GAS CLOUDS IN BETWEEN STARS

"interstellar clouds"

(i) diffuse interstellar clouds

(mostly hydrogen)

density LOW — about 10 atoms/cm^3

(air at sea level 10^{19} atoms/cm^3

vacuum flask 10^5 atoms/cm^3)

temperature low — about 100 K

(ii) dense molecular clouds

denser — about 10^6 atoms/cm^3

colder — 10 - 30 K

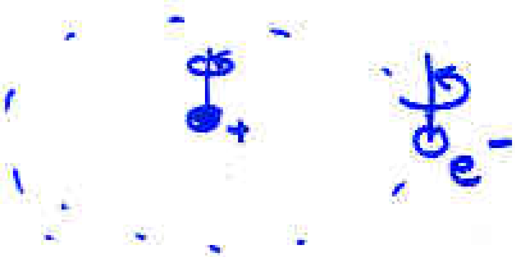
cool and dense enough to form molecules

also contain dust grains

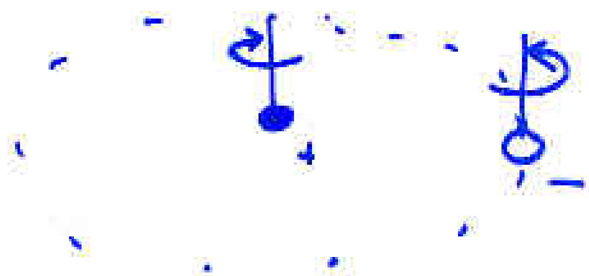
It is very difficult to detect hydrogen in molecular form (H_2)

Much simpler to detect neutral (atomic) hydrogen

In ground state of hydrogen atom, two possible arrangements of spin of electron & proton



spin same way



opposite way

These two states have slightly different energies

$\boxed{Q}$ When the hydrogen atom changes from the 'spins aligned' state to the 'spins different' state, a photon is emitted. What region of the electromagnetic spectrum would this photon come from? Why?

Photon has wavelength 21 cm

Thus we can use radio waves to detect hydrogen atoms in interstellar space

Molecular hydrogen is effectively invisible to astronomers

But other molecules can be detected in the millimeter region (near IR - radio transition)

A useful molecule is carbon monoxide (CO)

Astronomers try to infer the amount of molecular hydrogen from the amount of CO

Hot hydrogen gas is much easier to detect, if it is hot enough to ionize the hydrogen atom

Then the hot gas (about 10,000 K) is visible in the optical region, looks reddish

$\boxed{Q}$ What is the physical process which causes ionized hydrogen to glow?

Hot clouds of gas around hot stars are called H II regions

means ionized

STAR FORMATION

$\boxed{Q}$ Say we have a large cloud of gas & dust, 100 × mass of current solar system, but with radius 0.5 pc.

What will encourage it to collapse & form a star? What will prevent it?

$\boxed{Q.}$

Why might dust be a useful thing to have around when a star is forming?

(Hint: if you heat gas, will it expand or contract?)

Stars form from cool, dense clouds of gas & dust

If the gas is heated (for example, by a newly formed young star) then it will expand

Thus the cloud needs to be cool so it can collapse further

Dust will help keep the central regions of the cloud cool by absorbing radiation from nearby stars so they cannot heat the central core

Simple criterion for gravitational collapse

Gravitationally bound

$\Rightarrow$ Total energy negative

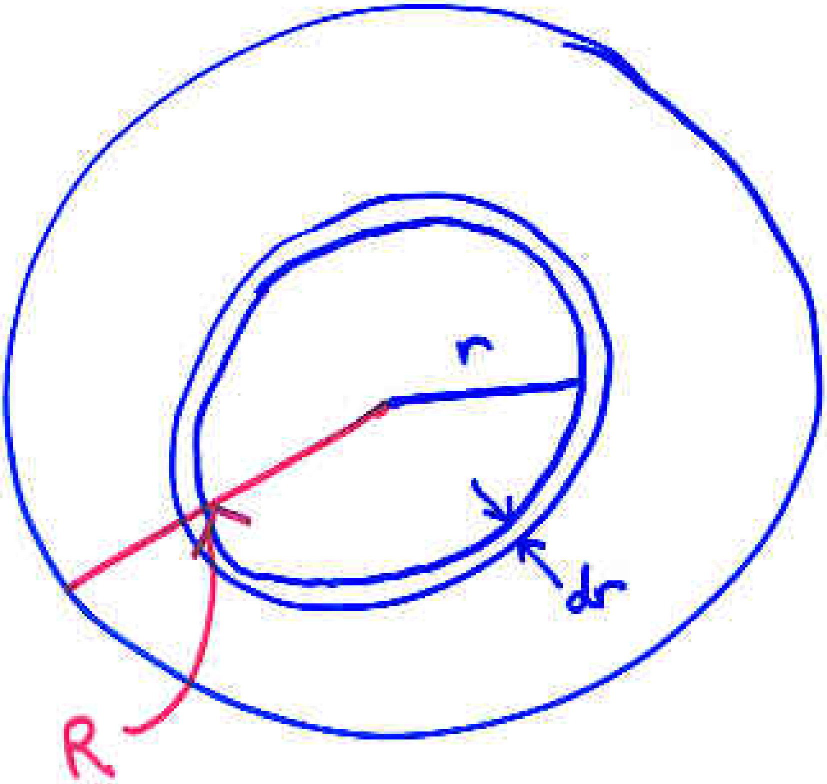
kinetic + potential energy

Simple example for basic physical understanding : uniform density sphere

Mass M, radius R, density ρ

$$M = \frac{4}{3}\pi R^3 \rho$$

Work out its total gravitational potential energy by assembling it in shells from ∞



If assemble shells thru radius r, how much work to bring in next shell, thickness dr ?

Shell volume $dV = 4\pi r^2 dr$

mass $dm = 4\pi r^2 \rho \, dr$

Mass already assembled inside r is $m(r) = \frac{4}{3}\pi r^3 \rho$

For two <u>point</u> masses m_1 & m_2, r apart

grav. potential energy $U = -G\dfrac{m_1 m_2}{r}$

m_1 is $M(r)$

m_2 is shell mass dM

$$dU(r) = -\frac{G\,M(r)\,dM}{r}$$

$$= -\frac{G \cdot \frac{4}{3}\pi r^3 \rho \cdot 4\pi r^2 \rho\, dr}{r}$$

$$= -G \cdot \frac{16}{3}\pi^2 r^4 \rho\, dr$$

Total potential energy

$$U = \int_0^R dU(r)$$

$$= -G \cdot \frac{16}{3}\pi^2 \rho \int_0^R r^4\, dr$$

Integrating, we get

$$U = -\frac{3}{5} G M^2/R$$

Kinetic (thermal) energy is $\frac{3}{2}kT$ per particle.

For particles of mass m, there are $\frac{M}{m}$ particles in total so

total kinetic energy $= \frac{3}{2} \frac{M}{m} kT$

For cloud to be gravitationally bound we find

$$\frac{3}{5} G M^2/R \geq \frac{3}{2} kT \frac{M}{m}$$

potential thermal

So $\frac{M}{R} \geqslant \frac{5}{2} \frac{kT}{Gm}$

But, M, R are not independent

$$\rho = \frac{4}{3}\pi \frac{M}{R^3}$$

We can use this to estimate size (or mass) to make a cloud gravitationally bound.

Make $\geqslant$ into $=$ for bound/unbound boundary

eliminate M

$$\frac{4}{3}\pi R^3 \rho / R = 5kT/2Gm$$

"Jeans length" $R_J = \sqrt{\frac{15kT}{8\pi G m \rho}}$

Since $\sqrt{\frac{15}{8\pi}} \simeq 1$ we say that

$$R_J \simeq \sqrt{\frac{kT}{Gm\rho}}$$

(assumptions like const. density also produce approx. relation but it's close)

Jeans mass is the <u>smallest</u> size for which the cloud is gravitationally bound

Can also eliminate R and get smallest mass

$$\text{"Jeans mass"} = 4\left(\frac{kT}{Gm}\right)^{3/2} \rho^{-1/2}.$$

MAGNETIC FIELDS

Faraday's Law:

$$\oint \vec{E} \cdot d\vec{l} = - \frac{d\Phi_B}{dt}$$

magnetic flux thru surface

integral around closed path

If the material has some conductivity currents will flow to oppose change in magnetic flux

$\rightarrow$ flux constant ("frozen in")

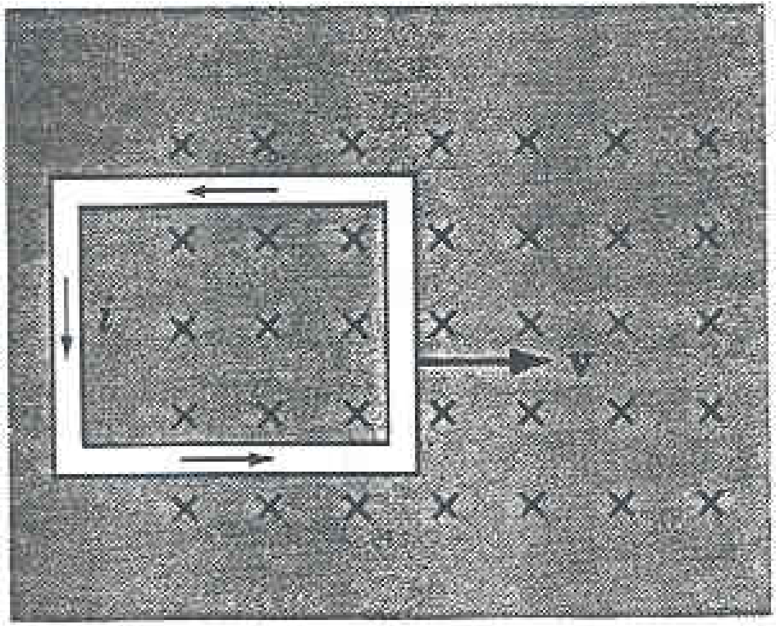


FIG 31-3. *A conducting loop one end of which moves through a transverse magnetic field* $\mathbf{B}$.

Electric current induced in loop could go ~~g~~ in 2 directions ; but one will violate energy conservation, because it will create a stronger magnetic field, speed up loop, etc .....

So current will <u>oppose</u> change in magnetic flux

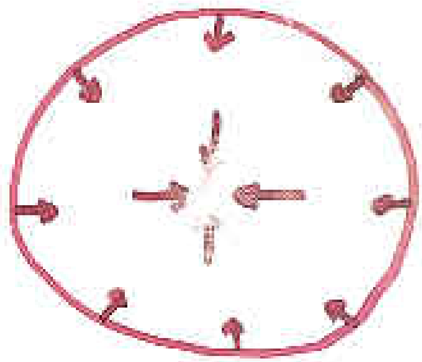
Magnetic fields ignored in Jeans length calculation

- If we do include them, they will provide another source of support against collapse (as well as the pressure that comes from a high temperature)

Collapse of a proto-star

Source of energy : gravity <u>only</u>.

- 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.

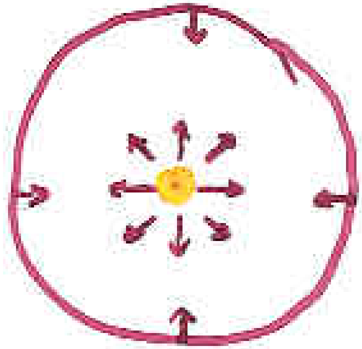
Even if cloud starts with roughly uniform density, this changes fast

$\boxed{Q}$ Why?

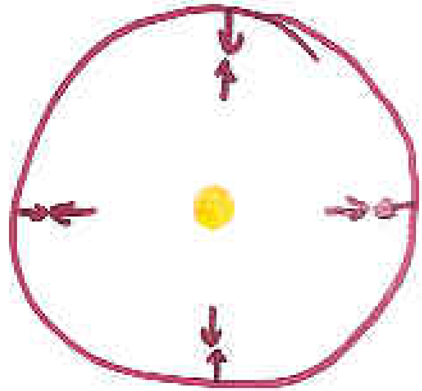
- Particles close to the center collapse inward ~~faster~~ first (less distance to travel) and density increases faster there
- as it becomes denser, gravitational forces are larger so collapse time shorter

...... etc

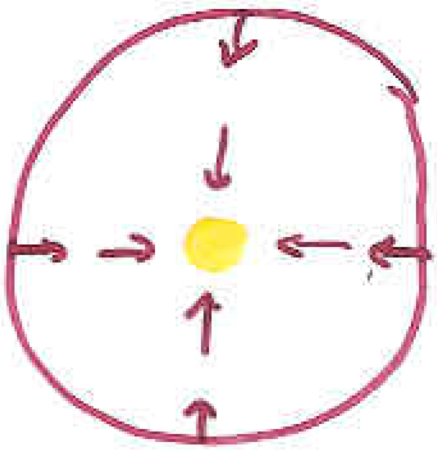
- core 'bounce' : pressure builds up & core expands



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



- core density increases until photons can't escape (optically thick)



Free-fall time :

little m

Consider particle, mass, @ edge of cloud, mass M, radius R, initial density ρ_0.

Particle falls straight to center

Follows ellyptical 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 :

$$\frac{P^2}{a^3} = \frac{4\pi^2}{GM}$$

$$P = \left(\frac{3\pi}{8G\rho_0}\right)^{1/2}$$

$$\boxed{\text{Free-fall time } \propto \rho^{-1/2}}$$

For a giant molecular cloud

$\rho \simeq 10^{-15}\ kg/m^3$

Free-fall time is $\sim 10^5$ years.

Virial theorem

For a system in equilibrium,

$$2\, E_{kinetic} = -\,U$$

potential energy

So if $E_{kinetic} + U = 0$

$$\text{Total energy} = \frac{U}{2}$$

Implications of virial theorem

E (total energy) $= \frac{p.e.}{2}$

So as cloud collapses, p.e decreases and
E decreases

$\Rightarrow$ 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 ~~k~~ kinetic energy (both infall & random motions)

Example on luminosity of protostar:

Virial Theorem says that amount of energy radiated is (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.

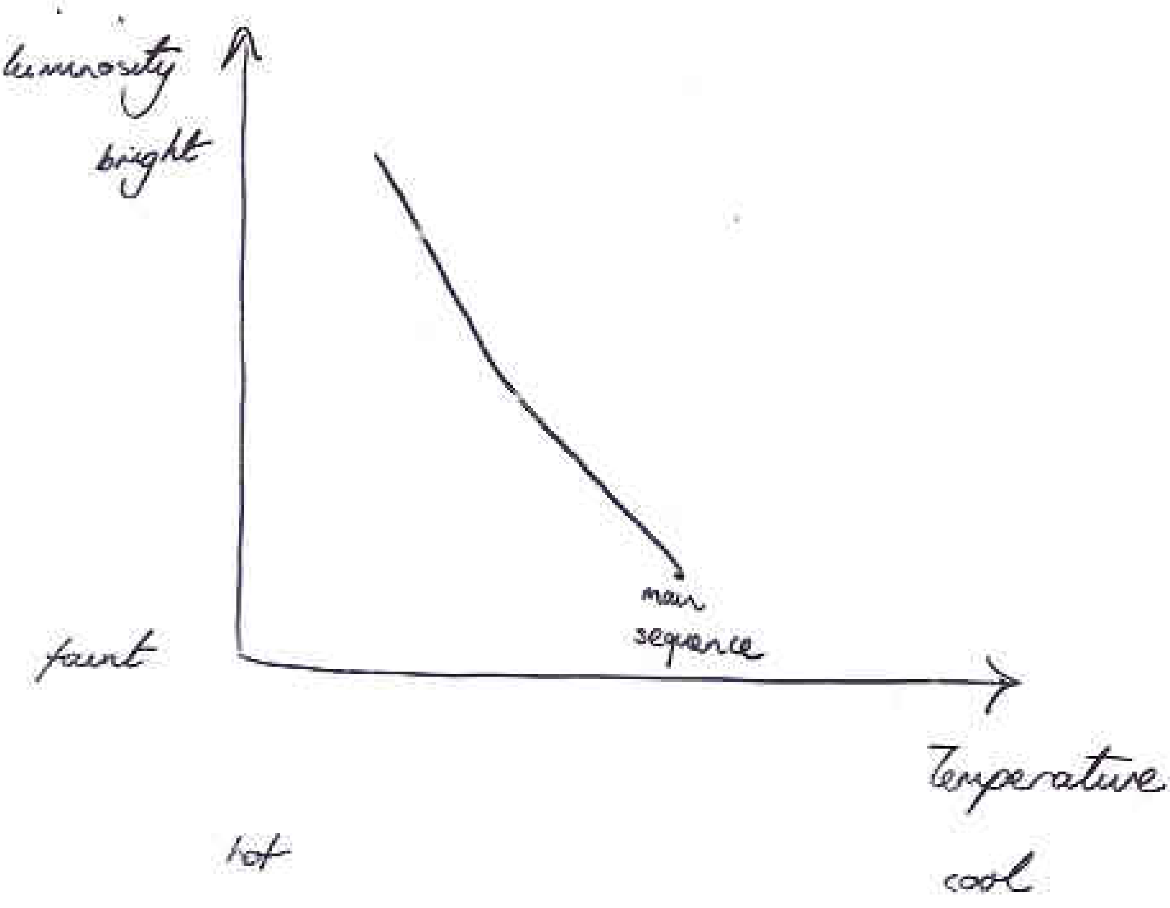
(note that a similar calculation can be made for the heating of a planet by accretion of planetesimals)

* 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 now

all stars, whatever mass, end up at

about the same temperature now

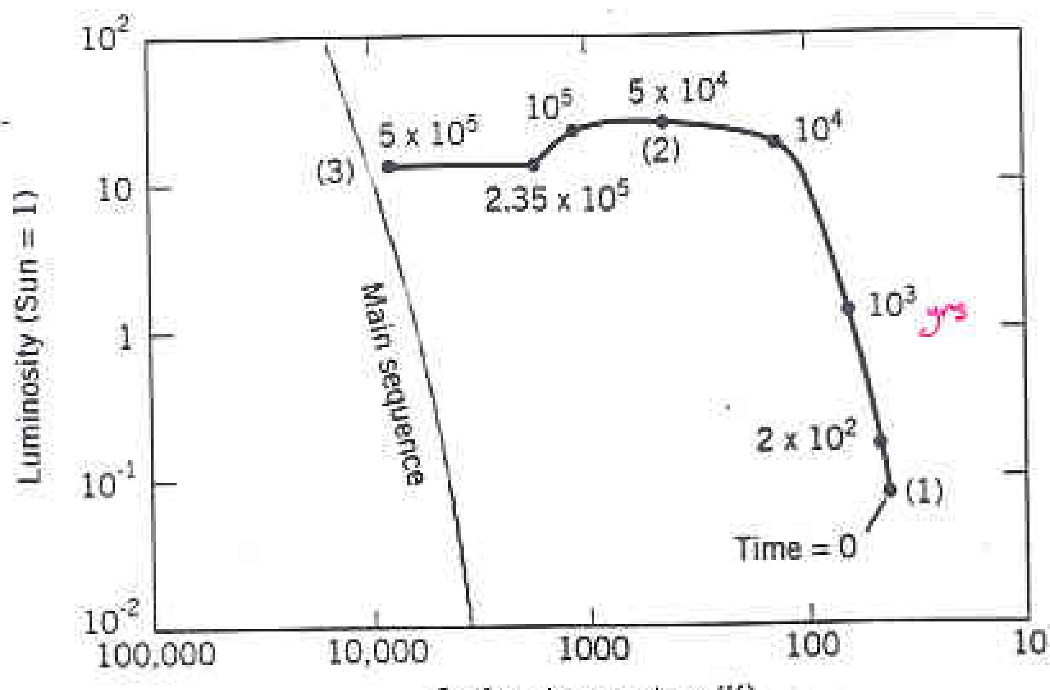


FIGURE 17–6. The path in the H-R diagram of a protostar during dynamical collapse.

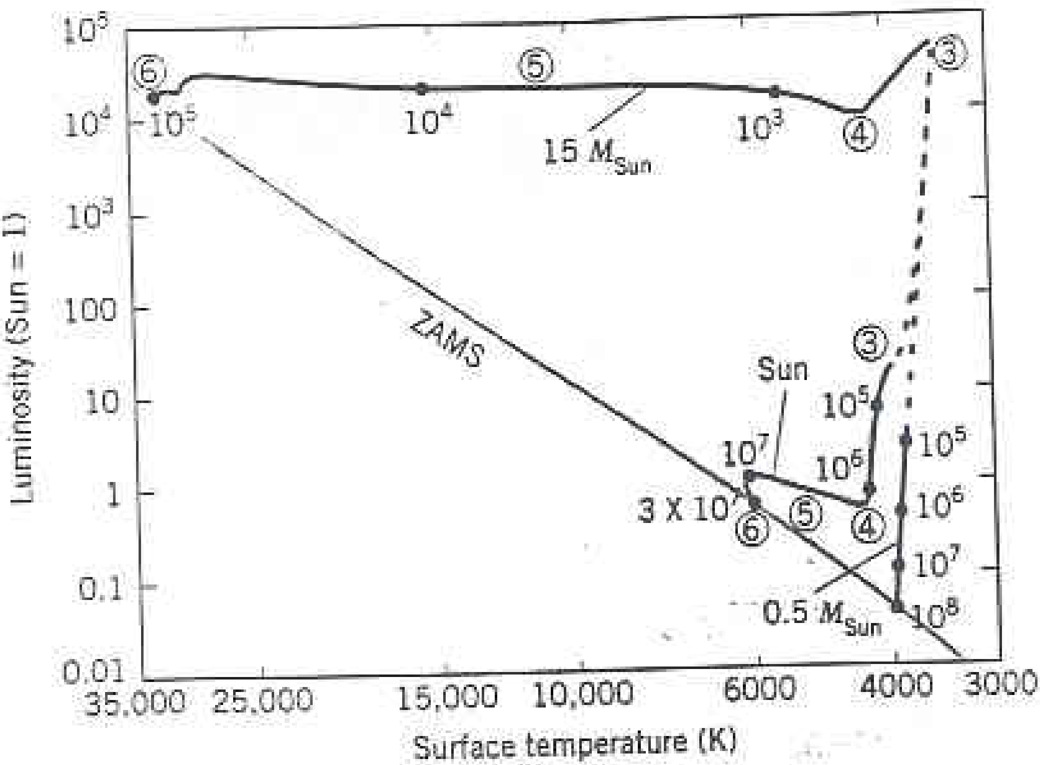


FIGURE 17–7. The path in the H-R diagram of protostars of different masses.

- completely convective ⇒ cooling keeps up with collapse

optically thick, no radiative cooling

"Hyashi track" Temperature almost constant

collapsing ⇒ $L \downarrow$ (cf $L \propto 4\pi R^2$)

- radiation takes over, surface Temp ↑
  still collapsing but T balances R &
  L stays ~ constant

- core temperature reaches ~ 10^7 K
  fusion reactions start
  star is on 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 ($10^2 - 10^3$ H_2 molecules / cm^3)
  - cool ($\sim 10K$)

- Conditions for gravitational collapse

  gravity vs pressure (ignore mag fields for the moment)

  (cf hydrostatic equilibrium)

- Conditions for sphere to be gravitationally bound

$$\text{k.e.} + \text{p.e.} \leq 0$$

$$\frac{3}{2}\frac{M}{m}kT - \frac{3}{5}G\frac{M^2}{R} \leq 0$$

gives Jeans length $R_J \simeq \sqrt{\frac{kT}{Gm\rho}}$

Jeans mass $M_J \simeq 4\left(\frac{kT}{Gm}\right)^{3/2}\left(\frac{1}{\rho}\right)^{1/2}$

- Timescale for collapse :

free fall time $t_{ff} \simeq \frac{1}{\sqrt{G\rho}}$

- Virial theorem : in equilibrium

$$\text{k.e.} = -\frac{\text{p.e.}}{2}$$