Heating and Cooling of ISM

Ref: Spitzer p. 133; Scheffler & Elsasser p. 285

Heating:

- Photoionization
- Ionization by cosmic rays
- Photoelectric effect on grain surface
- H_2 formation on grains
- Shock heating

Cooling:

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

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), $E = (3/2)kT$

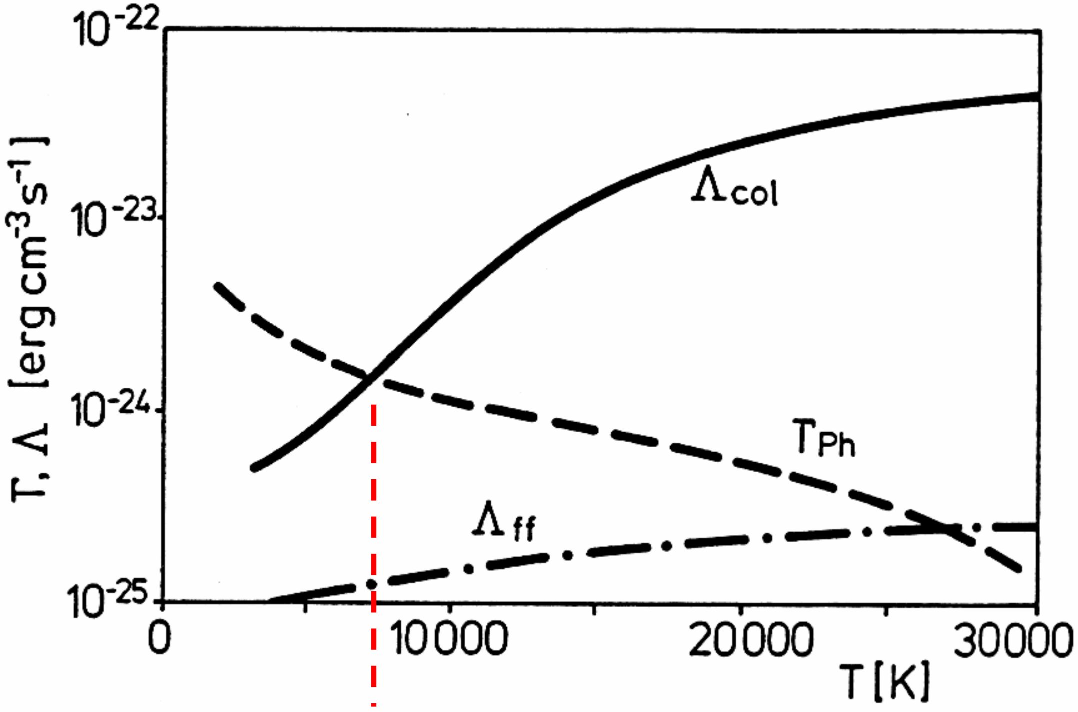
$$\frac{d}{dt}(\frac{3}{2}nkt) - \frac{5}{2}kt\frac{dn}{dt} = (3/2)kn\frac{dT}{dt} - kt\frac{dn}{dt} \equiv \Gamma - \Lambda$$

Γ : Energy Gain (i.e., heating)
Λ : Energy Loss (i.e., cooling)

[ergs cm^{-3} s^{-1}]

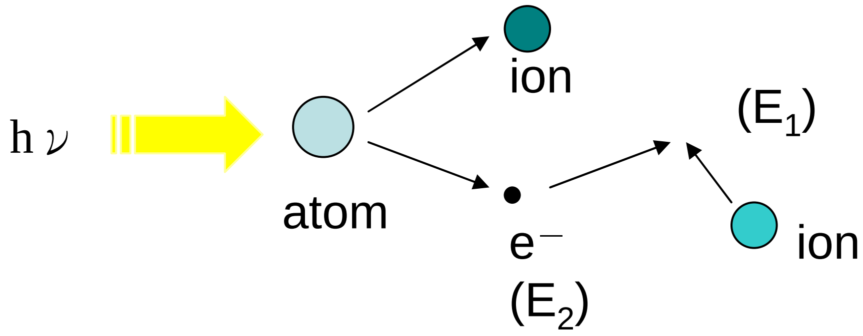
Note: This does not include evaporation, melting, conduction, or any time dependent effects (e.g., a collapsing cloud)

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



Tequilibrium

Heating by Photoionization



For each ionization the electron gains kinetic energy E_2.

Each recombination loses E_1.

Recall that # of photoionization = Recombination to all states

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

Averaging over Maxwellian distribution

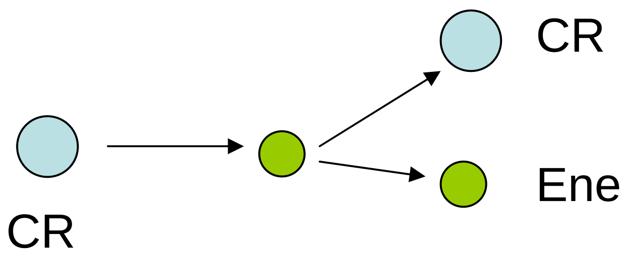
$$\begin{aligned} \Gamma_{ei} &= n_e n_i v \sigma_j E_2 - n_e n_i v' \sigma_j E1 \\ &= n_e n_i \{ < v\sigma_j > \bar{E}_2 - < v\sigma_j > \bar{E}_1 \} \\ &= n_e n_i \{ \alpha^{(1)} \bar{E}_2 - \frac{1}{2} m_e \sum_j < v^3 \sigma_{ij} > \} \end{aligned}$$

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



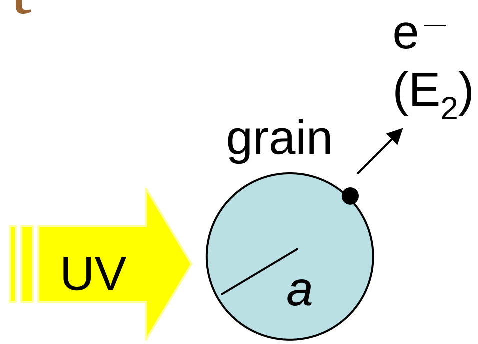
# of CR ionization [s^{-1} cm^{-3}] = $\zeta_H n_H$

<E> ~ 3.4 eV (Spitzer & Tomasko, 1968, ApJ)

$\zeta_H = 7 \times 10^{-18}\ s^{-1}$

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

Heating by Photoelectric Effect on Grain Surface



This effect is important in H I regions.

Stellar flux = $c\ u$

σ_d = cross section = $\pi a^2 Q_{abs}$ (expect Q_{abs} ~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, $\langle E_2 \rangle \sim 5$ 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, $u_\lambda \sim u_{\lambda 0}\, e^{-\tau}$

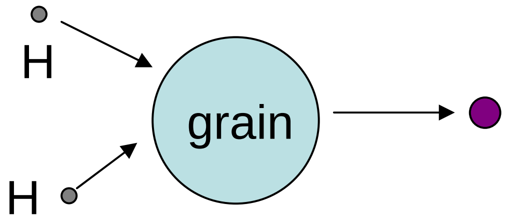
$$\Gamma_{ed} = 1.8 \times 10^{-25}\, y_e n_H\, e^{-\tau} \text{ ergs s}^{-1} \text{ cm}^{-3}$$

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

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

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

Heating by H_2 Formation on Grains



of H_2 formed [s^{-1} cm^{-3}] = R n_H n_H R ~ 10^{-17} [s^{-1} cm^{-3}]

Binding energy of H2, Eb(H_2) = 4.48 [eV]

→ Kinetic energy of H_2 afterwards = z_{H2} • 4.48 [eV]

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

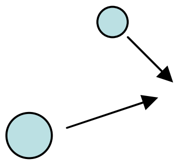
z_{H2} = 0.04 – 0.1

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

Summary of ISM Heating

Process	Ergs s^{-1} cm^{-3}
photoionization	$8 \times 10^{-25} n_H^2$
Cosmic rays	$3.8 \times 10^{-29} n_H$
photoelectric	$2 \times 10^{-25} n_H$
H2 formation	$2 \times 10^{-29} n_H^2$

Cooling by Collisional Excitation



j → k (collisional excitation) ➔ k→ 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 eexcitation

With Te ~ 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}]

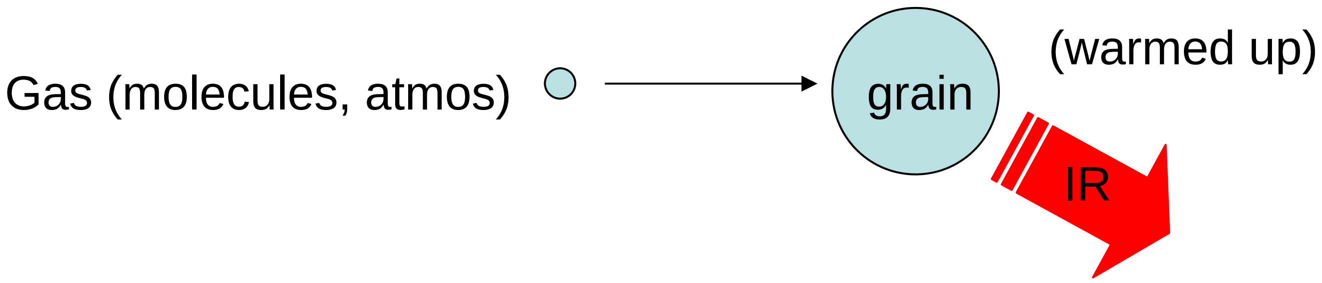
➔ Inelastic collisions between electrons and ions are important cooling mechanisms in both H I and H II regions.

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



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)