

Lecture 11 Molecular Clouds 1

Outline

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| <ul style="list-style-type: none"> 11.1 Observations of Molecular Clouds. 11.2 Molecular Hydrogen 11.3 Other Major molecules 11.4 Self shielding 11.5 Thermal Balance 11.6 Turbulence 11.7 Larson's laws 11.8 Shocks 11.9 Filaments & Cores 11.10 Pictorial of MC before star formation | } | <p>Temperature</p> <p>Gas freeze out</p> |
|---|---|--|
- Next lecture

11.1 Observations of Molecular Clouds

Category	Size (pc)	n_H (cm^{-3})	M (M_\odot)	Line width (kms)	AV (mag)
GMC Complex	25-200	50-300	$10^5 - 10^{6.8}$	4-17	3-10
Dark Cloud Complex	4-25	$10^2 - 10^3$	$10^3 - 10^{4.5}$	1.5-5	4-12
GMC	2-20	$10^3 - 10^4$	$10^3 - 10^{5.3}$	2-9	9-25
Dark Cloud	0.3-6	$10^2 - 10^4$	5-500	0.4-2	3-15
Star forming clump	0.2-2	$10^4 - 10^5$	$10 - 10^3$	0.5-3	4-90
Core	0.02-0.4	$10^4 - 10^6$	$0.3 - 10^2$	0.3-2	30-200

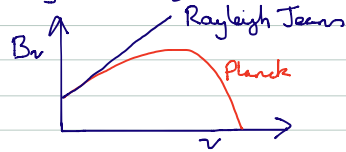
Methods of observing :-

- Star Counts
 - e.g. Herschel 1785 observation of background stars by dust now primarily in near infrared bands
 - extinction in the infrared is a good method of estimating column densities. NICE
- Molecular Radio Bands e.g. CO $J=1 \rightarrow 0$
 - an X-factor is used to convert from CO to H_2
 - e.g. $X_{CO} = 1.8 \times 10^{20} H_2 \text{ cm}^{-2} / K \text{ km s}^{-1}$ (Dame et al. 2001)
 - however CO is an optically thick species so may not see all of the gas
 - molecular line transitions are the only method of determining velocities.
- FIR dust emission
 - from depletion measurements we know that clouds have a near constant gas to dust ratio of ~ 0.01
 - dust grains emit as black bodies with most of their emission in the infrared, at $\lambda \geq 300 \mu m$ optically thin

$$M_{\text{dust}} = \frac{F_\nu D^2}{K_\nu B_\nu(T_{\text{dust}})} \leftarrow \text{distance}$$

$\xrightarrow{\text{dust opacity at } \nu}$
 $\xrightarrow{\text{blackbody function}}$

At long wavelengths we can apply the Rayleigh-Jeans law



$$B_\nu(T) = \frac{2\nu^2 kT}{c^2} \propto T$$

- Zeeman effect

- In the presence of a static magnetic field spectral lines may be split into several components. The distance between the sublevels is a function of the field strength.

- Crutcher et. al. 2010 find

$$B \approx 5 \mu\text{G} \quad n_4 < 0.03 \quad \text{where } n_4 = n_H / 10^4$$

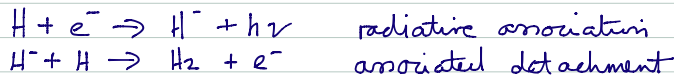
$$\approx 49 n_4^{0.65} \mu\text{G} \quad n_4 > 0.03$$

these values are close to the energy in turbulence in molecular clouds so fields may be dynamically important.

+ also γ -ray, HII, IR point sources, masers

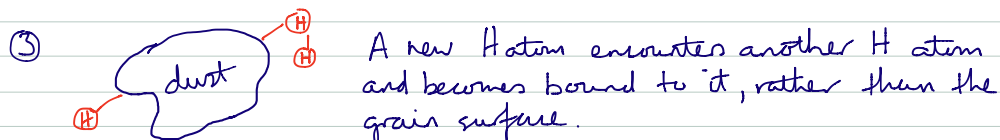
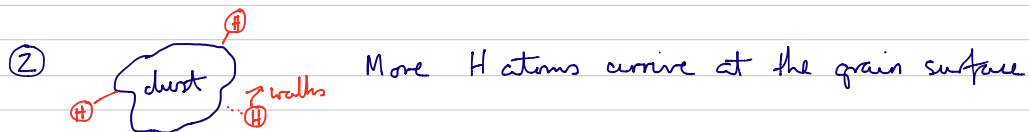
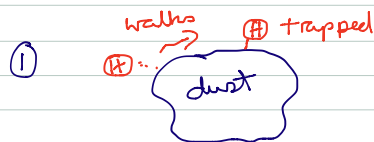
11.2 Molecular Hydrogen

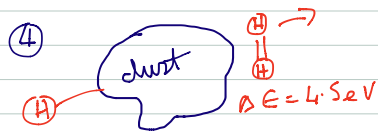
- In the gas phase



However the first reaction is slow and H^- is rapidly destroyed.

- Dust phase via grain catalysis.





Hydrogen atoms react to form H_2 in an exothermic reaction that releases a binding energy of 4.5 eV. This energy frees the H_2 from the grain surface.

The total grain cross section per H nucleus is

$$\Sigma_{gr} = \frac{1}{n_H} \int da \frac{dn_{gr}}{da} + a^2 \quad a = \text{grain radius}$$

From UV extinction observations we know that $\Sigma_{gr} > 10^{-21}$

$$R_{gr} = 7.3 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1} \left(\frac{T}{100 \text{ K}} \right)^{1/2} \langle \epsilon_{gr} \rangle \left(\frac{\Sigma_{gr}}{10^{-21}} \right)$$

Is the rate coefficient, where $\langle \epsilon \rangle$ is the formation efficiency averaged over grain surface.

- Photo-dissociation of H_2 is the main destruction mechanism of H_2



H_2 only absorbs strongly over a limited range of wavelengths of about 1000 Å and so the rate of photo-dissociation depends on the intensity at this wavelength

$$\chi = \frac{(J_{UV})_{1000\text{\AA}}}{4 \times 10^{-14} \text{ erg cm}^{-3}} \quad \chi = 1 \quad \text{Habing 1968}$$

The steady state abundance of H_2 is given between the balance between photo-dissociation and formation on grains

$$\frac{n(H_2)}{n_H} = \frac{R_{gr} n(H)}{R_{dis}} = 1.8 \times 10^{-5} \left(\frac{n(H)}{30 \text{ cm}^{-3}} \right) \left(\frac{R_{gr}}{3 \times 10^{-17} \text{ cm}^3 \text{ s}^{-1}} \right) \left(\frac{5 \times 10^{-11} \text{ s}^{-1}}{R_{dis}} \right)$$

i.e. diffuse HI clouds should contain only trace amounts of H_2

- Self Shielding

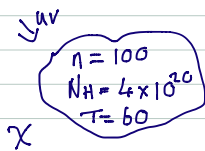
The above suggests that there should be very little H_2 in the ISM, yet we observe H_2 at densities of $n_H = 100 \text{ cm}^{-3}$.

Self-shielding:- when the photoexcitation channels become optically thick, so that the molecule is "shielded" by itself.

Above H_2 column densities of $N_{H_2} = 5 \times 10^{14} \text{ cm}^{-2}$ the shielding factor relative to the optically thin case is

$$f_{sh} = \left(\frac{N_{H_2}}{5 \times 10^{14} \text{ cm}^{-2}} \right)^{-3/4}$$

Let us consider the case of a small test cloud for illustration



H_2 formation on grains
 $R_{gr} \sim 2 \times 10^{17} n n_H$

Dissociation
 $R_{dis} \sim 6 \times 10^{-11} f_{sh} n_{H_2}$

$n_{H_2} = x_{H_2} n_H$ x_{H_2} H_2 abundance

$$R_{dis} = 6 \times 10^{-11} \left(\frac{2 \times 10^{20} x_{H_2}}{5 \times 10^{14}} \right)^{-3/4} n_{H_2}$$

$$\sim 4 \times 10^{-15} x_{H_2}^{1/4} n$$

In equilibrium

$$2 \times 10^{17} n (1 - 2x_{H_2}) = 4 \times 10^{-15} x_{H_2}^{1/4}$$

for $n = 100 \text{ cm}^{-3}$

$$\frac{x_{H_2}^{1/4}}{1 - 2x_{H_2}} = \frac{1}{2} \quad \text{solve numerically for } x_{H_2}$$

$x_{H_2} \sim 0.05$
 ie about 10% of hydrogen is molecular

11.3 Major Chemical Processes

Once H_2 has been formed, other chemical reactions can follow. Most of the gas will be neutral but due to cosmic rays there will also be ions present.

There are 5 types of reactions that can be important.

- 1) Photoionisation $AB + h\nu \rightarrow AB^+ + e^-$ $k \sim 10^{-11} - 10^{-9} \text{ s}^{-1}$
 ISRF contains photons with $h\nu < 13.6 \text{ eV}$. For molecules with an ionisation threshold $< 13 \text{ eV}$ photoionisation rates are typically in the range $10^{-11} - 10^{-9} \text{ s}^{-1}$. Note that the ionisation threshold for H_2 is 15.43 eV so H_2 is not ionised even in H_2 regions.

2) Photo dissociation $AB + h\nu \rightarrow AB^* \rightarrow A + B$ $k \sim 10^{11} - 10^9 s^{-1}$
 for the species H_2 and CO (the major coolant in MCs)
 photoexcitation leading to dissociation occurs via line rather than
 via continuum allowing the species to self shield.

3) Neutral-neutral exchange $AB + C \rightarrow AC + B$
 As MCs are mainly neutral, neutral-neutral collisions are common.
 However even for an exothermic process there is often an energy
 barrier to overcome as the reaction complex ABC must pass
 through intermediate steps.

eg. $OH + H \rightarrow O + H_2$ $k \sim 1.5 \times 10^{-12} e^{-19.5} cm^3 s^{-1}$
 has an energy barrier despite being an
 exothermic process. So this is not the major
 channel to form H_2 .

$C + OH \rightarrow CO + H$ $k \sim 10^{-10} cm^3 s^{-1}$
 however has no such barrier and can
 operate at the low temperatures found in MCs

4) Ion-neutral exchange $AB^+ + C \rightarrow AC^+ + B$ $k \sim 2 \times 10^{-9} cm^3 s^{-1}$
 Important for two main reasons 1) exothermic reactions tend
 to lack energy barriers 2) reaction rates are high due to
 the large dipole

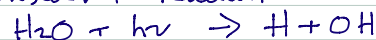
5) Radiative association $A + B \xrightleftharpoons[k_d]{k_f} (AB)^* \xrightarrow{h\nu} AB + h\nu$ $k \sim 10^{-17} cm^3 s^{-1}$

First an excited complex AB^* is formed this will fall apart
 in a vibrational time ($\sim 10^{-14} s$) unless a photon is emitted
 that carries away the excess energy.

• The importance of dust.

The rates of photoionisation and photodissociation are rather
 high and so in the diffuse ISM small molecules are quickly destroyed.
 However in MCs the UV field is attenuated by dust. The local rate
 within a cloud will therefore depend of the column density between a
 given location and the closest UV source.

eg. consider the reaction



for a Draine field

$$AV = 0$$

$$k = 5.9 \times 10^{-10} s^{-1}$$

$$AV = 0.5$$

$$k = 1.1 \times 10^{-10} s^{-1}$$

$$AV = 1$$

$$k = 1.7 \times 10^{-11} s^{-1}$$

$$AV = 3$$

$$k = 1.2 \times 10^{-14} s^{-1}$$

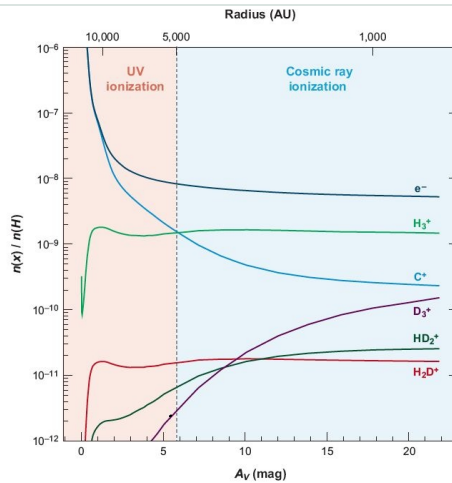
AV is the optical extinction

$$N_H (cm^{-2}) = (2.21 \pm 0.09) \times 10^{21} AV \text{ (mag)}$$

Güver & Öed 2009

Generally in GMCs at an $A_V \sim 3$ photodissociation can be reduced by 3-5 orders of magnitude. This means external sources of UV photons are generally unimportant.

However remember that cosmic rays can penetrate the cloud and will excite H_2 . This will result in the production of H_2 Lyman and Werner band UV photons at a rate proportional to the cosmic ray ionisation rate.



Berlin 07 fig 11

11.4 Heating and Cooling

1) Gas temperature

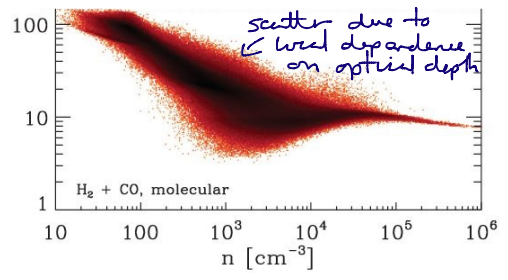
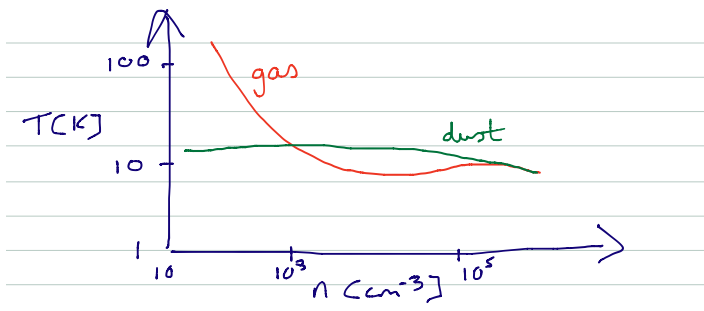
For the gas in the MC that is not in dense cores gas heating occurs predominantly through heating by cosmic rays.

Cooling is principally via rovibrational transitions of CO. The CO molecule has its lowest rotational state at only 5.5 K above ground so it is easily excited. That, combined with its abundance makes it the dominant gas phase coolant.

2) Dust temperature

The dust is mainly heated by the interstellar radiation field and cooled by thermal radiation from the grains in the far-IR. See previous lecture for more details.

At densities above $\sim 10^4 \text{ cm}^{-3}$ the gas and dust become thermally coupled. At this point the dust controls the gas temperature by emitting as a black body.



At $n < 10^5 \text{ cm}^{-3}$

$$T \propto \rho^{-0.25}$$

$$P \propto \rho^{0.75}$$

In other words the equation of state of the gas is softer than isothermal ($P \propto \rho$). This means that the local Jeans mass decreases rapidly with increasing density.

11.7 Gas Freeze Out

In the densest cores within a molecular cloud the abundance of various species is seen to decrease. For example at densities below $4 \times 10^4 \text{ cm}^{-3}$ CO has an abundance of $\sim 4 \times 10^{-9}$ relative to H_2 , but above this value the abundance falls off exponentially.

$$A[\text{CO}] = 4 \times 10^{-9} e^{-n/n_d}$$

$$n_d = 4 \times 10^4 \text{ cm}^{-3}$$

Correspondingly spatial mapping of ices within cores shows that the abundance of CO ice significantly increases above $n \sim 10^5 \text{ cm}^{-3}$ (Pontoppidan 2006) leading to the conclusion that the CO freezes onto dust grains.

Furthermore the relative "depletion" of gas onto dust grains depends on the species studied.

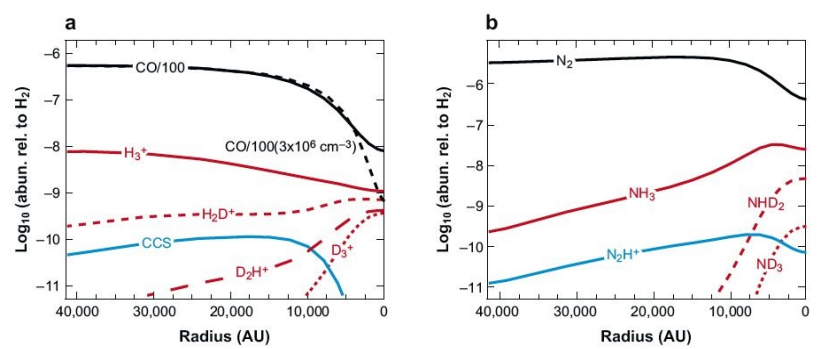


Figure 9
 Plot of chemical abundances as a function of core depth for selected species from a chemical and dynamical model of a contracting Bonnor-Ebert sphere (taken from Aikawa et al. 2005). All species are shown at a timescale where $n_{\text{H}}(\text{center}) = 3 \times 10^5 \text{ cm}^{-3}$, excluding CO, which is also shown at $n_{\text{H}}(\text{center}) = 3 \times 10^6 \text{ cm}^{-3}$.

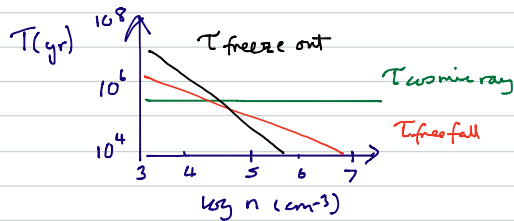
Atoms & molecules freeze onto grain surfaces at a rate

$$k_{fo} = \underbrace{\sigma}_{\substack{\text{cross section} \\ \sim 0.1 \mu\text{m}}} \underbrace{v}_{\substack{\text{mean} \\ \text{velocity}}} \underbrace{n_g}_{\substack{\text{grain} \\ \text{density}}} S \quad \text{s}^{-1}$$

sticking probability

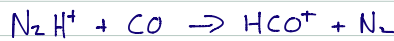
for CO at 10K this equates to a freeze out time of

$$T_{fo} = k_{fo}^{-1} \sim 5 \times 10^9 / n_{H_2} (\text{cm}^{-3}) \text{ s}$$



$t_{dyn} \propto r$ but $T_{freeze} \propto n$
As the core evolves the effects of freeze out are magnified.

The abundances of nitrogen and deuterium rich species actually increase towards core centres. This is due to the rapid freeze out of carbon bearing species. CO is a major destroyer of molecular ions and its removal from the gas leads to a change in the relative abundance of major charge carriers such as H^+ . For example CO is a major destroyer of N_2H^+



with CO removed from the gas phase the forward reaction will be more important

