Collapse of a proto-star

Source of energy: gravity only

- Gravitationally unstable cloud
  - Cool, large, low luminosity
  - Dust enshrouded, need IR when collapses, some p.e. heats cloud
    - Some radiated away (optically thin)
      - Some cooling so collapse continues

- Inner region collapses more rapidly, pre-stellar core forms
Timescale for collapse

Think of the early stages of collapse of the gas cloud. Can ignore pressure at this stage because density is so low.

Even if cloud starts with roughly uniform density, this changes fast.

Q: Why?

- Particles close to the center collapse inward faster (less distance to travel) and density increases faster there.

- As it becomes denser, gravitational forces are larger so collapse time shorter.

........ etc
- core 'bounce': pressure builds up & core expands

- interaction between infalling & expanding material
  bounce stops, collapse proceeds

- core density increases until photons can't escape (optically thick)
Free-fall Time:

Consider particle, mass, $m$, at edge of cloud, mass $M$, radius $R$, initial density $\rho_0$.

Particle falls straight to center, follows elliptical orbit with $e = 1$ and semi-major axis $a = R/2$.

\[ m = \frac{4}{3} \pi R^3 \rho_0 = \frac{32}{3} \pi a^3 \rho_0 \]

Kepler's third law:

\[ \frac{\rho^2}{a^3} = \frac{4\pi^2}{GM} \]

\[ \rho = \left( \frac{3\pi}{8G\rho_0} \right)^{1/2} \]

Free-fall time:

\[ \propto \rho^{-1/2} \]
For a giant molecular cloud
\[ p = 10^{-15} \text{ kg/m}^3 \]
Free-fall time is \( \sim 10^5 \) years.

**Viral theorem**

For a system in equilibrium,
\[ 2E_{\text{kinetic}} = -U \]
\[ \uparrow \text{potential energy} \]

So if \( E_{\text{kinetic}} + U = 0 \)
\[ \text{Total energy} = \frac{U}{2} \]
Implications of virial theorem

\[ E \ (\text{total energy}) = \frac{p.e.}{2} \]

So as cloud collapses, \( p.e. \) decreases and \( E \) decreases.

\[ \Rightarrow \text{some of energy of cloud is radiated away} \]

Since \( k.e. = -\frac{p.e.}{2} \), half of energy gained is lost, half goes to increasing kinetic energy (both infall & random motions).

Example on luminosity of protostar:

Viral theorem says that amount of energy radiated is \( (\text{current } p.e.)/2 \).

Over 100 years, collapse of 1 \( M_\odot \) to 500 \( R_\odot \) gives 170 \( L_\odot \).
The other half is available for heating cloud, speeding up collapse, etc.

(note that a similar calculation can be made for the heating of a planet by accretion of planetesimals)

* Balance between heating and energy loss means that star formation is possible *

* Theoretical calculations of gravitational collapse of protostars give evolutionary tracks which can be compared with observations of "young stellar objects"
Question

As a dense molecular cloud starts the collapse that will lead to the birth of a star, where should it be plotted on the H-R diagram?
Another core bounce

Temperature ↑ and star ends up on HR diag

Completely convective row

All stars, whatever mass, end up at about the same temperature now

**FIGURE 17-6.** The path in the H-R diagram of a protostar during dynamical collapse.
**FIGURE 17-7.** The path in the H-R diagram of protostars of different masses.

- completely convective $\Rightarrow$ cooling keeps up with collapse
- optically thick, no radiative cooling
- "Hayashi track" temperature almost constant
- collapsing $\Rightarrow L \downarrow (\propto L \propto 4\pi R^2)$
...radiation takes over, surface temperature stays constant.

stellar core: temperature reaches $10^7 \text{ K}$

...protons can fuse in main sequence where it will spend most of its life...
STAR FORMATION

The story so far ......

- importance of understanding how stars form
galaxy formation
cosmology

- initial conditions: giant molecular cloud
  \( \sim 10^6 \, M_\odot \) of gas & dust
  low density \( (10^2 - 10^3 \, \text{H}_2 \text{ molecules/cm}^3) \)
  cool \( (\sim 10 \, K) \)

- Conditions for gravitational collapse
  gravity vs pressure (ignore mag fields for the moment)
  (of hydrostatic equilibrium)
Conditions for sphere to be gravitationally bound

\[ k.e. + p.e. \leq 0 \]

\[ \frac{3}{2} \frac{m}{M} kT - \frac{3}{5} \frac{GM^2}{R} \leq 0 \]

This gives Jeans length

\[ R_J = \sqrt{\frac{kT}{GmP}} \]

Jeans mass

\[ M_J \approx 4 \left( \frac{kT}{GM} \right)^{3/2} \left( \frac{1}{P} \right)^{1/2} \]

Timescale for collapse:

Free fall time

\[ t_{ff} \approx \frac{1}{\sqrt{GP}} \]

Viral theorem: in equilibrium

\[ k.e. = -\frac{p.e.}{2} \]