Lecture 26
Clouds, Clumps and Cores

1. Review of Dense Gas Observations
2. Atomic Hydrogen and GMCs
3. Formation of Molecular Clouds
4. Internal Structure
5. Observing Cores
6. Preliminary Comments on Core Stability

References
Bergin & Tafalla, ARAA 45 339 2007
Blitz & Williams, “Molecular Clouds”
Myers, “Physical Conditions in Molecular Clouds”
In Origins of Stars & Planetary Systems
http://www.cfa.harvard.edu/events/1999crete

Review of Molecular Clouds
Dame et al. (2001) CfA CO survey

recent star formation is associated with GMCs

empirical correlations

$\sigma \approx N^{1/2} \sqrt{M/R} \approx \sigma^2$

are not independent
2. HI Content of GMCs
Tentative Ideas

- HI envelopes around molecular clouds are probably common.
- Local GMCs may have comparable masses of HI and H$_2$
- HI is more spatially extended
- GMC HI probably varies throughout the Milky Way, e.g., HI merges into a continuous background in the 5-kpc ring.
- Origin of the HI in and near GMCs: Photodissociation of H$_2$? Remains of the GMC formation from HI?
- Basic, interesting, and challenging topic for future study?

![HI and $^{13}$CO in the Rosette Molecular Cloud](image)

*Figure 5.* An HI envelope around the Rosette molecular cloud. The grayscale, range 450 to 650 K km s$^{-1}$, shows HI data from Arecibo observations by Kuchar & Bania (1995). Contours, beginning from and with increment 18 K km s$^{-1}$, are CO emission from Bell Labs observations by Blitz & Stark (1986). Emission has been summed over a velocity range $v = 4$–25 km s$^{-1}$. The cross marks the OB association that lies at the center of the Rosette nebula and has cleared out the neutral gas. The regions of strong HI emission (lighter colors) lie on the CO cloud boundaries, forming an envelope around the cloud.
3. Formation of Molecular Clouds

• Gravity must play a role: GMCs are self-gravitating, but not low-mass clouds ($M < 10^3 M_\odot$), e.g., high-latitude clouds.

• GMCs may be short lived, as indicated by the age of the oldest sub-associations (10-20 Myr) still associated with GMCs.

• In principle, the age should be greater than the crossing time, but sound speeds are low. For purposes of estimation, use the original line width size relation:
  $$R/\sigma \sim 2 \text{ Myr} \ (\sigma / \text{ km s}^{-1}),$$
  somewhat shorter than the above estimate of 10-20 Myr.

Formation is an Unsolved Problem

Many processes are involved – gravity, magnetic fields, turbulence, shocks, radiation, etc., but which is dominant?

Formation Mechanisms

Three are often discussed (e.g., Elmegreen in “Evolution of the ISM”, ASP 1990)
  – Collisonal agglomeration of smaller clouds
  – Formation from HI, e.g. by “gravo-thermal” instability
  – Shocks in a turbulent ISM, generated by outflows from massive stars and SN remnants

• If GMCs are formed from the coalescence (agglomeration) of molecular fragments, where are they?
• Is it the chaff seen in spiral arms and in the vicinity of GMCs?
• How much precursor gas is preserved by star formation?
4. Structure of Molecular Clouds

CO maps show that molecular gas is heterogeneous. What is the topology of molecular clouds? Is it useful to talk about discrete structures? Blitz & Williams discuss three levels of structure: clouds, clumps, and cores, illustrated by the following maps of the Rosette Molecular Cloud in CO, C\(^{18}\)O, and CS:

![Maps of Rosette Molecular Cloud](image)

**Figure 4.** Hierarchical cloud structure. The three panels show a representative view from cloud to clump to core. The bulk of the molecular gas (cloud; left panel) is best seen in CO which, although optically thick, faithfully outlines the location of the H\(_2\). Internal structure (clumps; middle panel) is observed at higher resolution in an optically thin line such as C\(^{18}\)O. With a higher density tracer such as CS, cores (right panel) stand out. The observations here are of the Rosette molecular cloud and are respectively, Bell Labs (90\(^\circ\)), FCRAO data (50\(^\circ\)), and BIMA data (10\(^\circ\)).
Clumps in GMCs


• These clouds have similar masses ~ $10^5 M_\odot$, but orders of magnitude different star formation rates, as traced by FIR dust emission:
  • Rosette: ~ 17 OB plus numerous embedded sources
  • G216-2.5: no OB stars and $L_{IR}/M(H_2) < 0.07 L_\odot/M_\odot$
  • Star formation in the RMC occurs in gravitationally bound clumps; the MMC has none.

Why is there no star formation in MMC?

Clump Properties of the RMC and MMC


• Clump masses derived with an X-factor calibrated with $^{13}$CO ~ 1/2 of the galactic average
• Spatial resolution for both clouds is similar ~ 0.7 pc.
• Clumps are similar, but those in MMC are bigger and have larger line widths.
• Both clouds are bound, but none of the MMC clumps are.
Properties of Dark Clods, Clumps and Cores
Bergin & Tafalla (ARAA 45 339 2007)

Table 1 Properties of dark clouds, clumps, and cores

<table>
<thead>
<tr>
<th></th>
<th>Clouds$^a$</th>
<th>Clumps$^b$</th>
<th>Cores$^c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass ($M_\odot$)</td>
<td>$10^3 - 10^4$</td>
<td>50–500</td>
<td>0.5–5</td>
</tr>
<tr>
<td>Size (pc)</td>
<td>2–15</td>
<td>0.3–3</td>
<td>0.03–0.2</td>
</tr>
<tr>
<td>Mean density (cm$^{-3}$)</td>
<td>50–500</td>
<td>$10^3 - 10^4$</td>
<td>$10^4 - 10^7$</td>
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<tr>
<td>Velocity extent (km s$^{-1}$)</td>
<td>2–5</td>
<td>0.3–3</td>
<td>0.1–0.3</td>
</tr>
<tr>
<td>Crossing time (Myr)</td>
<td>2–4</td>
<td>$\approx 1$</td>
<td>0.5–1</td>
</tr>
<tr>
<td>Gas temperature (K)</td>
<td>$\approx 10$</td>
<td>10–20</td>
<td>8–12</td>
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<tr>
<td>Examples</td>
<td>Taurus, Oph, B213, L1709</td>
<td>L1544, L1498, B68</td>
<td></td>
</tr>
</tbody>
</table>

$^a$Cloud masses and sizes from the extinction maps by Cambrésy (1999), velocities and temperatures from individual cloud CO studies.


$^c$Core properties from Jijina, Myers & Adams (1999), Caselli et al. (2002a), Motte, André & Neri (1998), and individual studies using NH$_3$ and N$_2$H$^+$.

5. Molecular Cloud Cores

- Star formation occurs in the densest parts of GMCs called molecular cloud cores.
- About 1/2 of known cores are luminous IR sources powered by newborn stars.
- Molecular core properties provide the initial conditions for star formation and may determine the properties of the stars they form.
- Keys to observing cores are molecular lines that trace high density rather than low density gas and IR measurements of warm dust heated by newborn stars.

References
Bergin & Tafalla, ARAA 45 339 2007
Some Dense Gas Tracers

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transition</th>
<th>Frequency (GHz)</th>
<th>( E/k ) (K)</th>
<th>( n_{\text{crit}} ) (cm(^{-3}) ) @ 10 K</th>
<th>( n_{\text{eff}} ) (cm(^{-3}) ) @ 10 K</th>
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<td>CS</td>
<td>1-0</td>
<td>49.0</td>
<td>2.4</td>
<td>4.6 x 10^4</td>
<td>7.0 x 10^3</td>
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<td></td>
<td>2-1</td>
<td>98.0</td>
<td>7.1</td>
<td>3.0 x 10^5</td>
<td>1.8 x 10^4</td>
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<td></td>
<td>3-2</td>
<td>147.0</td>
<td>14</td>
<td>1.3 x 10^6</td>
<td>7.0 x 10^4</td>
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<td>HCO(^+)</td>
<td>1-0</td>
<td>89.2</td>
<td>4.3</td>
<td>1.7 x 10^5</td>
<td>2.4 x 10^3</td>
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<td></td>
<td>3-2</td>
<td>267.6</td>
<td>26</td>
<td>4.2 x 10^6</td>
<td>6.3 x 10^4</td>
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<td>HCN</td>
<td>1-0</td>
<td>88.6</td>
<td>4.3</td>
<td>2.6 x 10^6</td>
<td>2.9 x 10^4</td>
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<td></td>
<td>3-2</td>
<td>265.9</td>
<td>26</td>
<td>7.8 x 10^7</td>
<td>7.0 x 10^5</td>
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<td>( \text{H}_2\text{CO} )</td>
<td>2_{12}^{-1}_{11}</td>
<td>140.8</td>
<td>6.8</td>
<td>1.1 x 10^6</td>
<td>6.0 x 10^4</td>
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<td></td>
<td>3_{13}^{-2}_{12}</td>
<td>211.2</td>
<td>17</td>
<td>5.6 x 10^6</td>
<td>3.2 x 10^5</td>
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<tr>
<td></td>
<td>4_{14}^{-3}_{13}</td>
<td>281.5</td>
<td>30</td>
<td>9.7 x 10^6</td>
<td>2.2 x 10^6</td>
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<td>( \text{NH}_3 )</td>
<td>(1,1)</td>
<td>23.7</td>
<td>1.1</td>
<td>1.8 x 10^3</td>
<td>1.2 x 10^3</td>
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<tr>
<td></td>
<td>(2,2)</td>
<td>23.7</td>
<td>42</td>
<td>2.1 x 10^3</td>
<td>3.6 x 10^2</td>
</tr>
</tbody>
</table>


Measurement of Core Temperatures

Although almost any optically-thick rotational ladder may work, the \textit{inversion spectrum} of \( \text{NH}_3 \) is the most useful. The basic reference is Townes & Schawlow, Ch. 12.

In the ground state, the N atom is located on either side of the 3 H atoms in the plane. To get to the other side, it has to tunnel through the potential barrier, whose height is \( \sim 2,000 \text{ cm}^{-1} \). The tunneling frequency is very small and is in the cm radio band.

Similar splittings occur for methanol (\( \text{CH}_3\text{OH} \)).
**NH₃ Temperature Measurement**

NH₃ is a symmetric rotor with a dipole moment of 1.48 D. The allowed rotational transitions satisfy |ΔJ| = 1 and ΔK = 0, but the frequencies are so high they require space observations.

But the levels are split by tunneling in the 25-GHz band that depends on (J,K). The transitions usually observed are at the bottom of each K-ladder. The splittings of these (K,K) levels are:

- (1,1) 23.694 GHz
- (2,2) 23.723 GHz
- (3,3) 23.870 GHz
- (4,4) 24.139 GHz
- (5,5) 24.533 GHz
- (6,6) 25.056 GHz

The hyperfine splittings are also shown.

**NH₃ Temperatures**

The beauty of measuring the inversion transitions of the NH₃ (K,K) levels is that they span a large range of excitation temperature but require measurements in just one radio band (using the same instrumentation for all transitions). The transitions listed above cover the temperature range up to 500 K.

This is to be contrasted with a non-hydride rotor like CO where a large range of excitation temperatures can only be achieved by using different telescopes with different resolution.

The often used (J,K)=(1,1) level occurs at 1.27 cm and has a moderate critical density.
Shapes of Molecular Cloud Cores
Myers et al. 376 561 1991

Notice the different map sizes for CO, CS and NH$_3$, and the elongation in the case of C$^{18}$O

Survey of 264 NH$_3$ Cores

\begin{tabular}{ccc}
NH$_3$ Column & Radius & Aspect Ratio \\
\end{tabular}

![Graphs showing distributions of core gas properties: column density, NH$_3$ (cm$^{-3}$), core size, R (pc), and aspect ratio.](image)

Fig. 1: Distributions of the core gas properties: column density, N$_{NH_3}$ (cm$^{-3}$), core size, R (pc), and aspect ratio, a/R, for the entire sample containing all cores as well as subsamples defined by the IRAS and cluster criteria. Refer to Tables B1-B3 for the statistics and to J for a discussion.
Jijina et al. NH$_3$ Core Survey

Line width  Temperature  Velocity gradient

Fig. 3.—Distributions of the core gas properties: intrinsic velocity, $\Delta v_\text{int}$ (km s$^{-1}$), kinetic temperature, $T_\text{kin}$ (K), and velocity gradient, $V_\text{grad}$ (km s$^{-1}$ pc$^{-1}$), for the core sample containing all cores as well as for subsamples defined by the IRAS and cluster criteria. Refer to Tables B1-83 for the statistics and to §3 for a discussion.

Jijina et al. NH$_3$ Core Survey

Mass distribution

Fig. 3.—Distributions of the core mass distributions, $M_{\text{core}}/M_{\odot}$, for the core sample containing all cores as well as for subsamples defined by the IRAS and cluster criteria. Refer to Tables B1-83 for the statistics and to §3 for a discussion.
Non-Thermal vs. Thermal Core Line Widths
Myers (Crete 1999)

Typical FWHM: 0.5 km s\(^{-1}\)

Turbulent cores are warmer than quiescent cores

Consistency of Cores and Virial Equilibrium

- Models of virial equilibrium (funny symbols) easily fit the observations (solid circles [NH\(_3\)] and squares [C\(^{18}\)O]).
- The Larson/Solomon relations would imply that both the ordinate and abscissa are near constant. Myers’ data seemed to illustrate this approximately for a diverse sample of cores.
- Linewidth-size relations have been found for the larger cores
  \[ \Delta v \sim R^p \quad 0.3 < p < 0.7 \]
  until the cores are dominated by thermal rather than turbulent motions (Goodman et al. ApJ504 223 1998)
Observed Core Properties

1. associated with star formation: 50% or more have embedded protostars (Spitzer found a few more)
2. elongated (aspect ratio \( \sim 2:1 \))
3. cold: \( T \sim 6 - 30 \) K
4. internal dynamics dominated by thermal or turbulent motion: Myers’ NH\(_3\) cores are roughly equally split between thermal and non-thermal.

\[
\Delta v_{\text{FWHM}}^2 = \Delta_{\text{turb}}^2 + 8 \ln 2 \left( \frac{kT}{m} \right)
\]

\[
\Delta v_{\text{th}} = \sqrt{8 \ln 2 \left( \frac{kT}{m} \right)} = 0.675 \text{ km s}^{-1} \sqrt{\frac{m_{\text{H}_2}}{m} \left( \frac{10 \text{ K}}{T} \right)}
\]

5. typical size: \( R \sim 0.1 \) pc
6. ionization: \( x_e \sim 10^{-7} \)

7. approximate virial equilibrium
8. size-linewidth relation may apply
   An interesting exception is the Pipe Nebula (Lada et al. 2008)
9. mass spectrum similar to GMCs

Figure 6. The mass spectrum of dense cores in the L1448 cloud from the study of H. The spectrum can be characterized by a power law with an index of -4.6.

The fact that different definitions of clump were employed in each case [26, 132].
6. Comments on Stability of Cloud Cores

Summary of molecular cloud core properties,
Many of which still need to be quantified

1. Location of star formation
2. Elongated (aspect ratio ~ 2:1)
3. Internal dynamics dominated by thermal
   or by turbulent motion
4. Often in approximate virial equilibrium
5. Temperature: $T \sim 5 - 30$ K
6. Typical size: $R \sim 0.1$ pc
7. Ionization fraction: $x_e \sim 10^{-7}$
8. Size-line width relation may apply
9. Mass spectrum similar to GMCs.

First Consideration of Core Stability

- Virial equilibrium might be an appropriate state from
  which cores proceed to make stars. However, a
  significant fraction of cores have embedded
  protostars (IRAS observations). They can’t be
  quiescent forever.

- Core stability is an important issue, e.g., why are they
  stable (if they are), and how do they become de-
  stabilized and collapse under gravity to form stars?

- Although Myer’s data suggest thermal and/or non-
  thermal) pressure may stabilize cores against collapse,
  other possibilities need to be considered, in particular
  rotation and magnetic fields.
Effects of Rotation

Molecular cloud cores have modest velocity gradients, 0.4 - 3 km s\(^{-1}\) pc\(^{-1}\) and angular speeds \(\Omega \sim 10^{-14} - 10^{-13}\) rad s\(^{-1}\).

\[ \beta = \frac{E_{\text{rot}}}{E_{\text{grav}}} \sim 0.02 \]

Cores do not appear to be supported by rotation.

NB Not all of the observed gradients correspond to the overall rotation of the core.

Magnetic Fields

- Magnetic fields are difficult to measure in cloud cores with the Zeeman effect.
- Example of dark cloud B1:
  \(|B| \cos \theta \approx -19 \pm 4\, \mu\text{G}
  B^2 / 8\pi \sim 3 \times 10^5\, \text{K cm}^{-3}
- This value of \(B^2 / 8\pi\) is much greater than the thermal pressure of a 10 K core with \(n \sim 10^3\, \text{cm}^{-3}\). Cores do have higher densities, whereas OH probes \(n_H \approx 10^3\, \text{cm}^{-3}\).
- Magnetic fields are potentially important.