Giant Molecular Clouds

Observed properties
Dynamical State
Formation

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The components of the ISM

Diffuse ISM neutral atomic clouds embedded in ionized medium

Dense ISM neutral molecular clouds

Ionized nebulae H II regions, planetary nebulae, supernova remnants

ρ Ophiuchi cloud complex (NASA/WISE).

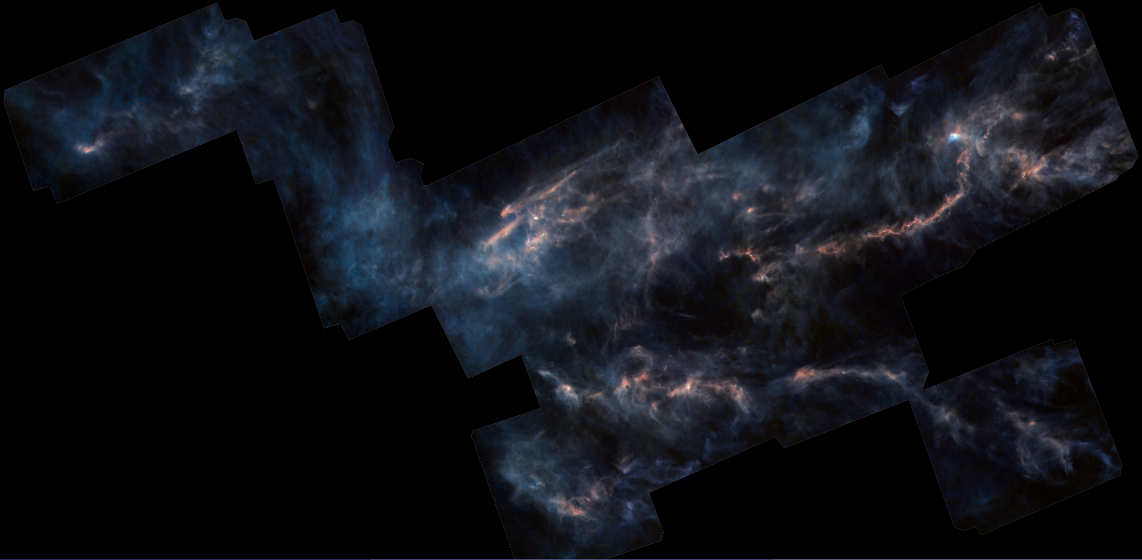
The components of the ISM: Dense ISM

Dense ISM: H, neutral and mostly molecular instead of atomic, in the form of clouds with densities $n_{H_2} = 10 - 10^6$ cm^{-3}. Temperature is $10 - 100$ K, mass is $10^3 - 10^6 M_\odot$.

- As much mass (total in Galaxy) as the diffuse ISM, $10^9 - 10^{10} M_\odot$, but volume is small in comparison.
- **Molecular cloud complexes** are usually physically connected to complexes of diffuse atomic clouds.
- The visual extinction through a molecular cloud is $\gg 1$.
- Best spectra line tracers are rotational lines of CO. H_2 radiates too poorly and is excited too inefficiently to be an effective tracer.
- So far, 234 molecular species have been detected in interstellar clouds. Smallest molecule: H_2; largest: C_{70} fullerene.

Giant molecular clouds

Taurus molecular cloud (*Herschel*)



Molecular clouds: Internal structure

- Molecular clouds are **clumpy**; they tend to consist of denser clumps in a range of sizes and masses, blending into a less-dense background.
- Molecular clouds are **cold**; they tend to have $T < 20$ K.
- Molecular clouds are **turbulent**: the random internal velocities are typically ~ 1 km/s, much larger than the average molecular speeds in a quiescent gas in equilibrium at the same temperature.
- Molecular clouds (and clumps) generally **rotate** slowly.
- Molecular clouds are **magnetized**: they are threaded by the same magnetic flux present when the material was diffuse and atomic. Now it has been compressed to a much smaller size, and the fields are correspondingly larger.

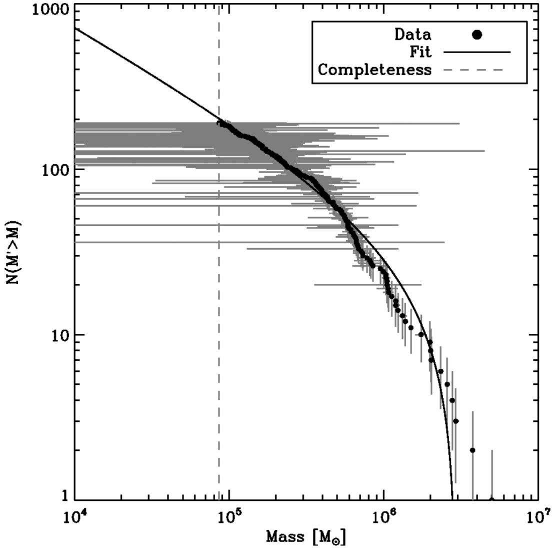
Mass distribution in GMCs

$$\frac{dN}{d\ln M} = N_u \left(\frac{M}{M_u}\right)^{\xi} \qquad M \lesssim M_u$$

where $0.3 < \xi < 0.9$ and $M_u \sim 5 \times 10^6 M_\odot$.

In GMC cores, $0.9 < \xi < 1.5$ with $M \gtrsim 1 M_\odot$.

GMC mass distribution in the inner MW (Rosolowsky, 2005)



GMC scaling relations

In the range $10^2 M_\odot \lesssim M \lesssim 10^6 M_\odot$,

$$M \propto R^2$$

and

$$\Delta v \propto R^{1/2} \propto \rho^{-1/2}$$

Molecular clouds & star formation

- Clumps get massive enough and cold enough that the gas pressure cannot hold up their weight, and they collapse.
  - As clumps collapse, they heat in their cores.
  - If they are sufficiently massive and collapse to a small enough scale, temperatures can reach the fusion ignition point and a star is formed.
- The clumps are constantly being rearranged, compressed, or distended by turbulence.
- Collapse does not happen with spherical symmetry; often collapse is easier along the axis of rotation because of centrifugal forces.

Jeans criterion & Jeans mass

Critical wavelength (or critical wavenumber) between a stable and unstable equilibrium in a gas cloud supported by internal gas pressure:

$$\lambda_J = c_x \left(\frac{\pi}{G\rho_0} \right)^{1/2} \qquad k_J = \frac{2\pi}{\lambda_J}$$

Any perturbation with $\lambda > \lambda_J$ (or $k < k_J$) is unstable and will result in a runaway gravitational collapse of the gas cloud.

Critical mass

The corresponding critical mass contained within a sphere with diameter λ_J is the Jeans mass.

$$M_J = \frac{\pi^{5/2}}{6} \frac{c_s^3}{(G^3 \rho_0)^{1/2}} \simeq 40 M_\odot \left(\frac{c_s}{0.2\ \mathrm{km/s}} \right)^3 \left(\frac{n_{H_2}}{100 \mathrm{cm}^{-3}} \right)^{-1/2}$$

A GMC will collapse under its own gravity if its mass exceeds the Jeans mass.

For an isothermal sphere in pressure equilibrium with its surroundings, the critical mass is the Bonner-Ebert mass,

$$M_{BE} = 1.182 \frac{c_s^3}{(G^3 \rho_0)^{1/2}}$$

Since both GMCs and molecular clumps have masses exceeding both the Jeans mass and the Bonner-Ebert mass, they should collapse under their own gravity *if* they are supported by nothing more than thermal pressure.

Free-fall time & non-thermal pressures

The timescale within which they will collapse is equal to the free-fall time,

$$t_{ff} = \sqrt{\frac{3\pi}{32G\rho_0}} \simeq 3.6 \times 10^6 \text{ yr} \left(\frac{n_{H_2}}{100 \text{ cm}^{-3}}\right)^{-1/2}$$

Turbulence can provide additional pressure support if mean square velocity, σ, is high enough. Replace sound speed with effective sound speed,

$$c_{s,eff}^2 = c_s^2 + \sigma^2$$

Magnetic fields are also a potential non-thermal pressure source. If a cloud's potential energy is equal to the magnetic energy, then the critical mass with a uniform magnetic field is

$$M_\Phi \equiv \frac{5^{3/2}}{48\pi^2} \frac{B^3}{G^{3/2}\rho_0^2} \simeq 1.6 \times 10^5 M_\odot \left(\frac{n_{H_2}}{100 \text{ cm}^{-3}}\right)^{-2} \left(\frac{B}{30\mu\text{G}}\right)^3$$

H_2 in the ISM

Formation is dominated by recombination on dust grain surfaces.

$$t_{\text{form}} = 1.5 \times 10^7 \text{ yr} \left(\frac{n}{100 \text{ cm}^{-3}} \right)^{-1}$$

for a mass ratio of ~100 hydrogen atoms to dust.

Destruction is dominated by photodissociation.

- In an unattenduated interstellar radiation field, $t_{\text{life}} \sim 600$ yr.
- Inside interstellar clouds, H_2 is protected by radiation attenuation by dust grains and itself (self-shielding).