10^{45}$ ergs

Thermal energy $U \approx (3\, MkT/2m_H) \approx 10^{46}$ ergs

So clouds generally are not gravitationally bound.

Internal energy — heat

$$dE = \delta Q - pdV \rightarrow \frac{dQ}{dt} = \frac{dE}{dt} + p\,\frac{dV}{dt}$$

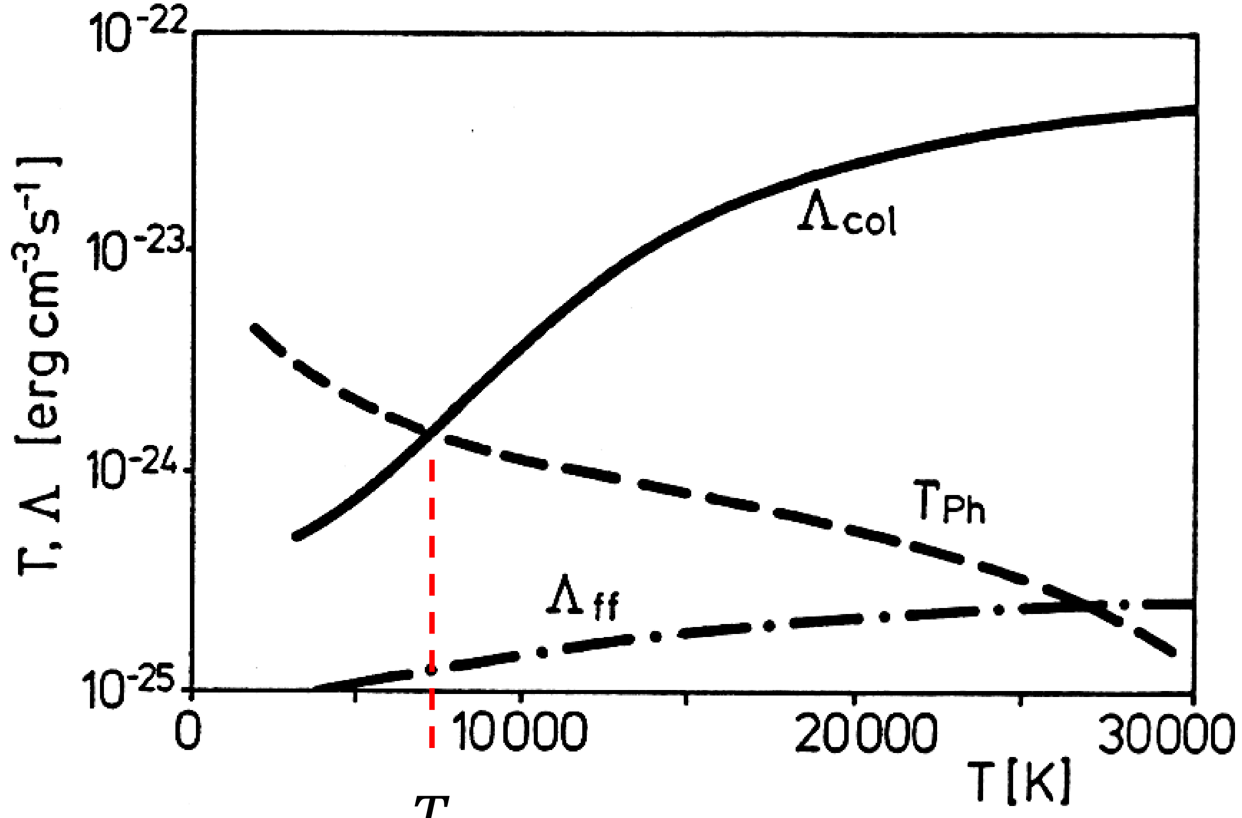
For monatomic gas (w/o internal degree of freedom),
$E = (3/2)kT$

$$\frac{d}{dt}(\frac{3}{2}nkt) - \frac{5}{2}kt\frac{dn}{dt} = (3/2)kn\frac{dT}{dt} - kt\frac{dn}{dt} \equiv \Gamma - \Lambda$$

Γ: Energy Gain (i.e., heating) [ergs s^{-1} cm^{-3}]
Λ: Energy Loss (i.e., cooling)

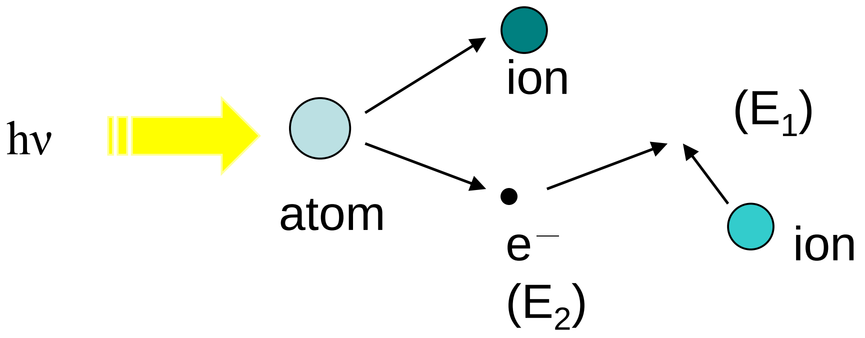
Note: This does not include evaporation, melting, conduction, or any time dependent effects (e.g., a collapsing cloud).

In a steady state, $\Gamma(T) = \Lambda(T)$



$T_{\text{equilibrium}}$

Heating by Photoionization



For each ionization, the electron gains kinetic energy E_2.

Each recombination loses E_1.

Recall [# of photoionization] = [Recombination to all states]

$$n_e n_i \alpha^{(1)} = n_e n_i \sum v\sigma(v)$$

$$\begin{aligned}
\Gamma_{ei} &= n_e n_i v \sigma_j E_2 - n_e n_i v' \sigma_j E1 \\
&= n_e n_i \{ < v\sigma_j > \bar{E}_2 - < v\sigma_j > \bar{E}_1 \} \\
&= n_e n_i \{ \alpha^{(1)} \bar{E}_2 - \frac{1}{2} m_e \sum_j < v^3 \sigma_{ij} > \}
\end{aligned}$$

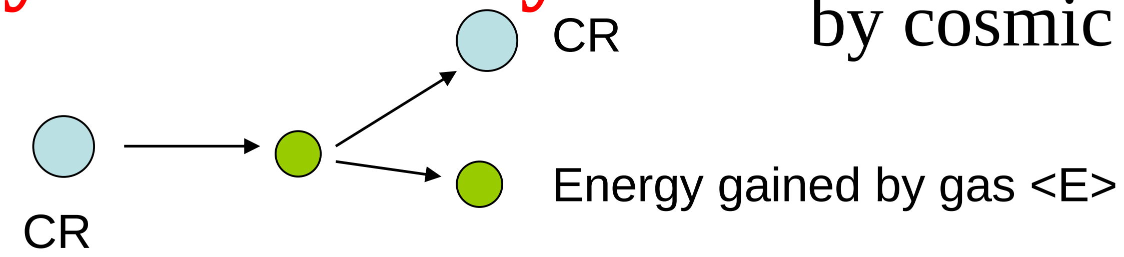
Averaging over the Maxwellian-Boltzmann distribution

For protons (Spitzer, p. 136)

$$\Gamma_{ph} = \frac{2.07 \times 10^{-11} n_e n_p}{\sqrt{T}} \{\bar{E}_2 \phi_1(\beta) - kT\chi_1(\beta)\} \text{ ergs s}^{-1} \text{ cm}^{-3}$$

Heating by Cosmic Rays

Collisional ionization of H
by cosmic ray particles



$$\#\text{ of CR ionization } [\mathrm{s^{-1}cm^{-3}}] = \zeta_{CR}\, n_H$$

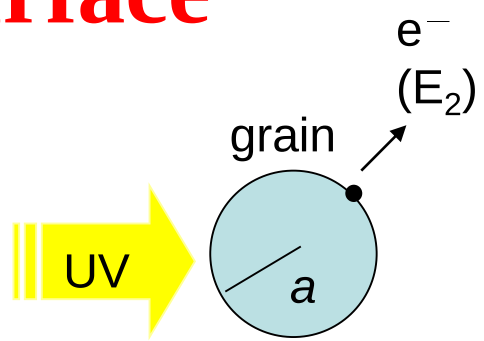
$\langle E \rangle \approx 3.4$ eV (Spitzer & Tomasko, 1968, ApJ)

$$\zeta_{CR} = 7 \times 10^{-18}\ \mathrm{s^{-1}}$$

Each "primary" ionization by a CR creates a "secondary" electron with mean kinetic energy of ~35 eV, which may ionize or excite bound states of H, H_2, and He which will deexcite radiatively.

$$\Gamma_{cr} = 3.8 \times 10^{-29}\, n_H \text{ ergs s}^{-1}\text{ cm}^{-3}$$

Photoelectric Heating on Grain Surface



This effect is important in H I regions.

Stellar flux $= c\, u$

$\sigma_d =$ cross section $= \pi a^2\, Q_{abs}$ (expect $Q_{abs} \sim 1$ at UV)

$y_e =$ yield factor $=$ [# of e$^-$ given off]/[# of photon incident]

i.e., not every photon liberates an electron

$E_2 =$ energy gained off by the electron to the gas; for small particles, $< E_2 > \sim 5$ eV

$$\Gamma_{ed} = n_d \int \frac{\sigma_d(\lambda) c u_\lambda y_e E_2}{h\nu}\, d\nu$$

Within a cloud at an optical depth, $u_\lambda \sim u_{\lambda 0}\, e^{-\tau}$

$$\Gamma_{ed} = 1.8 \times 10^{-25}\, y_e n_H\, e^{-\tau} \text{ ergs s}^{-1} \text{ cm}^{-3}$$

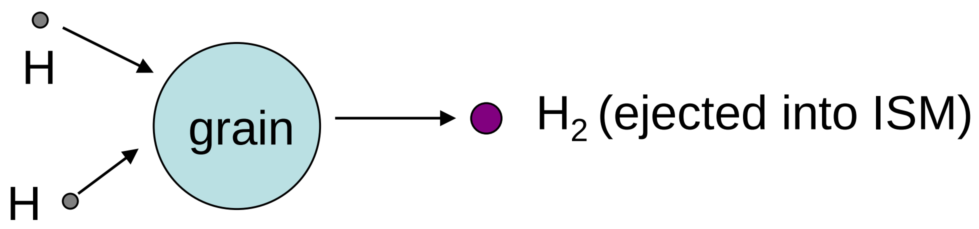
$0.01 < y_e < 1.0$ if $10 \text{ eV} < h\nu < 13.6 \text{ eV}$

For example, if $\tau \ll 1$, $y_e \sim 1$

→ $\Gamma_{\rm ed} \sim 2 \times 10^{-25}\, n_H$ [ergs s^{-1} cm^{-3}]

- The work function for graphite is 4.5 eV; it is 5.0 eV for lunar surface material.
- Photons > 8 eV dominate photoelectric heating by dust.
- Small grains absorb UV effectively, and have larger photoelectric yields, so $\Gamma_{\rm ed}$ is dominated by photoelectrons from very small grains, including the PAHs.

Heating by H_2 Formation on Grains



of H_2 formed $[\mathrm{s}^{-1}\ \mathrm{cm}^{-3}] = R\, n_H\, n_H$; $R \sim 10^{-17}\ [\mathrm{s}^{-1}\ \mathrm{cm}^{-3}]$

Binding energy of H_2, $E_b(H_2) = 4.48$ [eV]

→ Kinetic energy of H_2 afterwards $= z_{H2} \times 4.48$ [eV]

$$\begin{aligned} \Gamma_{H2} &= (4.48 \times z_{H2}) R\, n_H\, n_H \\ &= 2.2 \times 10^{-28} z_{H2}\, n_H^2 \ \mathrm{ergs\ s^{-1}\ cm^{-3}} \end{aligned}$$

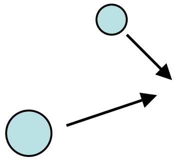
$z_{H2} = 0.04 – 0.1$

$$\Gamma_{H2} \approx 2 \times 10^{-29}\, n_H^2 \ \mathrm{ergs\ s^{-1}\ cm^{-3}}$$

Summary of ISM Heating

Process	$\mathrm{ergs\ s^{-1}\ cm^{-3}}$
photoionization	$8 \times 10^{-25}\ n_H^2$
Cosmic rays	$3.8 \times 10^{-29}\ n_H$
photoelectric	$2 \times 10^{-25}\ n_H$
H_2 formation	$2 \times 10^{-29}\ n_H^2$

Cooling by Collisional Excitation



$j \quad k$ (collisional excitation) ➔ $k \rightarrow j$ (radiative deexcitation)

$h\nu = E_k - E_j$

$$\Lambda_{ei} = n_e \Sigma_{j>k} \left(n_{ij}\gamma_{jk} - n_{ik}\gamma_{kj} \right)$$

collisional deexcitation

With $T_e \sim 7{,}000$ K for the primary coolants O II, O III and N II,
$\Lambda / n_e n_p \sim 10^{-24}$ [ergs $s^{-1} cm^{-3}$]

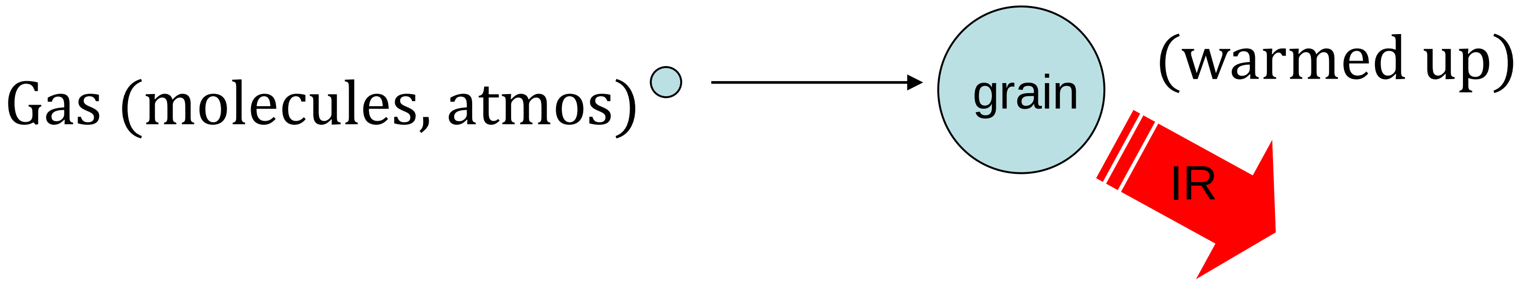
➔ Inelastic collisions between electrons and ions are important cooling mechanisms in both H I and H II regions.

Cooling by Free-Free Emission of Electrons

$$\Lambda_{ff} = 4\pi\epsilon_{ff} = 1.426\times10^{-27}\, Z^2\sqrt{T}\, n_e n_i \bar{g}_{ff}\ \text{ergs s}^{-1}\ \text{cm}^{-3}$$

~ 1.3 (1.0 to 1.5)

Cooling by Collisions between Gas and Dust

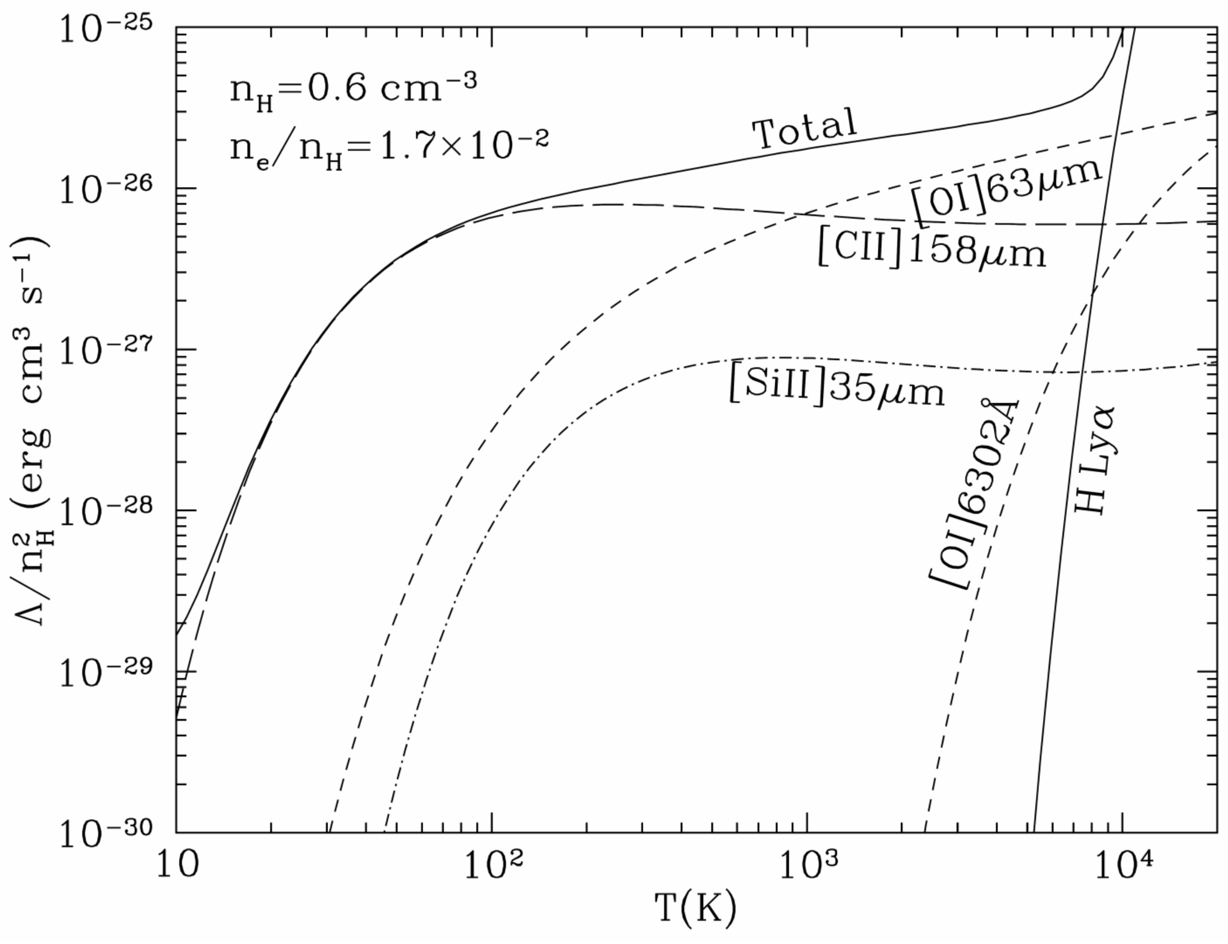


Cooling In H I cloud

$< 10^4$ K $\longrightarrow$ mainly by the [C II] 158 μm fine structure line,

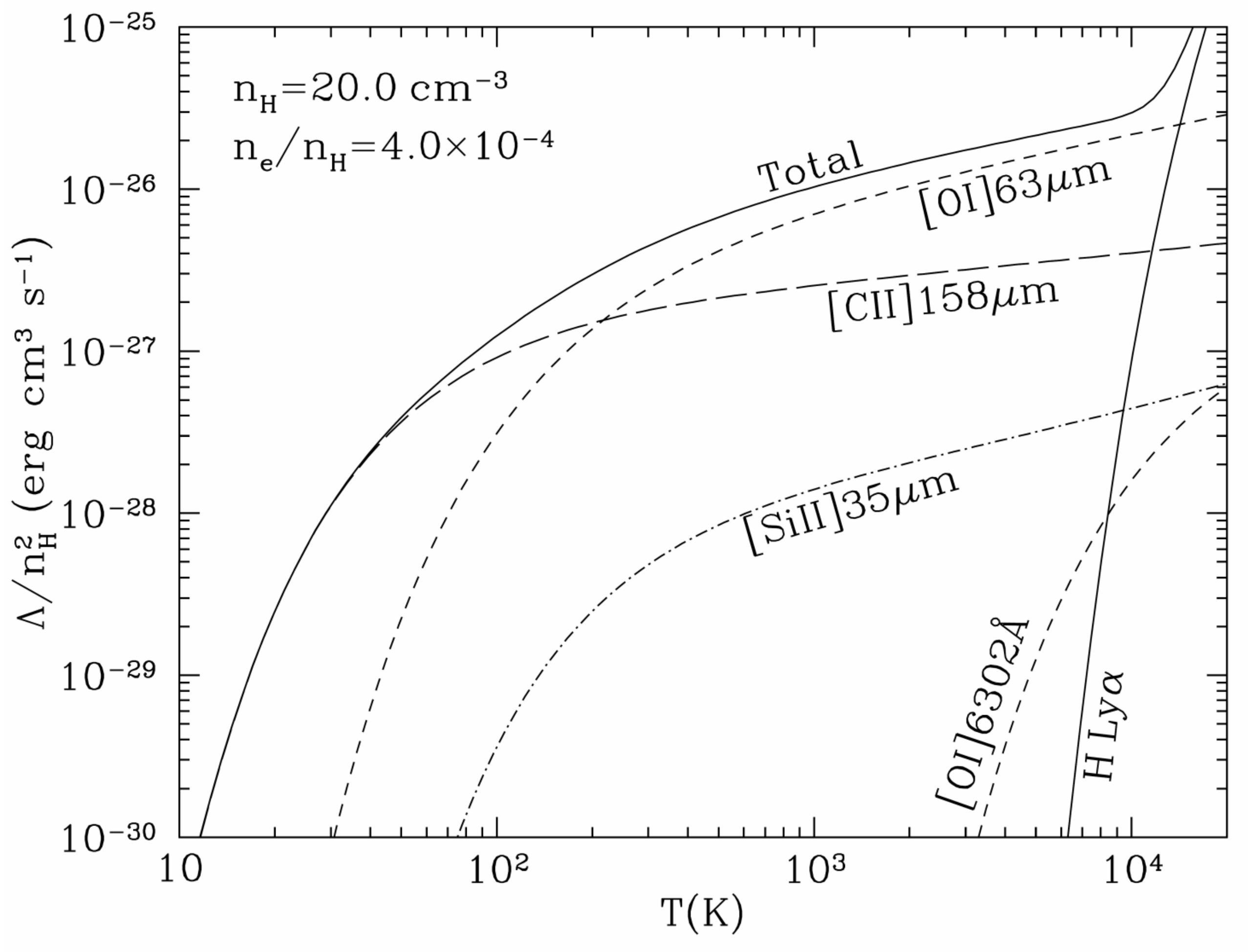
> 100 K $\longrightarrow$ [O I] 63 μm plays a role

$> 10^4$ K $\longrightarrow$ Lyman alpha dominates



Draine Fig 30.1

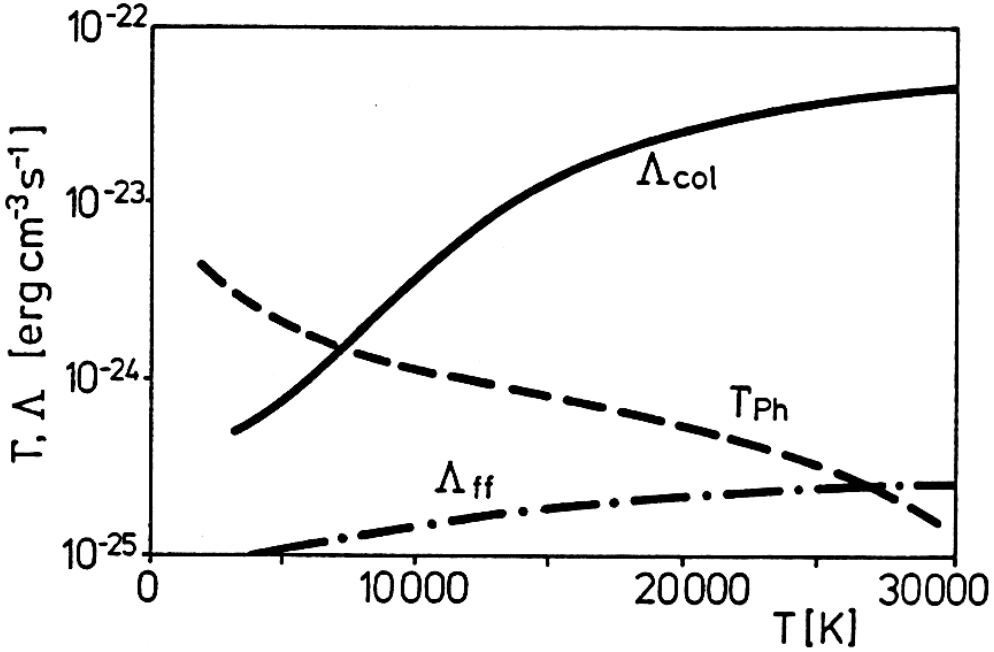
For low-ionization environs



Thermal Equilibrium in H II Regions

Heating: primarily by photoionization

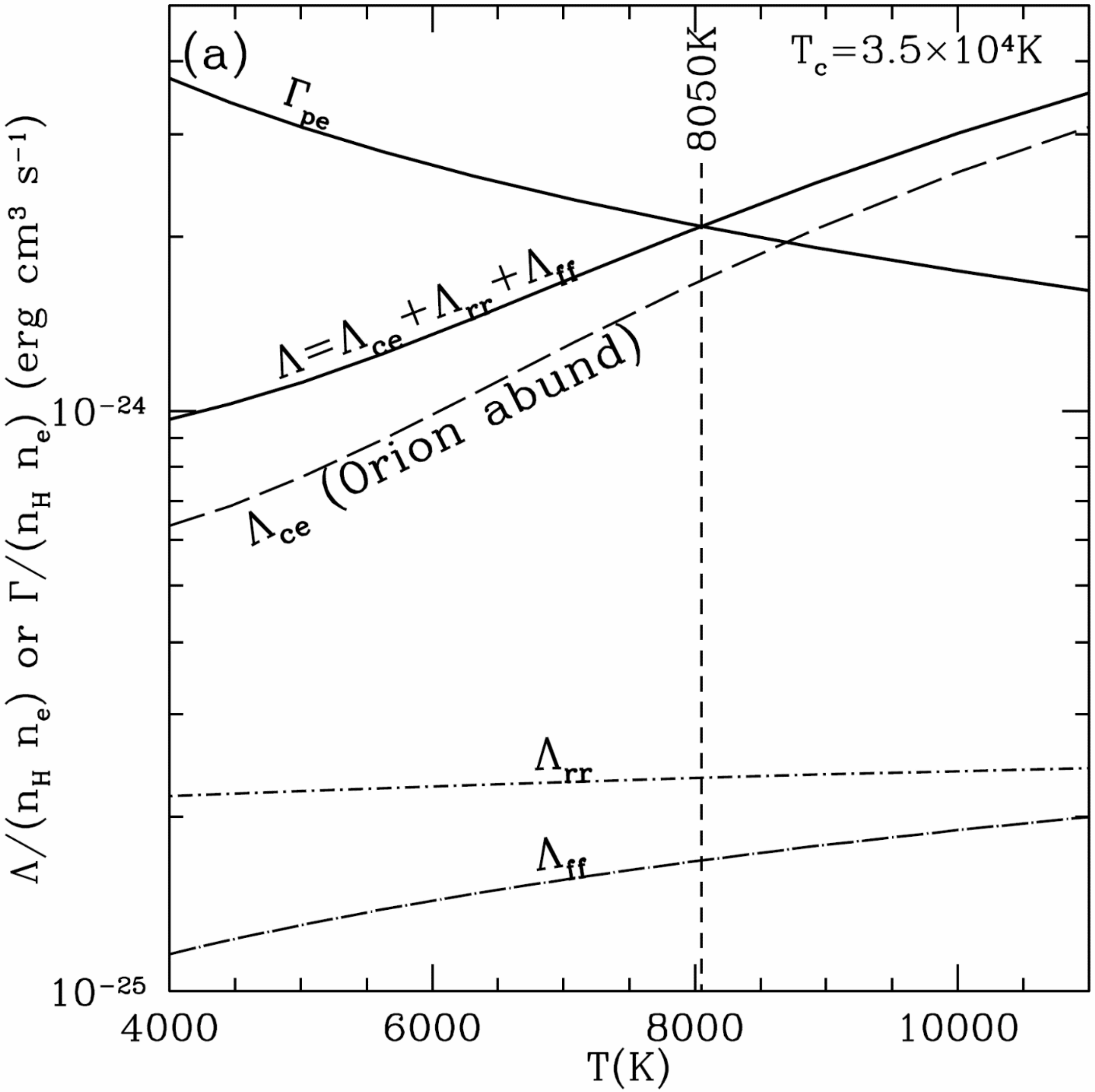
Cooling: excitation of C, N, O, Ne (excitation levels of a few eV above ground level) very efficient;
but (fortunately?) of relative low abundances with respect to H (excitation energy 10.2 eV)



Main Collisionally Excited Cooling Lines in H II Regions

Ion	lines
N II	6585 Å, 6550 Å
O II	3730 Å, 3727 Å
O III	88.36 μm, 51.81 μm, 5008 Å, 4960 Å
Ne II	12.81 μm
S II	6733 Å, 6718 Å
S III	33.48 μm, 18.71 μm, 9071 Å, 9533 Å

Draine Table 27.2



Draine Figure 27.1a