Lecture 5: Molecular Clouds (2)
Dense Cores

Dense Cores within Molecular Clouds

“Starless” Core L1014

Spitzer Space Telescope • IRAC • MIPS

Visible

Infrared

NH$_3$ cores
(Benson & Myers 1989)

C$^{18}$O
Onishi et al. 1998
M $\sim$ 5x10$^4$ M$_\odot$

TMC-2
N$_2$H$^+$(1-0)
M $\sim$ 5 M$_\odot$
0.3 ly

SFR $\sim$ 2 M$_\odot$ yr$^{-1}$
Isolated Clouds (also known as Bok globules)

- small, dense, almost spherical clouds

- typical parameters:
  - $T \sim 10$ K, number densities $n \sim 10^4$ cm$^{-3}$, masses 10-50 $M\odot$, sizes $\sim 1$ pc
  - infrared surveys reveal many harbor young stars in their centres active star formation sites - but mainly low-mass stars

Tracers of Core Structure

- Molecular lines (CO, CS, NH$_3$, etc): different molecular lines trace conditions of different densities and temperatures (see next lecture). Also, some molecules may become frozen-out onto the surface of dust grains to form ice mantles.

- sub-mm and mm dust thermal emission (Wien’s law) - i.e. modified black body radiation

- dust extinction
Line Widths

Thermal width due to Maxwell-Boltzmann distribution:

\[ T_A(V_r) \propto \exp \left( -\frac{m_X V_r^2}{2k_B T} \right) \]

Thermal root-mean-square value of \( V_r \):

\[ \sigma_{th} = \left( \frac{k_B T}{m_X} \right)^{1/2} \]

Thermal full-width half-maximum extent:

\[ \Delta V_{FWHM,th} = \left( \frac{8 \ln(2) k_B T}{m_X} \right)^{1/2} = 2.355 \sigma_{th} \]

Total line width (thermal + turbulent):

\[ \Delta V_{FWHM,tot}^2 = \Delta V_{FWHM,th}^2 + \Delta V_{FWHM,turb}^2 \]

Ammonia (NH\(_3\)) line at 1.3cm tracing gas in a dense core. Dashed line is thermal profile for T=9K. Solid line is total including contribution from turbulence.
Recall: The line width-size relation (Larson’s law)

\[ \Delta V = \Delta V_0 \left( \frac{L}{L_0} \right)^n \]

\( n \sim 0.5, \Delta V_0 \sim 1 \text{ km/s for } L_0 = 1 \text{ pc} \)

Line widths of cores with and without stars: evidence for some increase in line width in star-forming cores, perhaps due to the bipolar outflows they launch.
Core Shapes

Observed cores have mean observed (i.e. projected) axial ratios ~0.6

What does this imply about their intrinsic 3D shape?

Both oblate and prolate structures are possible.

But structures observed to be very elongated are likely to be prolate (filamentary)

Magnetic Fields

- Measured via polarized emission or absorption from aligned dust grains
- Or from Zeeman splitting of certain molecular lines (molecules with magnetic moment, i.e., due to an unpaired e-) (discussed later)
Polarization of Starlight

The polarization is produced by dust grains. Prior to the scattering event, the incident electric field vector $\mathbf{E}$ oscillates randomly within the plane normal to the propagation direction $\mathbf{n}$.

For the radiation scattered into directions $90^\circ$ from $\mathbf{n}$, the scattered field $\mathbf{E}$ only oscillates along the line that is the projection of the new plane and the old $\mathbf{n}$; the radiation is linearly polarized. Scattering into other directions results in partial polarization ($\mathbf{E}$ oscillates along two orthogonal lines but with unequal amplitude).

If one rotates a polarizing filter in front of a source, the received intensity at any $\lambda$ varies from $I_{\text{min}}$ to $I_{\text{max}}$. The orientation of the polarizer corresponding to $I_{\text{max}}$ is the position angle of $\mathbf{E}$; the degree of polarization is defined to be:

$$P \equiv \frac{I_{\text{max}} - I_{\text{min}}}{I_{\text{max}} + I_{\text{min}}}$$

In the presence of a magnetic field, grains also polarize radiation through dichroic extinction. This is because the particles are irregular structures that tend to rotate about their shortest axes.

Grain material has a small electric charge and is paramagnetic; grains acquire a magnetic moment $\mathbf{M}$ that points along the axis of rotation.

Interaction with the ambient magnetic field then creates a torque $\mathbf{MxB}$ that gradually forces the grain’s short axis to align with the field (in this way the grain sees a time-independent magnetic field as it spins). Thus, grains tend to line up such that their time-averaged projected lengths are longer in the direction $\perp \mathbf{B}$.

The electric field is most effective in driving charges down the body’s long axis. This direction thus becomes the one of maximum absorption of the impinging electromagnetic wave. The electric vector of the transmitted radiation lies along the ambient $\mathbf{B}$. 

Dichroic Extinction
Each line is associated with a star for which the polarization has been measured. The line direction indicates the polarization angle (direction of $\mathbf{E}$, parallel to $\mathbf{B}$ for dichroic extinction) and the length shows the magnitude.

The large-scale field decreases slowly with Galactic radius and height, and has a strength of $\sim 4 \mu \text{G}$ near the Sun. The field is often morphologically related to the interstellar gas -- e.g. parallel or perpendicular to filaments, and systematically oriented in large shells.

**Optical polarization map**

Due to absorption by magnetically aligned dust grains: then direction of $\mathbf{E}$-field vector (shown) is same as $\mathbf{B}$-field.

Magnetic fields appear to influence morphologies of molecular cloud structures and make a significant contribution to core energetics (virial equation)
Core Rotation

We can measure line-of-sight radial velocity gradients across cores from a spectrum at each position.

Typically measure ~1 km/s /pc

Core Rotation

Rotational energy of uniform sphere with diameter $L = 2R$, mass $M$, and angular velocity $\Omega$ ($\Omega = V_{\text{rot}}/R$):

$$T_{\text{rot}} = \frac{1}{20} ML^2 \Omega^2$$

Compare with gravitational energy

$$W = \frac{6}{5} GM^2/L$$

$$\frac{T_{\text{rot}}}{|W|} \approx \frac{\Omega^2 L^3}{24GM}$$

$$= 1 \times 10^{-3} \left( \frac{\Omega}{1 \text{ km s}^{-1} \text{ pc}^{-1}} \right)^2 \left( \frac{L}{0.1 \text{ pc}} \right)^3 \left( \frac{M}{10 M_\odot} \right)^{-1}$$

Cores are not rotationally supported...
But this gives measure of angular momentum at start of gravitational collapse.