Lecture 10;
HI clouds & Instabilities

10.1 The multiphase ISM reminder
↳ now consider the CNM, WNM
10.2 Observations of HI
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10.1 The multiphase ISM

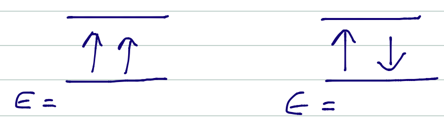
The ISM has 5 phases
- Hot Ionised
- Warm Ionised
- Warm Neutral → 60% $n \sim 0.3$, $T \sim 6 \times 10^4$ K — Studied using 21 cm line
- Cold Neutral → 40% $n \sim 10-100$, $T \sim 100$ K — Studied in absorption & using CII, CI, OI
- Molecular Clouds

78% of ISM

"Let us consider now the neutral medium. HI clouds."

10.2 Observations of HI

- The 21 cm line
  → caused by a change in spin in hydrogen atom

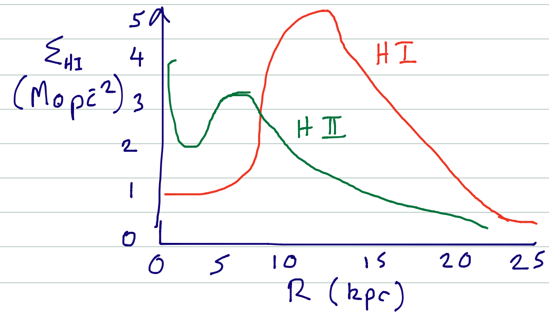


This is the main tracer of neutral gas in the Universe.

- Optical & UV absorption
  ↳ using OI / OII ratio (usually same as HI / HII ratio)
  ↳ using fine structure excitation lines of CI & CII can constrain the density & temperature of HI.

- Infrared Emission
  → emission from dust embedded within HI
  COBE found that 21cm emission & 100 μm emission were well correlated
  ie dust & neutral gas is well mixed.

Radial HI distribution from 21 cm



Radial distribution of HI from 21 cm studies (Nakanishi & Sofue 2003)

Peaks in the middle of the disk.

10.3 Heating & Cooling Processes

Heating :-

Photo-electric heating :-

UV radiation can liberate photoelectrons from dust grains. The work function of graphite is 4.5eV so even large carbonaceous grains can be photoionised.

Some of the incoming photons energy is used to overcome the dust grains potential barrier, the rest heats the gas.

The size distribution of dust grains is $\propto r^{-3.5}$
$\Rightarrow$ grain area distribution is $\propto r^{-1.5}$

Therefore emission from small dust grains such as PAHs dominates the heating (see previous lecture)

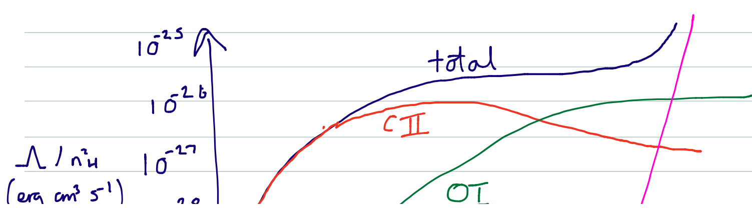
Heating rate per unit volume :

$$\Gamma_{pe} = n_H G_0 \times g(G_0/n_e, T)$$

Intensity of radiation field — $\propto$ grain charge

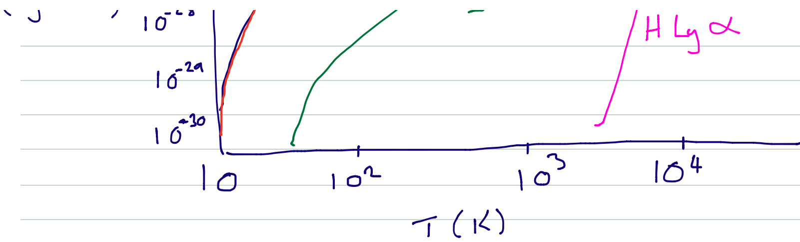
Cooling :-

Atomic Line cooling primarily from 2 fine structure lines



CII 158 μm
OI 63 μm

For $n_H = 0.6$ cm^{-3}



$n_e/n_H = 1.7 \times 10^{-2}$

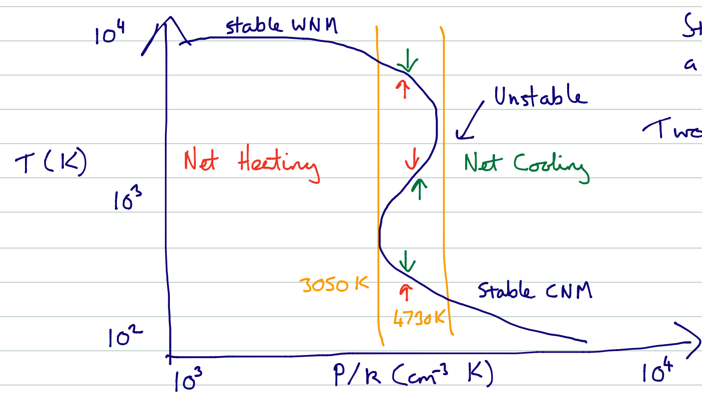
Above 10^4 K cooling rate is steep due to the $\exp(-157800/T)$ term in the excitation rate of Ly α

→ Below this the cooling rate is very flat

10.4 Two thermal phases

Gas with a flat dependence on temperature in its cooling function is prone to thermal instability.

→ At thermal equilibrium $\Gamma = \Lambda(T)$ for some steady state temperature. If we fix the thermal pressure $P = nkT$ what is the temperature where heating and cooling balance?



Steady State temperature as a function of thermal pressure.

Two stable equilibrium
WNM
CNM

10.5 Thermal Instability

Let us consider in more detail the theory of thermal instability

Let $\dot{Q}$ be the net cooling rate of the gas

$$\dot{Q} = n^2 \Lambda - n\Gamma$$

cooling generally proportional to density squared.

At equilibrium $\dot{Q} = 0$

1) Consider an isochoric perturbation ie. density constant

For thermal stability if T increases ⇒ $\dot{Q} > 0$
if T decreases ⇒ $\dot{Q} < 0$

Hence we require $\frac{\partial \dot{Q}}{\partial T} < 0$

$$\left[\frac{\partial \dot{Q}}{\partial T}\right]_P < 0 \quad \text{Is called the Parker criterion}$$

If we approximate the heating & cooling rates as power laws.

$$\Lambda = \Lambda_0 T^{\alpha} \qquad \Gamma = \Gamma_0 T^{\beta}$$

$$\frac{\partial \dot{Q}}{\partial T} = \frac{\partial}{\partial T}\left(n^2 \Lambda_0 T^{\alpha} - n \Gamma_0 T^{\beta}\right) = \frac{\alpha n^2 \Lambda}{T} - \frac{\beta n \Gamma}{T} < 0 \qquad (T^{\alpha-1} = T^{\alpha}/T)$$

rearrange by $\times T$ and $+/-\ \alpha \Gamma n$

$\alpha \Lambda n^2 - \alpha \Gamma n + \alpha \Gamma n - \beta \Gamma n$

$\Rightarrow \alpha (\underbrace{\Lambda n^2 - \Gamma n}_{\dot{Q}=0}) + (\alpha - \beta)\Gamma n < 0$

$\Rightarrow (\alpha - \beta)\Gamma n < 0$

when $\Gamma n > 0$ the medium is unstable when $\alpha < \beta$

- In the neutral medium assume a constant heating rate
  $\hookrightarrow \beta = 0$
- CII cooling $\Lambda = \Lambda_0 T^{\alpha}$
  if H collisions dominate $\alpha > 0$ STABLE
  if e^- collisions dominate $\alpha = -0.5$ UNSTABLE Why?

Instability will depend on the level of ionisation of the gas.

2) Consider an isobaric perturbation

$$\left[\frac{\partial \dot{Q}}{\partial T}\right]_P < 0$$

assuming a constant composition $P = \text{const} \Rightarrow n \propto T^{-1}$

$$c\,\frac{\partial}{\partial T}\left(\Lambda_0 T^{\alpha-2} - \Gamma_0 T^{\alpha-1}\right) < 0$$

$$\rightarrow (\alpha - 2)\frac{n^2 \Lambda}{T} - \frac{(\beta - 1) n \Gamma}{T} < 0$$

rearrange as before

$$(\alpha - 2)(\underbrace{\Lambda n^2 - \Gamma n}_{0}) + (\alpha - 2 - \beta + 1)\underbrace{n \Gamma}_{+ve} < 0$$

Therefore for instability

$$\alpha - \beta - 1 < 0$$

For a constant heating rate $\beta = 0$ have thermal instability when $\alpha < 1$ ie when Λ increases more slowly than $\Lambda \propto T$

In the range $100 < T < 6000$ K $\alpha < 1$

$\Rightarrow$ Medium is isobarically unstable

10.5 Sizescale of Instability

- For gas to be isobaric it must be able to maintain internal pressure equilibrium.

$$L_{iso} = c_s \, t_{cool}$$

soundspeed ↗ ↖ gas cooling time

@ $T = 100\,K$
$c_s \sim 1\,km\,s^{-1}$ $\quad \Lambda_{C^+} = 1.1 \times 10^{-27}\,erg\,cm^3\,s^{-1}$ if hydrogen collisions dominate

$$t_{cool} = \tfrac{3}{2}\, n k T \,/\, \Lambda n^2$$
$$= \frac{2.1 \times 10^{-14}}{1.1 \times 10^{-27}}\, n^{-1} = 0.6\, n^{-1}\, Myr$$
$$L_{iso} = 1\,km\,s^{-1} \cdot 0.6\, n^{-1}\, Myr$$
$$\sim 0.6\, n^{-1}\, pc$$

- The minimum length scale is set by thermal conduction
  ↳ as perturbation cools it becomes colder than surroundings, and it will be heated by conduction.

Heat flow $\quad \vec{q} = -K \vec{\nabla} T$
$\qquad$ ↖ thermal conductivity

in integral form $\quad \dot{Q} = K \oint \vec{\nabla} T . dS$

estimate $\quad \nabla T \sim T/L$

$$|\dot{Q}| \sim K\, T/L\; L^2 \sim K T L$$

for thermal conduction to balance cooling

$$\underbrace{n^2 \Lambda}_{\text{cooling}}\; \underbrace{L^3}_{\text{volume}} = \underbrace{K T L}_{\text{convective heating}}$$

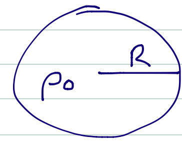
$$\Rightarrow \boxed{L_F = \left(\frac{K T}{n^2 \Lambda}\right)^{1/2}} \qquad \text{Fields length}$$

For low ionisations (or strong magnetic fields) thermal conducting is mainly from atomic hydrogen, $K = 2.5 \times 10^3\, T^{1/2}\, cm^{-1}\, K^{-1}\, s^{-1}$ and for 100 K gas $L_F \sim 0.02\, n^{-1}\, pc$ significantly smaller than L_{iso}.

10.7 Gravitational Instability

Another instability that can create dense structures in the ISM is the Jeans instability. The Jeans mass gives the typical length scale at which perturbations will experience runaway collapse.

Suppose we have a uniform spherical monatomic cloud of gas



$\gamma = 5/3$

From the virial theorem for hydrostatic equilibrium in a monatomic gas

$$-E_g = 2 E_{th}$$

$$E_{th} = 3/2\, N k_B T = \frac{3}{2}\frac{M kT}{\mu m_H} \qquad \text{as } N = \frac{M}{\mu m_H} \qquad \text{for a monatomic gas } \gamma = 5/3$$

$$E_g = -\frac{3}{5}\frac{GM^2}{R} \quad \text{for a spherical cloud}$$

for equilibrium

$$2 \times \frac{\cancel{3}}{\cancel{2}}\frac{MkT}{\mu m_H} = -\frac{\cancel{3}}{5}\frac{GM^{\cancel{2}}}{R}$$

$$5 \frac{R}{GM}\frac{kT}{\mu m_H} = 0 \qquad R = \left(\frac{3M}{4\pi\rho_0}\right)^{1/3} \quad \text{for a uniform sphere}$$

$$\frac{5kT}{G\mu m_H}\frac{1}{M}\left(\frac{3M}{4\pi\rho_0}\right)^{1/3} = 0$$

$$\frac{5kT}{G\mu m_H}\left(\frac{3}{4\pi\rho_0}\right)^{1/3} = M^{2/3}$$

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

We can also derive a Jeans radius which gives the typical length scale of perturbations

$$R_J = \left(\frac{5kT}{G\mu m_H}\right)^{1/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2} \qquad (\text{Note } 1/6 + 1/3 = 1/2)$$

Now note that

$$t_{ff} = \left(\frac{3\pi}{32 G\rho}\right)^{1/2} \qquad c_s = \left(\frac{\gamma kT}{\mu m_H}\right)^{1/2} \qquad \frac{0.24}{\rho_0}$$

This is just for me

$$\left\{\begin{array}{l} c_s t_{ff} = \left(\frac{5kT}{G\mu m_H}\right)^{1/2}\left(\frac{3\pi}{3.32\,\rho_0}\right)^{1/2} \qquad \left(\frac{0.1}{\rho_0}\right)^2 \\ L_J \sim 2.5\, c_s t_{ff} \end{array}\right.$$

Therefore $L_J \sim c_s t_{ff}$. Let us now compare this with our previous discussion of isobaric perturbations where

$$L < c_s t_{cool}$$

$\Rightarrow$ that for an isobaric perturbation to be unstable

$$t_{ff} < t_{cool}$$

for $T = 100\,K$ $\quad c_s \sim 1\,km\,s^{-1}$ $\quad t_{cool} = 0.6\, n^{-1}$ Myr

$t_{ff} \sim 51\, n^{-1/2}$ Myr

Isobaric pertubations are generally not unstable.

10.8 Formation of dense structures in the ISM

Dense structure in the ISM may be formed by thermal instability or gravitational instabilities. However gas may also be compressed by the intrinsic velocity field of the gas. Such compressive motions may themselves trigger thermal or gravitational instabilities forming cold dense regions to form in the ISM.

Sources of compressive motions e.g.

- Turbulence (see Lecture 12)
- Spiral Arms
- Instability of the Galactic disk
- Supernovae blast waves
- Converging flows