Prestellar Cores

- formation and structure

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Outline

• Observation
• Definition and classification
• Typical core
• Size distribution
• Physics in Play
  • Gravity and magnetic fields: Important mass scales ($M_J$, $M_{BE}$, $M_{cr}$)
  • Turbulence
• Formation models
• Initial formation and evolution
• Summary
Taurus Molecular Cloud

Bergin & Tafalla (2007)
Observation & Classification

- Cores - High density peaks in GMC:

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(^5)</td>
</tr>
<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>
</tr>
<tr>
<td>Examples</td>
<td>Taurus, Oph, Musca</td>
<td>B213, L1709</td>
<td>L1544, L1498, B68</td>
</tr>
</tbody>
</table>

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

\(^b\)Clump properties from Loren (1989) (\(^{13}\)CO data) and Williams, de Geus & Blitz (1994) (CO data).

\(^c\)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\(^+\).

Bergin & Tafalla (2007)
Observation & Classification

Before collapse:
• Starless cores ($^{18}\text{O}, \text{NH}_3, \text{dust extinction}$)
• Prestellar cores (starless but self-gravitating, dust continuum emission, $\text{NH}_3, \text{N}_2\text{H}^+$)

After collapse (More in Andrea’s talk):
• Class 0 protostellar cores (result from gravitational collapse: $M_{\text{star}} \ll M_{\text{env}}$)
• Class I, II, III protostars and YSOs
Barnard 68

Visible

Near infrared

Alves et. Al. (2001)
Summary of core properties I

- (Median?) Size: $2 M_\odot$, 0.1pc
- Density: $(10^4-10^7 \text{ cm}^{-3})$
  dust emission (absorption) => $N(\text{dust})$=>$N(\text{gas})$
- Molecular lines
- Temperature: (dust: 15-20K ; gas: 10-12 K)
  Well coupled by collision

Bergin & Tafalla (2007)
Summary of core properties:

- **Velocity structure:**
  - External: supersonic (Sasha’s talk)
  - Internal: subsonic
  - \( C_s \approx 0.2, 0.66, 2 \) km/s for 
  - \( T \approx 10, 100, 1000 \) K

- **Magnetic field:**
  - Zeeman splitting and polarization measurement
  - (>5-10 \( \mu \) G)

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Core life time

Andre et. al. (2008)
Core Mass Function
CMF
More in Elisa’s talk

Alves (2007)

Andre et. al. (2010)
Physics in play:

Gravity, Magnetic field, Turbulence, and more …
Self Gravity

- Jeans Mass vs Boner-Ebert Mass

Jeans Mass: an infinite homogeneous gravitating system:

\[ M_J = \left( \frac{4\pi}{3} \right) \rho R_J^3 = \left( \frac{\pi}{6} \right) \frac{c_s^3}{G^{3/2} \rho^{1/2}} \approx (2 \, M_\odot) \left( \frac{c_s}{0.2 \, \text{km s}^{-1}} \right)^3 \left( \frac{n}{10^3 \, \text{cm}^{-3}} \right)^{-1/2}. \]

In discussing formula (1.2) Terletsky seems to have in mind a static mass of gas of uniform density. This is unsatisfactory because if the mass is finite the equation of hydrostatic equilibrium is not satisfied.

In this paper I obtain the equation of state for a large gas sphere of constant mass and temperature, but non-uniform density, and I construct its \( p-V \) curve. This amounts to an investigation of the equilibrium under its own gravitation and an applied external pressure of an isothermal gas sphere containing a fixed mass.

Bonnor 1956
Bonnor-Ebert Mass

- For a pressure bound isothermal sphere:
  The virial theorem gives:

\[ 0 = \frac{3}{2} M \sigma^2 - 4\pi R^3 P_S - a \frac{GM^2}{R}, \]

The maximum allowed external pressure => the maximum allowed enclosure mass

\[ P_S = \frac{3^7 \sigma^8}{2^{14} \pi a^3 G^3 M^2}. \]

\[ M_{BE} \approx 1.18 \frac{\sigma^4}{G^{3/2} P_S^{1/2}} = 0.47 M_\odot \left( \frac{\sigma}{0.2 \text{ km s}^{-1}} \right)^4 \left( \frac{P_S}{k_B} \right)^{-1/2}. \]

For typical prestellar cores: \( M_{BE} \approx 1.18 M_J \)
A self-gravitating, pressure confined isothermal sphere

Alves et. al. (2001)
Ways to support the cores against self-gravity:

Magnetic field

\[ t_{\text{core}} > t_{\text{ff}} \]

Andre et.al. (2008)
Role of Magnetic Fields?

Magneticphobic

vs.

Magnetic

-Aholic
Magnetic fields in interstellar clouds

Crutcher (2010)

Alves (2008)

Polarization measurement in Pipe

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Magnetic Critical mass

• Let’s look at the virial theorem including the magnetic term:

\[ \frac{1}{2} \ddot{I} = 2(T - T_s) + \mathcal{M} + \mathcal{W} \]

\[ T_s = \int_S rPdS \]

\[ \mathcal{M} = \frac{1}{8\pi} \int_V (B^2 - B_0^2) dV. \]

Spherical cloud and uniform magnetic field:

\[ \mathcal{M} \approx \frac{B^2 R^3}{6} - \frac{B_0^2 R_0^2}{6} = \frac{1}{6\pi^2} \left( \frac{\Phi_B^2}{R} - \frac{\Phi_B^2}{R_0} \right) \approx \frac{\Phi_B^2}{6\pi^2 R}. \]

\[ \mathcal{M} + \mathcal{W} = \frac{\Phi_B^2}{6\pi^2 R} - \frac{3GM^2}{5} \equiv \frac{3}{5} \frac{G}{R} \left( M_\Phi^2 - M^2 \right) \]

\[ M_\Phi \equiv \sqrt{\frac{5}{2}} \left( \frac{\Phi_B}{3\pi G^{1/2}} \right) \]

\[ M_{cr} = 0.13 \frac{\Phi}{G \nu^{1/2}} \approx 10^3 M_\odot \left( \frac{B}{30 \mu G} \right) \left( \frac{R}{2 \text{pc}} \right)^2. \]

<0 supercritical

>0 subcritical
Standard Model  
(Shu, Adams & Lizano 1987)

- **Supercritical** - Magnetically diluted fragmentation  
High mass star formation or high star formation efficiency

- **Subcritical** - dominated by the time scale of ambipolar diffusion  
Low mass star formation and low star formation efficiency.

\[
\tau_{slip} = \frac{L}{2|v_i - v_n|} \approx 7 \times 10^7 n_4^{-1.42} \text{ yr.}
\]

(Drain 2011)
Turbulence

Transient (decaying) Turbulence

• Supersonic in the gas and cores;
• Core-to-Core dispersion higher than gas dispersion

Regenerated (driven) Turbulence

• Supersonic outside cores, transsonic inside cores;
• Core-to-Core dispersion similar to that of gas;

Offner (2008)
Formation Scenarios (I)  
Initial CMF

- Gravitational Fragmentation (linear perturbations)
- Turbulent Fragmentation (non-linear perturbations)

Andre et.al. (2008)
Formation Scenarios (II)

Evolution

- Relevant Time Scales:

**Freefall:**

\[ t_{ff} \approx \frac{3\pi}{32G\rho} \approx 0.9\text{Myr} \left( \frac{2 \times 10^3 \text{cm}^{-3}}{n_{H_2}} \right)^{1/2} \]

**Sound crossing time:**

\[ t_{cs} = \frac{2R_c}{C_s} \approx 1\text{Myr} \frac{R_c}{0.1\text{pc}} \frac{0.2\text{km/s}}{C_s} \]
Formation Scenarios (II) Evolution

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Collision: 
\[ \tau_{\text{coag}} \sim \frac{1}{2\pi R_c^2 n_c \sigma} = 1\text{Myr} \left( \frac{R_c}{0.1\text{ pc}} \right) \left( \frac{f_f}{0.1} \right)^{-1} \left( \frac{\sigma}{2\text{ km/s}^{-1}} \right)^{-1} \]
Evidence for core collision

Barnard 68
Formation Scenarios (II)

Evolution

- Relevant Time Scales:

  
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  **Mass loss:**
  
  for example, Kelvin-Helmholtz instability (unbound cores)

\[ \tau_{\text{KH}} = \left( \frac{\sigma}{R_c(m) D_r^{1/2}} \right)^{-1} = 1\text{Myr} \left( \frac{\sigma}{\text{kms}^{-1}} \right)^{-1} \left( \frac{R_c(m)}{0.1\text{pc}} \right) \left( \frac{D_r}{100} \right)^{1/2} \]
KH instability for a core in the wind

Murray et.al 1993
Fabian & Hartmann (2008)

\[ t = 0.76 \, \text{Myr} \]
Summary

• Cores are density peaks in GMCs.
• The core mass distribution may resemble IMF
• Magnetic fields and turbulence are important in the formation of cores.
• Other physics processes such as accretion may also be important in the evolution of cores.
• Need more data to constrain the models

$t \sim 1 \text{Myr}$  \hspace{2cm} $M \sim 1 \text{M}_\odot$
Reference

• http://ned.ipac.caltech.edu/level5/Sept10/Krumholz/Krumholz_contents.html
• Andre,P. et. al.(2010) From filamentary clouds to prestellar cores to stellar IMF: Initial highlights from the Herschel Gould Belt Survey
• Bergin & Tafalla (2007) Cold dark clouds: the initial conditions for star formation
• Bonnor (1956) Boyle’s law and gravitational instability
• Drain (2011) Physics of the interstellar and intergalactic medium; Chapter 32,41
• Shu, Lizano and Adams (1987) Star formation in molecular cloud
Thanks for listening...
Pipe Nebula (Lada 2008)
Appendix

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Formation of cores in Simulation
Offner (2008)