Physical Processes in hot gas

- Collisional ionization §13.4
  Photo-ionization §13.1

- Radiative Recombination §14
  Die-electronic Recombination
  Charge Exchange

- Collisional Ionization Equilibrium §14.9

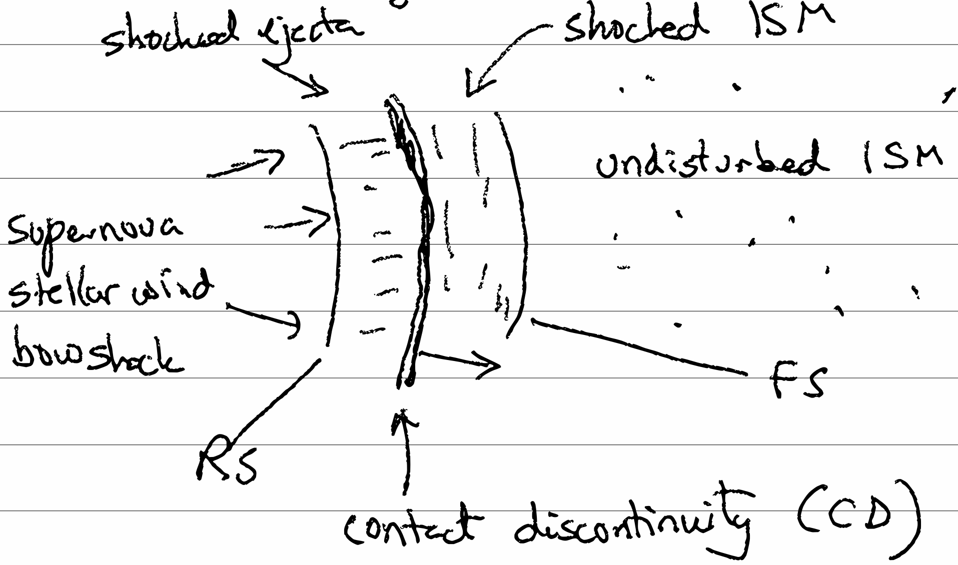
- Radiative Cooling §34
  Thermal Conduction

☐ When $T \gtrsim 10^4$ K, hydrogen starts to ionize and becomes dominant source of electrons
   ⇒ electron ionization
      cooling by electron collisions

☐ The ionization fraction depends only on temperature (not density)

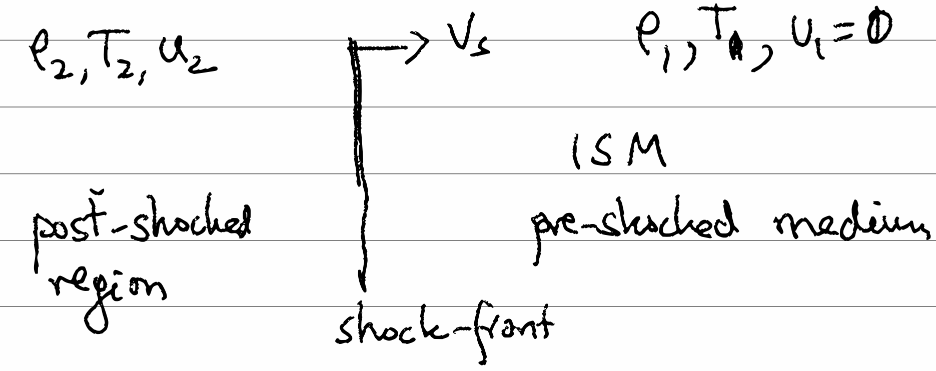
$$n_e\, n(X^{+n})\, \sigma_{ci} = n_e\, n(X^{+n+1})\, \alpha$$

Primer on strong shocks



FS : forward shock
RS : reverse shock

strong shock (summary, for now)



§32

$$\frac{\rho_2}{\rho_1} = \frac{\gamma+1}{\gamma-1} = 4 \quad \text{for } \gamma = 5/3$$

$$u_2 = \frac{\gamma-1}{\gamma+1} V_s = \frac{1}{4} V_s \quad \text{for } \gamma = 5/3$$

$$T_2 = \frac{2(\gamma-1)}{(\gamma+1)^2} \frac{\mu V_s^2}{k} = \frac{3}{16} \frac{\mu V_s^2}{k} \quad \text{for } \gamma = 5/3$$

Note: the shock accelerates particles $u_2 = \frac{1}{4} V_s$ and provides random velocity

The post-shocked particles gain velocity.

$\Rightarrow$ protons carry 2000 x relative to electrons.

Note: We have ignored non-thermal processes

- acceleraton of particle to relativistic energy
- amplification of magnetic field to levels comparable to thermal energy

Collisional Ionization by Electrons

For moderate energies $I < E \lesssim 3I$

I = ionization potential

$$\sigma_{ci}(E) \simeq C\pi a_0^2 \left(1 - \frac{I}{E}\right)$$

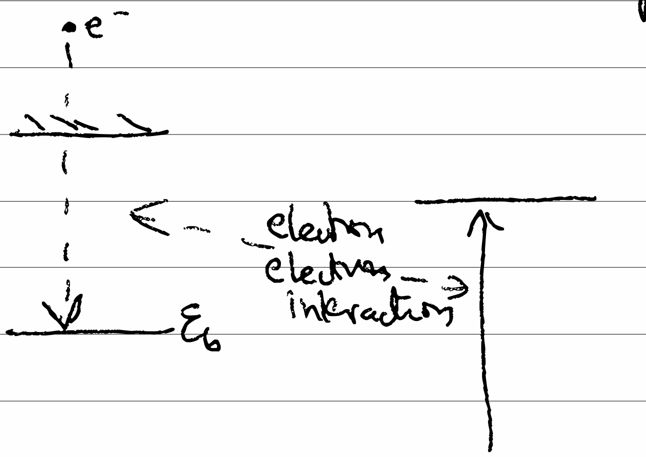
$$k_{ci} = \int_I^\infty \sigma_{ci}(E)\, v f_E \, dE$$

$$= C\pi a_0^2 \left(\frac{8kT}{\pi m_e}\right)^{1/2} e^{-I/kT}$$

For H, e^- $C \simeq 1.07$, $I = 13.6\,\text{eV}$

Dielectronic Recombination:

Radiative recombination is a slow process.
This process starts to dominate at high temperatures



followed by radiative decay.

Example of a low-temperature dielectronic recomb.

Electron recombines to fine-structure line of C^+
Another excited atom is raised to Rydberg state.

Charge-Exchange

$$A^+ + B \rightarrow A + B^+$$

This is particularly effective when the reaction is exo-thermic or endothermic (but within kT).

Special Example:

$$H^+ + H \rightarrow H + H^+$$

$$O^+ + H \Leftrightarrow O + H^+$$

Collision Ionization Equilibrium

Assume no incident photo-ionizing flux
optically thin to cooling radiation

$$n_e \langle \sigma v \rangle_{ci} \, n(X^{n}) = n_e \langle \sigma v \rangle_{rr} \, n(X^{n+1})$$

ci ... collisional ionization
rr .. radiative recombination

$$\sigma_{rr}(E) = \frac{g_l}{2g_u} \frac{(I+E)^2}{E m_e c^2} \underset{\uparrow \text{photo-ionization}}{\sigma_{pi}}(h\nu = I+E)$$

However,

$$h\int \sigma_{pi}(\nu)\, d\nu = h\left(\frac{\pi e^2}{m_e c}\right) \underset{\uparrow \text{oscillator strength}}{f_{pi}}$$

but $\sigma_{pi}(\nu) = \sigma_{pi,0}\left(\frac{\nu}{\nu_0}\right)^{-3}$

$$\therefore \quad \sigma_{pi,0} = \frac{2\pi e^2}{m_e c} f_{pi} \frac{h}{I}$$

Thus

$$\frac{\langle\sigma v\rangle_{rr}}{\langle\sigma v\rangle_{ci}} = 2\pi\alpha^3 \frac{f_{pi}}{C}\frac{I}{kT}e^{I/kT}$$

When this ratio is unity $n(X^{n}) = n(X^{n+1})$

$$\frac{I}{kT}e^{I/kT} = \frac{C}{2\pi f_{pi}}\frac{1}{\alpha^3}$$

ex. $C=1$, $f_{pi}\simeq 1$, $\frac{I}{kT} \simeq 10.6$

Thus 50% ionization at $kT = \frac{I}{10}$

for H ... $T \simeq 15{,}000\,K$.

Including dielectronic recombination.

$$n_e\langle\sigma v\rangle_{ci}\, n(X^{+n}) = \left[\langle\sigma v\rangle_{rr} + \langle\sigma v\rangle_{de}\right] n_e\, n X^{+n+1}$$