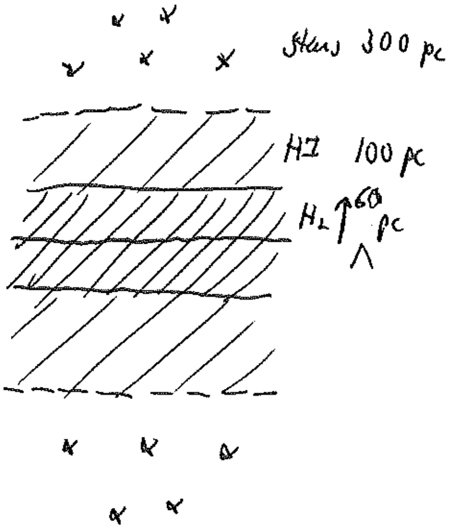
insert -
· de-reddening SEDs
· CM diagrams

L10 – ISM: I. General

Galactic Gas: HI

Almost all the gas is hydrogen – 10% by number is helium, <1% is "metals". Most of the hydrogen is neutral (HI) or molecular (HII). A smaller fraction is ionized (HII).



Looking at the Galaxy edge on, the HI is thicker than the H_2 gas. But both are thin compared to the stars. This means that the vertical velocities are in the order:

$$(V_\perp)_* > (V_\perp)_{HI} > (V_\perp)_{H_2}$$

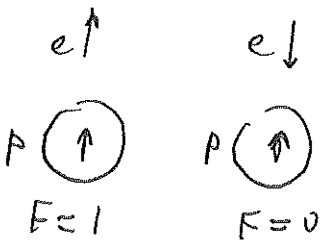
In surface density, $\Sigma(r)$, HI locally dominates. H_2 has an inner hole (the "molecular ring"). But near the Galactic Center, H_2 shoots upward. This spike coincides with greatly enhanced star formation at the center.

Show my Fig 2.3 – $\Sigma(\varpi)$ | handout

HI gas is concentrated in clouds. Typically,

$n \sim 30\ cm^{-3}$

$T \sim 80\ K$



$\Delta E = 5.9 \times 10^{-5}\ eV$

$\lambda = 21\ cm$

The HI gas itself is seen by 21 cm radiation. This is a "hyperfine" transition in the n=1 state. Physically, it is caused by the spin-orbit interaction between the electron & proton.

Usually the F=1 (excited) state is de-excited collisionally. But rarely ($\tau = 1 \times 10^7$ yr!), the excited atom emits a photon. Although $A = 10^{-7}\ yr^{-1}$, there is such a huge column density that HI is detectable.

Vertical Distribution of HI

The governing equation is hydrostatic balance:

$$-\frac{1}{\rho_{HI}}\vec{\nabla} P_{HI} - \vec{\nabla}\phi_g = 0$$

Here, ϕ_g is the gravitational potential from the Galaxy itself. Dotting with $\hat{z}$:

$$\frac{1}{\rho_{HI}}\frac{dP_{HI}}{dz} = \frac{-d\phi_g}{dz}$$

But $P_{HI} = \rho_{HI} C_{HI}^2$ where C_{HI} represents thermal motion of the gas. (sound speed) $C_{HI} = \sqrt{\frac{RT}{\mu}}$

Assume C_{HI} = constant

$$\frac{\rho_{HI}(z)}{\rho_{HI}(0)} = \exp\left[\frac{\phi_g(0) - \phi_g(z)}{C_{HI}^2}\right]$$

What is $\Phi_g(z)$? It is created by stars.

$$\nabla^2 \phi_g = 4\pi G \rho_* \rightarrow$$

$$\frac{d^2\phi_g}{dz^2} = 4\pi G \rho_*(z)$$

The scale height of stars is so large that we can replace $\rho_*(z) \rightarrow \rho_*(0)$. We integrate, noting that $d\phi_g/dz\,(0) = 0$ by symmetry

$$\phi_g(z) = \phi_g(0) + 2\pi G \rho_*(0) z^2 \qquad \text{so that}$$

$$\frac{\rho_{HI}(z)}{\rho_{HI}(0)} = \exp\left[\frac{-2\pi G \rho_*(0) z^2}{C_{HI}^2}\right] = e^{-(z/H)^2}$$

Scale height of HI gas: $\boxed{H = \left[\frac{2\pi G \rho_*(0)}{C_{HI}^2}\right]^{-1/2}}$

Values:

$\rho_*(0) = 0.18\ M_\odot\ pc^{-3}$

For c_{HI}, use $T = 80\ K \longrightarrow c_{HI} = 0.8$ km/s
We find

$$H = 10 \text{ pc}$$, about 10% of the observed value!

Lesson—
We should not be using the thermal temperature, but the bulk kinetic motion of the individual clouds.
In fact HI clouds have $V_\perp \sim 6$ km/s, giving a better value for H. √

Galactic Gas: H_2

The H_2 molecule itself has no electric dipole moment, & so is a very poor radio emitter. [It was first seen via electronic transitions excited by UV.]

CO — We need to use surrogates – eg CO ($\lambda = 2.6$ mm).
On the flip side, CO is ~~strong~~ such a strong emitter (and absorber), that H_2 clouds are optically thick to the radiation. We only see the surface ($\delta\tau_\lambda \sim 1$).

Must use rarer isotopes (eg ^{13}CO) to penetrate the cloud interior. For H_2 clouds, we find $T \sim 10\ K$, $n \sim 100 - 10^4\ cm^{-3}$.

Within the Galaxy, the scale height is thinner, reflecting lower vertical speed ($V_\perp \sim 4$ km/s). Since dominant source of gravity is (again) the stars, the falloff in Σ_* toward the outer part of the Galaxy leads to thickening of the H_2.

$>$ Note that we easily see both H_2 and HI in other galaxies. They trace the spiral arms in our own and other galaxies like the M. Way.

Galactic Gas: HII

HII regions are produced by O stars. Lyman continuum radiation ($E > 13.6$ eV) ionizes a sphere of gas. Recombinations lead either to other ionizing photons [which are trapped] OR to longer-λ photons that promptly escape. For example, we see Hα and other lines in the Balmer series. Also see radio recombination lines for high-n. Can see radio emission over long distances.

$>$ It is the radiation from HII regions that is the signpost of SF in the Universe.

Phases of the ISM

HII regions are a transient phenomenon.
There are other stable phases besides HI ($n \sim 30$ cm^{-3}, $T \sim 80$ K). There is a "warm neutral medium" ($n \sim 0.5$ cm^{-3}, $T \sim 8 \times 10^3$ K).

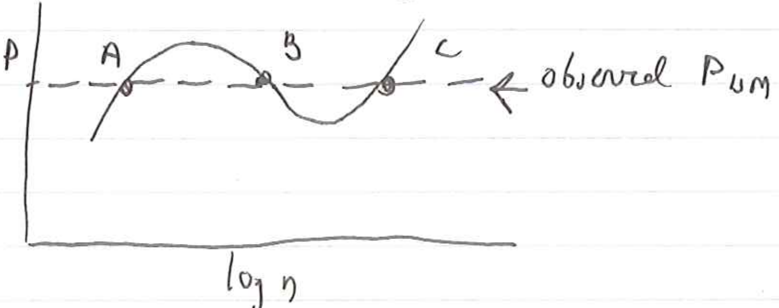
Notice that the product of nT ($\sim P$) is similar for both, $nT \sim 2 \times 10^3$ cm^{-3} K. It looks like these "phases" have a common pressure.

Let us pursue this idea quantitatively. Take a parcel of ISM gas and subject it to heating + cooling. At a given n, it will equilibrate to a fixed P.

[Main heating mechanism: photoelectric effect on ~~grains~~ grains
UV ejects electrons which heat gas.]

[Main cooling mechanisms: emission of Lyα (high T)
IR emission by CII (lower T)]

Result:



A parcel of gas lying above the curve [for a given n, T is too high] cools faster than it heats up.

A parcel of gas lying below the curve [for a given n, T is too low] heats ~~up~~ faster than it cools

Thermal Instability

Imagine gas in state Ⓑ. If it is compressed at fixed P, T drops and it enters the region above the equilibrium curve. It cools more and approaches Ⓒ.

Similarly, if the gas at Ⓑ expands (and T rises), it goes below the curve. It heats up until it reaches Ⓐ. Point $\boxed{\text{B is thermally unstable.}}$

But now suppose the gas starts at Ⓐ. If compressed at fixed P, so that T falls, it enters the region below the curve, It heats up + expands, returning to Ⓐ. Points Ⓐ + Ⓒ are "thermally stable"

Numerically, Ⓐ corresponds to the warm neutral medium.
Ⓒ " " HI clouds.

What about H_2? Its internal pressure is far above P_{ISM} $(P \gtrsim \overset{10^5}{10^4}\ \mathrm{cm^3\,K})$
It is not a "phase" in this sense. The higher pressure is from self-gravity.
No other ISM clouds are self-gravitating.

Interstellar Chemistry in Brief

In addition to CO, ~150 other molecules are observed. Some others are valuable traces of ISM properties. A great many are seen near the G. center.

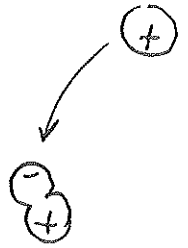
How do molecules arise in space?

- If two neutral atoms collide, they could release energy to a 3rd body. But such 3-body collisions are rare in space.

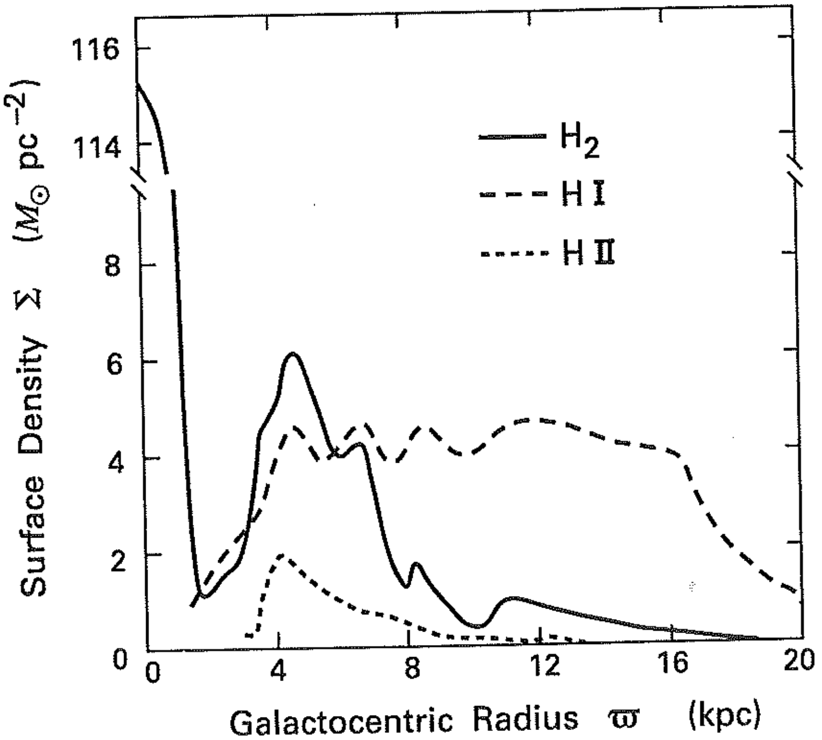
- They could collide and emit a photon. But, again, such "radiative association" is rare.

- In the lab, molecules are made by "neutral-neutral" reactions. One atom must penetrate another's cloud of electrons.* The atoms must overcome an "activation barrier". Typically, $\Delta E / k_B \sim 1000$ K, so negligible in the ISM

- The key is "ion-molecule" reactions. An ion creates an induced dipole moment in a neutral molecule.
Because of the dipole moment, the ion is attracted "tidally" and can react. Many molecules — including CO — are formed this way. But not H_2, whose abundance is much too large.



* Then the atoms recoil, carrying off extra energy in their KE


116
114
8
6
4
2
0
Surface Density Σ ($M_\odot$ pc^{-2})
H_2
H I
H II
0
4
8
12
16
20
Galactocentric Radius ϖ (kpc)