Outline

- Go over problem 4-9, 4-10, exam problem #4
- Star forming regions and molecular clouds
- Jeans instability
- Energy dissipation
- Star clusters
- Initial mass function
Interstellar Medium

- Interstellar medium (ISM) contains:
  - gas in molecular, atomic, ionized forms
  - dust
  - cosmic rays

- Molecular clouds are the densest region and where stars form
  - mass ~ $10^2 - 10^5$ solar masses
  - size ~ 10-100 parsecs
  - density ~ $10^2 - 10^4$ cm$^{-3}$
  - temperature ~ 10-100 K
Orion

Top: optical image without (left) and with (right) map of CO molecular emission.

Bottom:
Left: Near-infrared image zoomed in on sword.
Right: Near-infrared image zoomed in on Trapezium cluster within sword.

Center: Protoplanetary disks around young stars.
Jeans Instability

- When is a gas cloud unstable to collapse?

- Consider a spherical cloud of constant (initial) density and temperature with particles of mean mass \( m \). The cloud has a mass \( M \) and radius \( r \).

- The cloud undergoes a radial compression \( dr \).

- Gravitational energy:

  \[
  E_g \approx - \frac{GM^2}{r} \rightarrow dE_g = - \frac{GM^2}{r^2} dr
  \]

- Volume decrease \( dV = 4\pi r^2 dr \), causes thermal energy increase \( dE_{th} = PdV \).

- Use equation of state for ideal gas

  \[
  dE_{th} = nkT \ 4\pi r^2 dr = \frac{M}{\bar{m}} \ 4\pi r^2 kT \ dr = 3 \frac{M}{\bar{m}} \ kT \ \frac{dr}{r}
  \]
Jeans Instability

- Cloud is unstable to collapse if total energy decreases when compressed
  
  \[ dE_g + dE_{\text{th}} < 0 \rightarrow 3 \frac{M}{\bar{m}} kT \frac{dr}{r} < \frac{GM^2}{r^2} dr \]

- Gives the Jeans mass, radius, and density
  
  \[
  M > M_J = \frac{3kT r}{G \bar{m}} \quad r < r_J = \frac{G \bar{m} M}{3kT} \quad \rho > \rho_J = \frac{3}{4\pi M^2} \left( \frac{3kT}{G \bar{m}} \right)^3
  \]

- Jeans density increases as clump mass decreases
  - collapse begins on large scales
  - sub-clumps start to independently collapse as density increases
  - leads to formation of star clusters
Pleiades (left) is an open star cluster at a distance of 136 pc with about 1000 stars and a total mass of 800 solar masses. Cluster is about 100 Myr old and is not gravitationally bound, so will dissipate in ~300 Myr.

M80 (right) is globular cluster at a distance of 8.7kpc with a total mass of about $5 \times 10^5$ solar masses. Age is ~ 13 Gyr. Cluster is gravitationally bound.
Clusters form stars of a wide range of masses.

The distribution is the “initial mass function” (IMF) and gives the relative probability of forming stars of different masses.

Salpeter mass function is powerlaw with exponent of -2.35.

More recent work shows turn over at sub-solar masses.
Cloud Collapse

- For 1000 solar mass cloud at 20 K ($m \sim 2 m_H$ since gas is mostly $H_2$)
  - number density $\sim 1 \text{ cm}^{-3}$
  - free-fall time scale $\sim (3\pi/32G\rho)^{1/2} \sim 40,000,000$ years
- Anyone see a problem with this?

- Clouds that appear to be long lived have $n \sim 10^2 - 10^4 \text{ cm}^{-3}$
- Additional supported from supersonic turbulent motions of the gas and/or magnetic fields.
  - $u_K \sim nkT \sim 3\times10^{-15} \text{ erg/cm}^3$ for 1 cm$^{-3}$
  - $u_B \sim B^2/8\pi \sim 3\times10^{-13} \text{ erg/cm}^3$ for B $\sim 1 \mu\text{G}$ typical in ISM
- Need $n > 10^2 \text{ cm}^{-3}$ to overcome magnetic field support.
- Often star formation is triggered by an external event that creates density perturbations.
Cloud Collapse

• To collapse, needs means to dissipate energy:
  – Radiation - depends on temperature, chemical composition, optical depth of core, surroundings of core.
  – Dissociation of H$_2$ gives 4.5 eV/molecule
  – Ionization of H gives 13.6 eV per molecule

• Process is too complex for accurate analytical calculations
  – need to do large-scale magnetohydrodynamic (MHD) simulations

• Collapse of 1 solar mass core requires $10^7$-$10^8$ years.
Homework

• For next class:
  – Problem 5-1
  – Exam problem #5