Interstellar Medium lecture 8

What sets temperatures of ISM ?
→ Thermal balance

Two processes : heating + cooling

heating $\Gamma(T)$ cooling $\Lambda(T)$

To find T, put $\Gamma(T) = \Lambda(T)$
Usually $\Gamma(T)$ does not depend on temperature ?
HII regions always have $T \sim 8000 - 10.000$ K.

Heating mechanisms : radiative :
- radiation from stars
- " " " AGN

Mechanical :
- shock waves
- dissipation of turbulence

Cosmic ray heating
- usually p^+, but also e^-, α

~~Wha~~
Cosmic rays penetrate very deep. Starlight does not reach very far in the ISM very often. In those cases CR heating can become dominant inside the cloud.

HII region
Candidate heating source will be the star. In general this is the only source of ionization

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

$E - 13.6$ eV goes into kinetic energy of mainly e^-.

$$E_{kin}|_{e^-} = \cancel{13.6} \; h(\nu - \nu_0)$$

~13.6 eV

How much energy is dumped ~~into the~~ and how much heat does this produce?

photoionizations / sec / atom : $\zeta(H) = \int_{\nu_0}^{\infty} \sigma_{pi}(\nu) \frac{4\pi J_\nu}{h\nu} d\nu$

photo ionization rate $= \zeta(H)\, n_H$

$$\Gamma_{pi}(H) = n(HI) \int_{\nu_0}^{\infty} \sigma_{pi} \frac{4\pi J_\nu}{h\nu} h(\nu - \nu_0) d\nu$$

energy injected per photo-ionization $= \dfrac{\Gamma_{pi}(H)}{n(H)\,\zeta(H)}$

Average energy per photon:

photon energy typically kT_c:

ψ = fraction of E_γ used for heating

$$\psi = \frac{E_{pi}(H)}{kT_c} \approx 1$$

$\hookrightarrow \Gamma_{pi}(H) = n_H \zeta(H) \psi kT_c$

$\zeta(H)\, n(HI) = \alpha_B n_e n_p$

Heating rate:

$\Gamma_{pi}(H) = \alpha_B n_e n_H \psi kT_c$

color temperature of the star

Now the cooling rate

To radiate away photons we need to radiate away ~~it~~ with a ~~co~~ transition. Dust emission cannot ~~e~~ help cooling.

Infrared does not cool the gas because the dust and gas are not thermally coupled. So T_d and T_g are not the same

$$\Lambda_{rr} = \alpha_B n_e n_H \underbrace{\langle E_{rr} \rangle}$$

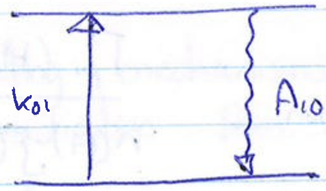
recomb rate

mean energy per recombination

→ $E_{kin} = \frac{3}{2} kT_e$

This ignores the cross section dependency on the velocity distn of electrons

↳ $\langle E \rangle \simeq 0.68\, kT_e$



Collisionally excited lines will cool the gas. Also in mol clouds, HII, etc

Important cooling lines: [OIII], [OII], [SII], [SIII], [NII]

Λ_{CE} : cooling by coll excitation

$$\rightarrow \underset{\text{heating}}{\sum \Gamma} = \underset{\text{cooling}}{\sum \Lambda}$$

First only cooling with recomb lines and free-free emission

$$\rightarrow \alpha_B n_H n_e \psi kT_c = \alpha_B n_H n_e (1.22\, kT_e)$$

$$↳ T_e = \frac{\psi}{1.22} T_c$$

So we have a clear indication to not exclude cooling by ~~exc~~ collisionally excited lines.

So our cooling rate ~~Λ~~ will be higher by a factor of a few.

Temperature by dominant cooling shuts off at $T \sim 10000\,K$
To have cooling we must excite upper level and thus need enough temperature.

Infrared lines have flat temperature dependence

$$n_{cr} = \frac{A_{10}}{k_{10}}$$

$$\begin{cases} n < n_{crit} & \frac{n_1}{n_0} \propto \frac{n}{n_{crit}} \\ n > n_{crit} : & \frac{n_1}{n_0} \text{ independent of } n \end{cases}$$

→ we don't want to be at very low densities. Furthermore we like somewhat low critical densities, ~~since~~ such that we are in the vicinity of the critical density → most efficient cooling.

Now to atomic medium

Heating :

- cosmic rays
- non-ionizing starlight

$4.5\,eV < E < 13.6\,eV$

and mostly $8-13\,eV$

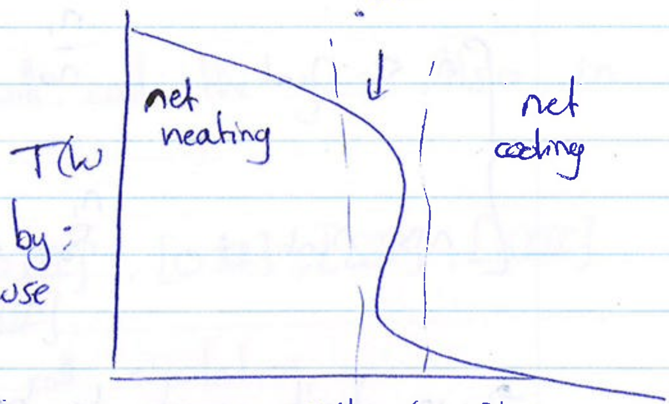
Primary cooling line : [CII] 158 μm : dominant.
Also [OI] 63 μm.

[CII] has $T_{up} \sim 92\,K = \frac{E_{up}}{k}$
$n_{crit} \sim$ few 100 cm^{-3} @ 100 K

High ~~temperator~~ density medium leads to lower temperature
Cooling goes as density^2, whereas heating goes ~~at~~ ~~with~~ linear with density

Two phase ISM (atomic)

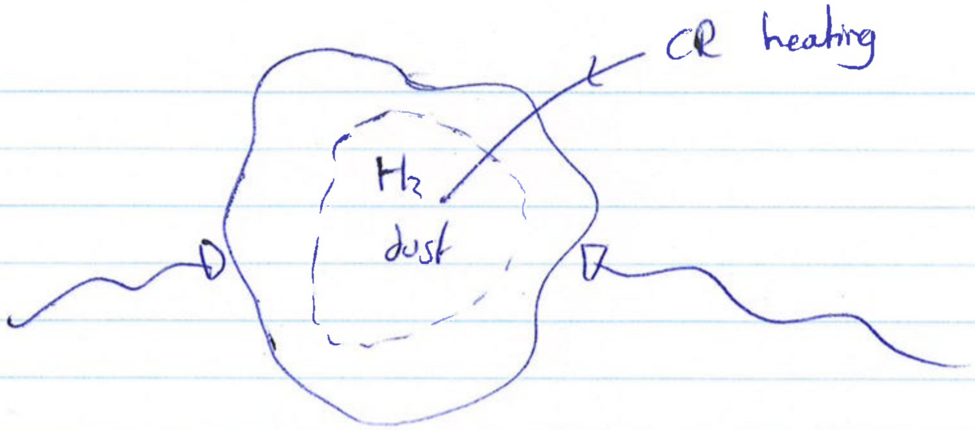
- thermal instability



Pressure of ISM is set by:
- hydrostatic equilibrium because of gravitational potential
- thermal pressure
- we can measure the pressure independent of theory.

Molecular Gas

Cools by coll. excited lines and heated by CR and starlight. Molecular cloud = self gravitating.



Outside : UV heating
Inside : CR heating

Cold neutral medium 30 - 100 K
In center of cloud, dominant cooling from coll. excited CO lines. Not from H_2 because very hard to excite (as $T_{ex} \sim 500$ K)

! CO cooling peaks at much lower densities than other molecules because CO has a very low critical density, so upper level is excited easily :

n / n_{crit}