22: Collapse & Fragmentation of Molecular Clouds

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Molecular Cores

- Initial conditions represent a substantial problem in star formation
- The study of star formation is intrinsically linked with the study of dense cores, the birthplace of stars
  - Progress has been made in the last few decades, since the radio astronomy made it possible to probe these dense regions in molecular clouds
  - Important tracers are CS and NH$_3$
- Cloud core properties serve as the initial conditions that likely determine the characteristics of the star(s) that form within them
  - Benson & Myers 1989 ApJS 71 743
  - Jijina et al. 1999 ApJS 125 161
# Dense Gas Tracers

<table>
<thead>
<tr>
<th>Molecule</th>
<th>Transitions</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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Molecular Cloud Cores

Fig. 1a — Half-maximum intensity contours of 16 dense cores in dark clouds, in the 1.3 cm (J, K) = (1,1) lines of NH$_3$, from Benson & Myers (1989), and in the 3.0 mm $J = 2 \to 1$ line of CS, and the 2.7 mm $J = 1 \to 0$ line of C$^{18}$O, from Fuller (1989). For each map, North is up, East is left, and the linear scale 0.2 pc is indicated. A cross indicates an associated star.
Molecular Cloud Cores

• Typically < 10% of the area of a GMCs is detected in dense gas tracers such as CS or NH$_3$
  – Typical molecular gas is defined as that traced by $^{12}$CO 1-0
  – Dense gas is non-uniformly distributed through the cloud within numerous discrete and localized cores

• The first stage of star formation starts from a process of contraction of molecular cloud cores

• Observations of the NH$_3$ J=1, K=1
  – Cold (kinetic temperature ($T_K \approx 10$ K) dense ($n_H \approx 10^4$ cm$^{-3}$) condensations
  – Size 0.1 pc (20,000 AU)
  – Mass of a few $M_\odot$
    • Properties depend on what molecular tracer is employed
Jijina et al. \textit{NH}_3 \textit{Core Survey}
Jijina et al. NH$_3$ Core Survey
Jijina et al. NH$_3$ Core Survey
Conditions for Collapse

• Supersonic motions are observed in molecular clouds
  – Approach thermal line widths on small scales

• If cloud cores make stars, then they must be gravitationally bound
  – For thermal support
    \[ GM/R \sim c^2 = kT/\mu m \]

\( c \) is the sound speed and \( \mu \approx 2.3 \) is the mean molecular \( R \approx 0.1 \left( M / M_\odot \right) \left( 10 \text{ K} / T \right) \text{ pc} \)
Rotation

- Most molecular cloud cores have modest spatial velocity gradients
  - $300 - 3000 \text{ m s}^{-1} \text{kpc}^{-1}$
  - $\Omega \sim 10^{-14} - 10^{-13} \text{ rad s}^{-1}$

- At the upper end of this range a core with $R \sim 0.1 \text{ pc}$ has a rotational component of $300 \text{ m s}^{-1}$
  - Comparable to thermal velocity
  - Rapid rotation is uncommon and most cores do not appear to be supported by rotation
Non-Thermal Pressure

- Magnetic fields are hard to measure in cloud cores
  - OH absorption measurements are difficult because of the small chance of a background radio source
- Single measurement of $|B| \cos \theta \approx -19 \pm 4 \ \mu G$ towards the B1 molecular cloud in the Perseus star forming region
  - OH probes $n_H \approx 10^3 \ cm^{-3}$
- $B^2/8\pi \approx 3 \times 10^5 \ K \ cm^{-3}$
  - Comparable to the thermal pressure of a 10 K core with $n \approx 10^4 \ cm^{-3}$
Magnetic Fields

- 850 μm polarimetry toward B1 shows polarized continuum emission
  - Aligned grains and hence a component of the magnetic field in the plane of the sky
  - No correlation between the polarization angles measured in optical polarimetry.

- The polarized emission from the interior is consistent with OH Zeeman data if the total uniform field strength is ~ 30 μG

Core Fragmentation

- Cores condense out of lower density regions of GMCs
  - How this happens is unclear
  - Formation of self-gravitating cores may be related to gravitational instabilities
    - Classical approach invokes the Jeans instability
  - Consider a uniform, isothermal gas
    - Hydrostatic equilibrium: gravity balanced by pressure gradient
  - Now suppose a spherical region is perturbed
    - $\rho \rightarrow X \rho$, where $X > 1$
Core Fragmentation

• In this disturbed system with over-density $X\rho$ within a radius $r$ there will be an outward pressure force per unit mass
  
  \[ F_p \sim \nabla P / \rho \sim Xc^2 / r \]

• The high density leads to an inward gravitational force per unit mass
  
  \[ F_G \sim GM / r^2 \sim GX\rho_0 r \]

• Gravity wins if
  
  \[ r^2 > \frac{c^2}{G\rho_0} \]
The Jeans Length & Mass

• Compare with the Jeans length

\[ \lambda_J^2 = \frac{\pi c^2}{G\rho_0} \]

• The corresponding mass is

\[ M_J = \lambda_J^3 \rho_0 = \left( \frac{\pi c^2}{G} \right)^{3/2} \rho_0^{-1/2} \]

• Length scales > \( \lambda_J \) or masses > \( M_J \) are unstable against collapse

• \( M_J \approx 7.5 \ T_{10}^{3/2} \ (n_{\text{H}_2} / 10^4 \ \text{cm}^{-3})^{-1/2} \ \text{M}_\odot \)
Jeans Analysis

• How relevant is a Jeans analysis?
  – Molecular clouds are not static
  – Turbulent on large scales
    • Turbulence provides and effective pressure support
      – $(kT/\mu m)^{1/2} \approx 0.19 \ (T / 10 \text{ K})^{1/2} \text{ km/s}$
      – Typical non-thermal line widths on pc scales are $\approx 0.6 \text{ km/s}$ on scales of a few pc

• Supersonic motions must be dissipated by shocks before collapse can proceed
  – As the gas condenses the Jeans mass decreases
    • $M_j \sim \rho^{-1/2}$
    • Suggests fragmentation (Hoyle 1953 ApJ 118 513)
Fragmentation?

- The dispersion relation for a perturbation $\delta \rho \sim e^{i(\omega t - kx)}$ in the Jeans problem is
  \[ \omega^2 = c^2 k^2 - 4\pi G \rho_0 \]
  or
  \[ \omega^2 = c^2 (k^2 - k_J^2), \quad k_J^2 = \frac{4\pi G \rho_0}{c^2} \]

- $k^2 - k_J^2 < 0$ makes $\omega$ imaginary
  - Exponential growth when $k < k_J$
  - Growth rate rate, $-i\omega$, increases monotonically with decreasing $k$
    - Longest wavelength perturbations (largest mass) grow fastest
    - Fastest collapse of the largest scales suggests fragmentation unlikely (Larson 1985 MNRAS 214 379)
Swindled by Jeans?

- The dispersion relation for a thin sheet of surface density $\Sigma$ is

$$\omega^2 = c^2 k^2 - 2\pi G \Sigma |k|$$

or

$$\omega^2 = c^2 ( k^2 - k_c |k| )$$

Exponential growth occurs for

$$k < k_c = 2\pi G \Sigma / c^2$$

with growth rate

$$-i \omega = ( 2\pi G \Sigma k - c^2 k^2 )^{1/2}$$

which is maximum at $k_f = k_c / 2 = \pi G \Sigma / c^2$

Preferred mass of $M_f \sim (2\pi / k_f)^2 \Sigma = 4 c^4 / G^2 \Sigma$
Preferred Length & Mass

• Assume the cores in the Taurus dark cloud are sheets
  – \( A(V) \approx 5 \) mag. or \( \sum \approx 0.032 \) g cm\(^{-2}\)
  – \( T = 10 \) K, \( c = 0.19 \) km/s
    • \( \lambda_c \approx 0.05 \) pc
    • \( \lambda_f \approx 0.1 \) pc, \( M_f \approx 2 \) M\(_\odot\)
    • \( t_f = \frac{\lambda_f}{\pi c} \approx 2 \times 10^5 \) yr

• More realistic analyses tend to show that when thermal pressure provides the dominant support against gravity there is a minimum length & mass scale which can grow
  – If the cloud is non-uniform there is a preferred scale
    • Typically \( \sim \) few times the characteristic length of the background, e.g., the scale height, \( H = \frac{c^2}{\pi G \Sigma} \), for a gaseous equilibrium sheet (Larson 1985 MNRAS 214 379)
Virial Theorem (Shu Vol. 2 Ch 24)

- An alternative approach begins by considering the stability of cores with well defined surfaces
  - The virial theorem is derived from $f=ma$

$$\rho \frac{D\vec{v}}{Dt} = -\vec{\nabla}P - \rho \vec{\nabla}\phi + \vec{\nabla} \cdot \vec{T}$$

$$T_{ij} = B_iB_j / 4\pi - B^2\delta_{ij} / 8\pi$$

$$\vec{\nabla} \cdot \vec{T} = -\frac{1}{8\pi} \nabla B^2 + \frac{1}{4\pi} (\vec{B} \cdot \vec{\nabla})\vec{B}$$
Virial Theorem

- The Virial theorem approach advocates that the equation of motion contains too much information
  - Take moments, specifically the first moment

\[ \int_V (\vec{f} \cdot \vec{r}) dV = \int_V (m\vec{a} \cdot \vec{r}) dV \]
Virial Theorem

- Take the dot product with \( \mathbf{r} \) and integrate over volume
  - The Virial theorem relates to integrated properties of the cloud

\[
\int_V \rho \dddot{\mathbf{r}} \cdot \mathbf{r} \, dV = \frac{1}{2} \frac{D^2}{Dt^2} \int_V (\dddot{\mathbf{r}} \cdot \mathbf{r}) \rho \, dV - \int_V (\dddot{\mathbf{v}} \cdot \mathbf{v}) \rho \, dV
\]

Since

\[
\frac{D^2}{Dt^2} (\dddot{\mathbf{r}} \cdot \mathbf{r}) = 2 (\dddot{\mathbf{r}} \cdot \dot{\mathbf{r}} + \dddot{\mathbf{r}} \cdot \dot{\mathbf{r}})
\]
Virial Theorem

• The LHS yields two terms
  – Moment of inertial $I$
  – Kinetic energy $E_k$

\[
\frac{1}{2} \frac{D^2}{Dt^2} \left( \int_v r^2 dm \right) - \int_v v^2 dm = \frac{1}{2} \frac{D^2 I}{Dt^2} - 2E_k
\]

where

[\[ dm = \rho dV \]]

• If the cloud is static both terms are zero
  – If the cloud is turbulent or rotating then $E_k \neq 0$
Virial Theorem

- The RHS yields volume & surface terms

\[
\int_v 3P \, dV + \int_v \frac{B^2}{8\pi} \, dV - \int_v (\vec{r} \cdot \vec{\nabla} \phi) \, dm
\]

\[
- \int_s \left( P + \frac{B^2}{8\pi} \right) \vec{r} \cdot d\vec{S} + \frac{1}{4\pi} \int_s (\vec{r} \cdot \vec{B})(\vec{B} \cdot d\vec{S})
\]

- Thermal, magnetic and gravitational potential energy volume integral
- Thermal and magnetic surface terms
  - Magnetic field appears twice because of isotropic pressure and tension terms
Virial Theorem

• Consider a spherical, isothermal, unmagnetized cloud in equilibrium ($D^2 I/Dt^2 = 0$) of mass, $M$, and radius, $R$

\[ 0 = \int \limits_V 3P \, dV - \int \limits_V \left( \overline{r} \cdot \overline{\nabla} \phi \right) \, dm - \int \limits_S P \, \overline{r} \cdot d\overline{S} \]

\[ 0 = 3c^2 M - \frac{3}{5} \frac{GM^2}{R} - 4\pi R^3 P \]

– If the cloud properties $M$ and $c$ (temperature) are constant and the environmental pressure $P$ is fixed
  • Sets the relation between $M$ and $R$
Virial Theorem

• If we ignore gravity ($G=0, R \to \infty$) internal and external pressure must balance, $P \sim R^{-3}$

\[ 0 = 3c^2 M - \frac{3}{5} \frac{GM^2}{R} - 4\pi R^3 P \]

– If $G \neq 0$ (finite $R$) the gravitational term dominates lowering the pressure needed to confine the cloud

\[ P = \frac{3c^2 M}{4\pi R^3} - \frac{3}{20} \frac{GM^2}{\pi R^4} \]
Virial Theorem

- There is a minimum radius where the cloud can no longer support itself against gravity

\[ P = \frac{3c^2 M}{4\pi R^3} - \frac{3}{20} \frac{GM^2}{\pi R^4} \]

- Beyond the critical point self-gravity decreases \( R \) without any help from \( P \)
- Equilibria states which require \( P \) to decrease with decreasing \( R \) are unstable
Stable and Unstable Virial Equilibria

- For a given $P$ there are two equilibria
  - Squeeze the cloud at $B$
    - Requires more pressure to confine it at its new radius
    - Re-expand (stable)
  - Squeeze the cloud at $A$
    - Requires less pressure to confine it
    - Contract (unstable)
Stable and Unstable Virial Equilibria

- The critical pressure is

\[
\frac{dP}{dR} = \frac{d}{dR} \left( \frac{3c^2 M}{4\pi R^3} - \frac{3}{20} \frac{GM^2}{\pi R^4} \right) = -\frac{9c^2 M}{4\pi R^4} + \frac{12}{20} \frac{GM^2}{\pi R^5} = 0
\]

\[
R_{\text{crit}} = \frac{4}{15} \frac{GM}{c^2}
\]

The critical mass

\[
M_{\text{crit}} = 4\pi R_{\text{crit}}^3 / 3 = \left( \frac{3}{4\pi} \right)^{1/2} \left( \frac{15}{4} \right)^{3/2} \left( \frac{c^2}{G} \right)^{3/2} \rho^{-1/2}
\]

- Same as the Jeans mass to factors \( \sim 1 \)
Virial Stability

- NH$_3$ Observations of cores in the Taurus dark cloud indicate $T \approx $ const.
  - For CR heating balanced by rotational CO cooling $T$ is weakly dependent on density
  - Isothermal assumption may be valid

$$\frac{\rho}{c^2} = \frac{45}{16\pi GR_{\text{crit}}^2}$$

Myers & Benson 1983 ApJ 266 309
Fragmentation vs. Stability

• Both approaches yield a similar characteristic “Jeans” mass
  – Distinction lies in the initial conditions
    • Cloud scenario assumes a self-gravitating cloud core in hydrostatic equilibrium
      – The cloud may or may not be close to the critical condition for collapse
    • In the gravitational fragmentation picture there is no “cloud”
      – It cannot be distinguished from the background until it has started to collapse
  – Both view points may be applicable to different parts of GMCs
    • There are pressure confined clumps in GMCs
      – Not strongly self-gravitating
    • Cores make stars
      – Must be self-gravitating
      – If fragmentation produces cores these must be collapsing and it is too late to apply virial equilibrium
Fragmentation vs. Stability

• Relevant question how quickly cores form (relative to the dynamical time scale)
  – NH$_3$ cores do seem to be close to virial equilibrium but they could be contracting (or expanding) slowly

• Statistics of cores with and without stars should reveal their ages
  – If cores are stable there should be many more cores without stars than with young stars
  – Comparison of NH$_3$ cores and IRAS sources suggests ~ 1/4 of cores have young stellar objects (Wood et al. 1994 ApJS 95 457)
    • Corresponding life time is < 1 Myr (Onishi et al. 1996 ApJ 465 815)
Magnetized Cloud

• Assume a uniformly magnetized cloud
  – Approximately dipole energy density outside
    • $B(r) \sim B(R/r)^{-3}$
    • Evaluate the virial theorem at a radius $>> R$
      
      $$0 = 3c^2 M - \frac{3}{5} \frac{GM^2}{R} + \frac{1}{3} R^3 B^2 - 4\pi R^3 P$$

      Magnetic flux is

      $$\Phi = \pi R^2 B = \text{const.}$$

      for a good conductor

• Gravitational and magnetic terms $\sim 1/R$
  i.e., they remain in constant proportion
Magnetized Cloud

• If the magnetic pressure cannot prevent collapse at one stage it cannot prevent it at a later one
  – Conversely flux freezing implies that magnetically dominated clouds will continue to resist collapse

• The gravitational energy exceeds the magnetic energy if $M$ is greater than some critical value

$$M_B = \frac{1}{\pi} \left( \frac{5}{9G} \right)^{1/2} \Phi$$
Magnetized Cloud

• Collapse can only proceed if $M > M_B$
  – Calculations for more realistic clouds
  • e.g, flattened & centrally condensed

$$M_B \approx 0.13 G^{-1/2} \Phi = 1.0 \left( \frac{B}{20 \mu G} \right)^3 \left( \frac{R}{0.1 \text{ pc}} \right)^2 M_\odot$$

– A 1 $M_\odot$ core can only collapse if $B < 20 \mu G$
Observations

<table>
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<tr>
<th>Cloud</th>
<th>$B_{nuc}$ (μG)</th>
<th>log $N$ (H$_2$ cm$^{-2}$)</th>
<th>log $n$ (H$_2$ cm$^{-3}$)</th>
<th>$\Delta V$ (km s$^{-1}$)</th>
<th>$T_K$ (K)</th>
<th>$R$ (parsec)</th>
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<td>1.0</td>
<td>10</td>
<td>1.2</td>
</tr>
<tr>
<td>L889</td>
<td>$&lt;7$</td>
<td>22.0</td>
<td>3</td>
<td>2.1</td>
<td>13</td>
<td>2.4</td>
</tr>
<tr>
<td>Tau 16</td>
<td>$&lt;7$</td>
<td>21.7</td>
<td>3</td>
<td>1.0</td>
<td>10</td>
<td>1.2</td>
</tr>
</tbody>
</table>
Magnetic Fields in Dense Gas

• Observations show that magnetic fields play an important role in shaping the structure and dynamics of molecular clouds
  – Polarization maps reveal that there is a magnetic field threading the molecular clouds that is ordered over large scales
  – Zeeman measurements imply that measured fields are invariably strong enough to yield a mass-to-flux ratio very close to the critical value
Collapse of a Magnetized Cloud

• Gravity amplifies anisotropic structure
  – An initially unstable fragment will first collapse along one dimension, forming a sheet, which will subsequently break into elongated filamentary structures
  – The presence of a large-scale magnetic field can enhance this effect, as the first stage of collapse is preferentially along the mean field direction
Magnetic Correlations

- The correlation of the line-of-sight field strength $B_{\text{los}}$ with the density is in apparent agreement with models of preferential flattening along the magnetic field:
  - $B \sim \rho^k$ with $k = 0.47 \pm 0.08$ rather than isotropic contraction ($B \sim \rho^{2/3}$) fit is to detections only

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*Crutcher 1991 ApJ 520 706*
Magnetic Correlations

• Consider a cloud that is flattened along the mean magnetic field direction
  – In this direction, hydrostatic equilibrium between an isotropic pressure and self-gravity yields
    \[ \rho_0 \sigma^2 = \frac{1}{2} \pi G \Sigma^2 \]
    \( \rho_0 \) is the mid plane density
    \( \sigma \) is the total 1-d velocity dispersion
    \( \Sigma \) is the total column density
  – The relation \( M / \Phi = \Sigma / B \equiv \mu (2\pi \sqrt{G})^{-1} \)
    defines the dimensionless ratio \( \mu \) of the mass-to-flux ratio to the critical value \( (2\pi \sqrt{G})^{-1} \) for a disk
  – Combining these relation
    \[ B = \sigma (8 \pi \rho)^{1/2} / \mu \]
Magnetic Correlations

- Solid line is the best least-squares fit
  - Slope is $1.00 \pm 0.09$
  - Dashed line is the theoretical relation with $\mu = 1$
- The correlation suggests that clouds are flattened along the magnetic field direction, even in the presence of turbulent motions, because of the dynamically important roles of self-gravity and the mean magnetic field.

Basu 2000 ApJL 540 103
MHD Turbulence Simulations

- Li et al. 2004 ApJ 605 800
  - $M_{\text{Cloud}} \sim 64 \, M_\odot$
  - $M_{\text{Cloud}} / M_{\text{CR}} \sim 8$
  - Followed for $\sim 3$ free-fall times
MHD Turbulence Simulations