Lec 22

Physical Properties of Molecular Clouds

1. Giant Molecular Clouds
2. Orion’s Clouds
3. Correlations of Observed Properties
4. The X-Factor

References

Origins of Stars & Planetary Systems eds. Lada & Kylafis
http://cfa-www.harvard.edu/crete

e.g.,
Myers, “Physical Conditions in Molecular Clouds”
Blitz & Williams, “Molecular Clouds”
1. Giant Molecular Clouds

In addition to containing molecules (and atoms too), molecular clouds are

Self-Gravitating
Magnetized
Turbulent

It is the central role of gravity, not the molecular aspect, that distinguishes them from other phases of the ISM.

Stars form only in molecular clouds: Understanding star formation starts with understanding molecular clouds
What is a Molecular Cloud?

Almost by definition, molecular clouds are where the gas is primarily molecular, but the term is usually used for large-mass clouds, especially giant molecular clouds (GMCs) with $10^4M_\odot < M < 6 \times 10^6M_\odot$. Sizes range from 10-100 pc, but some properties have narrow ranges.

The filing factor of the clouds is low, and they have as much atomic as molecular gas. Mean densities are only $\sim 100$ cm$^{-3}$, but molecular clouds are very inhomogeneous and have much higher density regions.

There is no accepted explanation for the sharp upper limit to the mass; tidal disruption or the action of massive stars have been suggested.
Giant Molecular Clouds

Attempts to define GMCs precisely is problematic because of the apparent lack of a physical scale: The mass spectrum is a power law with no natural mass or size.

GMCs found in large-scale CO surveys and those found by studying specific regions of star formation are indistinguishable, which suggests:

– Detailed studies of local clouds are likely to be of general applicability
– Star formation is the normal state of GMCs
2. Local GMCs: The Orion Clouds

Cloud A

Cloud B
Orion: The Large-scale Picture
Orion A & B in CO
Orion A & B as Seen by IRAS
Summary for Orion GMCs

• Cloud A (L1641) exhibits some typical features of GMCs
  – Elongated
    • Parallel to the plane of the Galaxy
  – Strong velocity gradient (rotation)
  – Well defined boundaries: GMCs are discrete objects
  – Lumpy
    • Near unity surface filling factors (traced by optically thick $^{12}$CO 1-0)
  – OB associations form in large GMCs
Molecular Clouds Means Star Formation

No local GMCs ($d < 1$ kpc) are without star formation

Within 3 kpc there is only one GMC without any star formation: Maddalena’s cloud $\sim 10^5 M_\odot$

Essentially all star formation occurs in molecular clouds
3. Basic Properties of Molecular Clouds
   a. Linewidth-Size Correlation

Linewidths are superthermal

Noticed by Larson (MNRAS 194 809 1981), who fitted $\sigma \sim S^{0.38}$ close to Kolmogorov 1/3.

Other authors find $\sigma \sim S^{0.5}$ ($\sigma$ in km s$^{-1}$ and $S$ in pc).

Could be a selection effect.

Alternatively, we can regard this as a fundamental empirical statement about turbulence in GMCs.

Linewidth-size correlation for 273 molecular clouds
b. Virial Mass Estimate

A second fundamental property is: **GMCs are gravitationally bound and in virial equilibrium.** Their masses can then be estimated using linewidths as a measure of the cloud velocities, following the arguments of Solomon et al.

This application of the virial theorem is a statement about the mean gravitational potential & kinetic energies:

\[-\langle V \rangle = 2\langle K \rangle = \langle mv^2 \rangle \text{ or } \langle \frac{GM}{R} \rangle = \langle v^2 \rangle = \sigma^2\]

We can use measurements of the radius R and the velocity dispersion \(\sigma\) to estimate the mass of the GMC:

\[M \approx \frac{R\sigma^2}{G}\]
Verification of the Virial Mass Estimate Using $^{12}$CO

\[ I_{CO} = \int T dv \]

is the line integrated intensity for optically thick $^{12}$CO. The CO luminosity of a cloud at distance $d$ is

\[ L_{CO} = d^2 \int I_{CO} d\Omega; \quad \text{hence} \quad L_{CO} \approx T_{CO} \Delta \nu \pi R^2 \]

where $T_{CO}$ is the peak brightness temperature, $\Delta \nu$ is the line width and $R$ is the cloud radius.

Substituting $\Delta \nu^2 \approx \frac{GM}{R}$ for virial equilibrium yields

\[ L_{CO} \approx \sqrt{3\pi G / 4 \rho} T_{CO} M \]
The Mass-CO Luminosity Correlation

This correlation supports the fundamental assumption that GMCs are in virial equilibrium.
c. Additional Correlations

We have discussed two observationally based correlations for GMCs:

\[ \sigma \approx R^{\frac{1}{2}} \quad \text{(line width size relation)} \]

\[ \frac{M}{R} \approx \sigma^2 \quad \text{(virial equilibrium)} \]

They now lead to other conclusions:

\[ N \approx \frac{M}{R^2} \approx \frac{\sigma^4}{R} \approx \text{constant} \]

\[ \rho \approx \frac{M}{R^3} \approx \frac{1}{R^2} \]

\[ M \approx \sigma^2 R \approx R^2 \quad \text{and} \quad M \approx \sigma^4 \]
Alternative Correlations

These additional relations all some observations to back them up. They may actually be preferred to the virial assumption if their validity could be demonstrated in a if they could be understood on physical grounds.

Of particular interest is that the surface density of GMCs are all about the same to within a factor of 2:

\[ N_H \sim 1.5 \times 10^{22} \text{ cm}^{-2} \]
\[ A_V \sim 10 \]
\[ \Sigma \sim 150 \ M_\odot \text{ pc}^{-2} \]
d. Mass Spectrum

The spectrum is incomplete at low masses.

Many interesting questions now follow, such as:

• What is the relation to the clumps cores in GMCs?
• What is the connection with the stellar initial mass function (IMF)?

\[
\frac{dN}{dM} \approx M^{-3/2}
\]

**Fig. 3.** The molecular cloud mass spectrum \( dN/dM \). A fit to the data above \( M = 7 \times 10^4 \, M_\odot \) gives \( dN/dM \propto M^{-3/2} \). There are 15 clouds in each bin and the standard deviation is \( \pm 24\% \). The turnover at low mass is due to undercounting of smaller clouds in the more distant parts of the galactic disk.
Approximate Typical Properties of Local GMCs

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number</td>
<td>4000</td>
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<tr>
<td>Mass</td>
<td>$2 \times 10^5 , M_\odot$</td>
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<tr>
<td>Mean diameter</td>
<td>45 pc</td>
</tr>
<tr>
<td>Projected surface area</td>
<td>2000 pc$^2$</td>
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<tr>
<td>Volume</td>
<td>$10^5 , pc^3$</td>
</tr>
<tr>
<td>Volume density (H$_2$)</td>
<td>300 cm$^{-3}$</td>
</tr>
<tr>
<td>Mean surface density</td>
<td>$1.5 \times 10^{22} , cm^{-2}$</td>
</tr>
<tr>
<td>Surface density</td>
<td>4 kpc$^{-2}$</td>
</tr>
<tr>
<td>Mean separation</td>
<td>500 pc</td>
</tr>
</tbody>
</table>
4. The CO / H₂ Conversion Factor

The integrated CO intensity $I_{\text{CO}} = \int T \, dv$ is used to measure the H₂ average column density. This connection is expected for optically thin tracers, but it holds for the main CO isotopes, despite the fact that they are not optically thin and despite the fact that the CO / H₂ ratio varies within a cloud and from cloud to cloud.

Most surprising is that a single conversion factor between H₂ column density and the integrated CO intensity (the so-called \textbf{X-factor}) applies on average to all GMCs in the Milky Way. The calibration between these quantities has been carried out by various methods, all of which agree to within a factor of a few.
X-factor Method 1: $I_{\text{CO}}$ vs. $A_V$

- Measure $I_{\text{CO}}$ for regions with high $A_V$
- Determine $A_V$ from IR star counts
- Extrapolate $N_H/A_V$ from diffuse clouds
- Assume all hydrogen is molecular

Result:

$$N(\text{H}_2)/I_{\text{CO}} \approx 4 \times 10^{20} \text{ cm}^{-2}/(\text{K km s}^{-1})$$

Problems:

- Inaccuracies in star-count $A_V$
- Variable dust properties
- Variable $N_H/A_V$
X-factor Method 2: $^{13}$CO vs. $A_V$

- Determine $A_V$ as in method 1
- Measure $^{13}$CO line intensity
- Assume $^{13}$CO optically thin, $^{12}$CO optically thick
- Assume $T_{ex}(^{13}$CO) = $T_{ex}(^{12}$CO)
- Assume $^{12}$CO/$^{13}$CO $\approx$ 40 ... 60 $\Rightarrow$ $\tau(^{13}$CO) $\Rightarrow$ $N(^{13}$CO) from LTE analysis
- Problems:
  - Determination of $A_V$ inaccurate
  - Often $T_{ex}(^{13}$CO) $<$ $T_{ex}(^{12}$CO)
  - $^{13}$CO may not be optically thin
X-factor Method 3: Virial Method

- Line intensity $I_{CO} \equiv I(^{12}\text{CO}) = T \Delta \nu$
- $N(\text{H}_2) = 2 \, R \, n(\text{H}_2)$
- Virial theorem: $\frac{GM}{R} \approx \sigma^2 = \left(\frac{\Delta \nu}{2.35}\right)^2$
- Simple mass estimate: $M = \frac{4\pi}{3} R^3 n_{\text{H}_2} \langle m \rangle$

- In $I_{CO}$, replace $\Delta \nu = 2.35 \, \sigma \sim (GM/R)^{1/2}$ to get:
  \[
  \frac{N(\text{H}_2)}{I_{CO}} \approx \frac{10K}{T} \left(\frac{n_H}{1000 \, \text{cm}^{-3}}\right)^{1/2} \times 3 \times 10^{20} \, \text{cm}^{-2} \, \text{K}^{-1} \, \text{km s}^{-1}
  \]
Notes on Method 3

• Does not assume any value for $n$(CO)/$n$(H$_2$)
• Method could be applied to any molecule
• Conversion factor depends on $T$ and $n$ in the cloud
  – Should be different for cold dark clouds and giant molecular clouds
• Problems:
  – Assumes virial equilibrium
  – Measures only mass within $\tau = 1$ surface
  – Practical difficulties in determining width of saturated $^{12}$CO line
X-factor Method 4: $\gamma$-Rays

High energy comic rays (> 1 GeV) produce neutral pions in collisions with protons in H and H$_2$, which then decay with the emission of two $\gamma$-rays

$$p + p \rightarrow p' + p' + \pi_0,$$
$$\pi_0 \rightarrow \gamma + \gamma$$

The $\gamma$-ray emission depends on the product of the cosmic ray density & the density of all protons, i.e., $n_H$.

Hunter et al. ApJ 481 205 1997 combine $\gamma$-ray measurements from COMPTON/EGRET with the Columbia-CfA CO survey to obtain the conversion factor,

$$N(H_2)/I_{CO} = (1.56 \pm 0.05) \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ kms}^{-1},$$

presumably assuming all hydrogen is molecular.

**NB** With high energy CRs, the modulation correction is small. Hunter et al. assume that the CR density is proportional to the mass density (?). They get good agreement for the $\gamma$-ray spectrum below 1 GeV.
CR enhancement factor varies by ~ 50% in order to fit γ-ray observations.

X-factor Method 5: HI/IRAS/CO

• Dame et al. (ApJ 547 792 2001) used IRAS far-IR emission as a tracer of total gas column density
  – Calibrated with the Leiden-Dwingeloo 21-cm HI survey in regions free of CO emission
  – Total gas map was differenced with the a HI map to obtain a complete and unbiased predicted map of H₂
    • Close agreement between this map and observed CO implies that few molecular clouds at |b| < 30 have been missed by the present CO survey
  – The ratio of the observed CO map to the predicted molecular map provides a measure of the local average X-factor for |b| > 5°:

\[ \frac{N(H₂)}{I_{CO}} = 1.8 \pm 0.3 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km s}^{-1} \]
Method 5: HI/IRAS/CO

Dame et al. compared IRAS far-IR (dust – But a measure of the total gas with 21 cm HI and 2.6 mm CO

(a) HI

(b) IRAS 100 µm

(c) $N_{\text{HI}}/I_{\text{100 µm}}$

(pixels with detected CO are white)
Method 5 Verification
CO/H₂ Conversion Factors: Summary

- Various methods agree remarkably well
- Apply to global scales, not locally
- Limits on applicability are unclear
- Give no information on $N(\text{H}_2) / N(\text{CO})$
- Conversion factors should depend on $T$, $n$, and metallicity
- Conversion factor derived for galactic disks is not valid for galactic nuclei (including Galactic Center region) or metal-poor systems
## CO/H$_2$ Conversion Factor: Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>X</th>
</tr>
</thead>
<tbody>
<tr>
<td>Early work</td>
<td>2-5</td>
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<tr>
<td>$\gamma$-rays Hunter et al. 1997</td>
<td>1.56 ±0.05</td>
</tr>
<tr>
<td>HI/IRAS/CO Dame et al. 2001</td>
<td>1.8±0.3</td>
</tr>
<tr>
<td>$A_V$ Lada et al. 2003</td>
<td>~ 4</td>
</tr>
</tbody>
</table>

Units for $X$: $10^{20}$ cm$^{-2}$ / K km s$^{-1}$