Star Formation

http://apod.nasa.gov/apod/astropix.html

PHASES OF THE INTERSTELLAR MEDIUM

Component	Fractional volume	Scale Height (pc)	Temperature	Density	State of Hydrogen	Observational Technique
Molecular Clouds	< 1%	70	10 - 20	10^2 - 10^6	H_2	Radio and infrared (molecules)
Cold Neutral Medium (CNM)	1 - 5%	100 - 300	50 - 100	20 - 50	H I	21 cm
Warm Neutral Medium (WNM)	10 - 20%	300 - 400	5000-8000	0.2 - 0.5	H I	21 cm
Warm Ionized Medium (WIM)	20 - 50%	1000	6000 - 12000	0.2 - 0.5	H II	H_α pulsar (n_e)
H II Regions	<1%	70	8000	10^2 - 10^4	H II	H_α
Coronal Gas (Hot Ionized Medium (HIM)	30 - 70%	1000 - 3000	10^6 = 10^7	10^{-4} - 10^{-2}	H II metals also ionized	x-ray ultraviolet

In which of these components can star formation take place?

A necessary condition is a region of gas that has greater gravitational binding energy than internal energy. (The force pulling the region together must be greater than the pressure pushing it apart.)

Since internal energy increases with the amount of mass that is present while binding energy increases as M^2, there is a critical mass that is bound.

The Jean's Mass

Ignore factor of 2 in the Virial Theorem. The clouds we are envisioning have not reached equilibrium.

$$\Omega \; ! \; KE$$

$$\Omega \; ! \; \frac{3}{5}\frac{GM^2}{R} \; ! \; (\text{Number of particles})\,(\frac{3}{2}kT)$$

$$! \; \frac{M}{m_H}\frac{3}{2}kT \quad (\text{if made of pure hydrogen})$$

$$= \mathrm{N_A}\, M\, \frac{3}{2}kT \quad (\mathrm{N_A} \text{ is Avogadro's Number, } 6.02 \quad 10^{23})$$

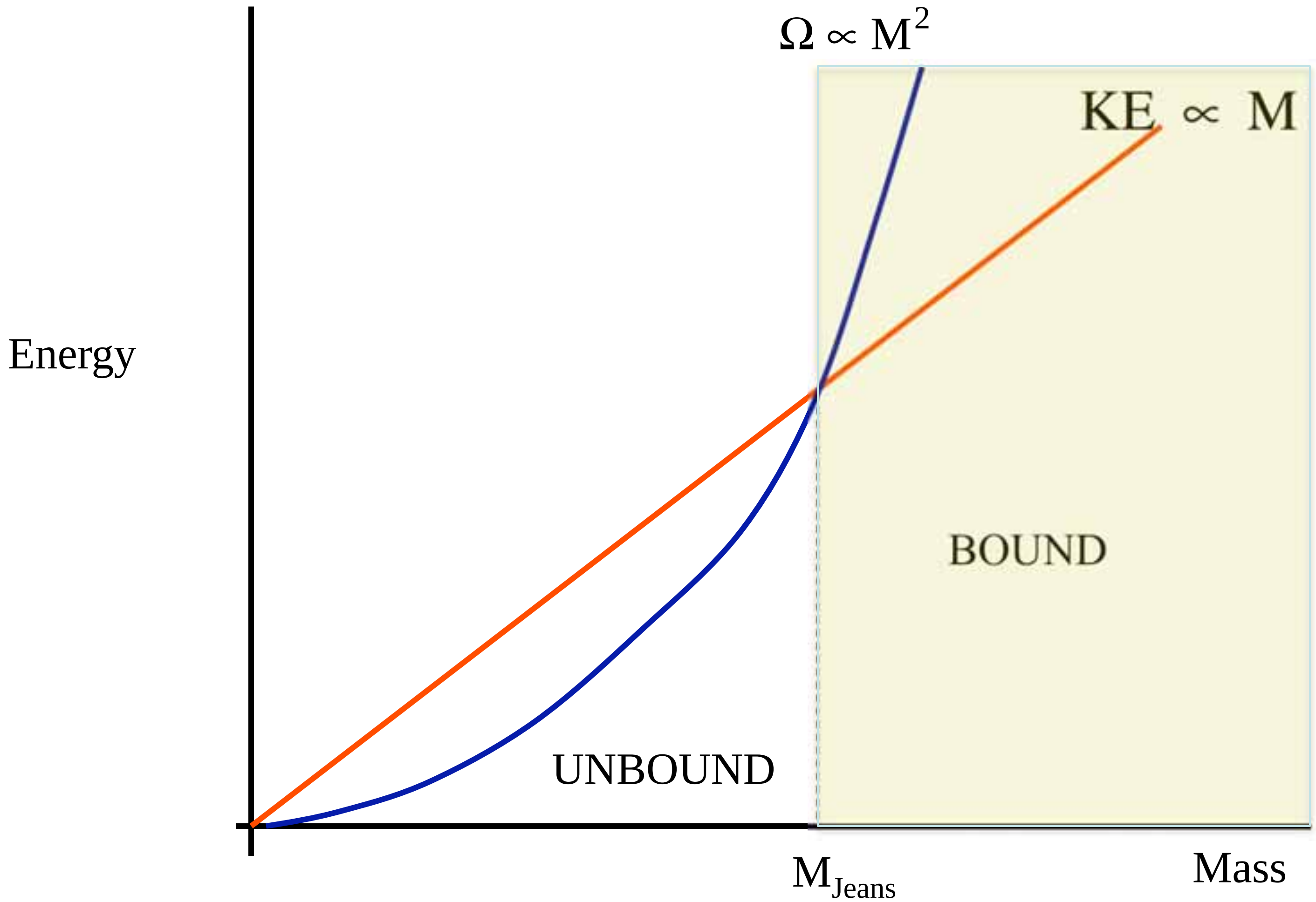
This can be solved for the "Jean's Mass", M_J

$$\frac{3}{5}\frac{GM_J^2}{R} = \frac{3}{2}N_A M_J kT$$

$$\mathrm{M_J} = \frac{5N_A kTR}{2G}$$

Clouds of gas with radius R and temperature T that have a mass bigger than this are unstable to gravitational collapse

For masses larger than the Jean's Mass gravitational binding energy exceeds internal energy



It is easier to measure densities and temperatures rather than radii, so the equation on the previous page can be transformed using

$$R = \left(\frac{3M}{4\pi\rho}\right)^{1/3}$$

assume sphere, constant density $M = \frac{4}{3}\pi R^3 \rho$

previous page $M_J = \frac{5N_A kTR}{2G} = \frac{5N_A kT}{2G}\left(\frac{3M_J}{4\pi\rho}\right)^{1/3}$

$$M_J^{2/3} = \frac{5N_A k}{2G}\left(\frac{3}{4\pi}\right)^{1/3}\left(\frac{T^3}{\rho}\right)^{1/3}$$

$$M_J = \left(\frac{5N_A k}{2G}\right)^{3/2}\left(\frac{3}{4\pi}\right)^{1/2}\left(\frac{T^3}{\rho}\right)^{1/2}$$

$$= 8.5\times10^{22} \text{ gm } \left(\frac{T^{3/2}}{\rho^{1/2}}\right) = 4.2\times10^{-11}\left(\frac{T^{3/2}}{\rho^{1/2}}\right) M_\odot$$

It is more frequent that one finds the density in this context expressed as atoms/cm^3 rather than gm/cm^3.

If $n = \rho N_A$ (actually true only for H I), then

$$M_J = 8.5\times10^{22}\frac{T^{3/2}N_A^{1/2}}{n^{1/2}}\ \text{gm}$$

$$M_J = 34\frac{T^{3/2}}{n^{1/2}}\ \text{M}_\odot$$

where n is the density in atoms cm^{-3}.

By this criterion, only molecular clouds and possibly portions of the coldest neutral medium (depending on mass) are unstable to collapse.

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Example: Molecular cloud; T = 20 K, n = 10^4 atoms cm^{-3}

$$M_J = 34 \frac{T^{3/2}}{n^{1/2}}$$

$$= 34 \frac{(20)^{3/2}}{(10^4)^{1/2}} = 34 \frac{89.4}{100}$$

$$= 30 \ M_\odot$$

Any cloud with this temperature and density and a mass over 30 solar masses is unstable to collapse

How long does the collapse take?

$$v_{esc} = \sqrt{\frac{2GM}{R}} \qquad \tau_{ff} \approx \frac{R}{v_{esc}} = \sqrt{\frac{R^3}{2GM}}$$

but, ρ, the density, is given by

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

so,

$$\tau_{ff} \approx \sqrt{\frac{3}{8\pi G\rho}} \approx 1000\,\text{seconds}/\sqrt{\rho}$$

Denser regions collapse faster

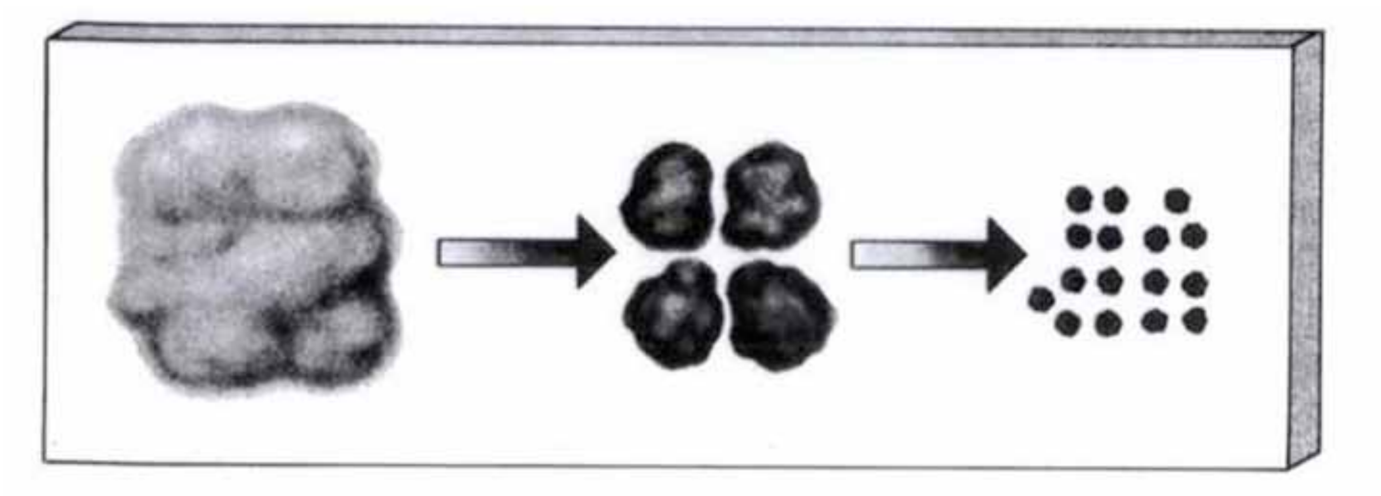
but $\rho \approx n/\text{N}_A$, so

$$\tau_{ff} \approx 10 \text{ million years}/\sqrt{n}$$

where n is the number of atoms per cubic cm.

1 million years if n = 10^4 atoms/cm^3

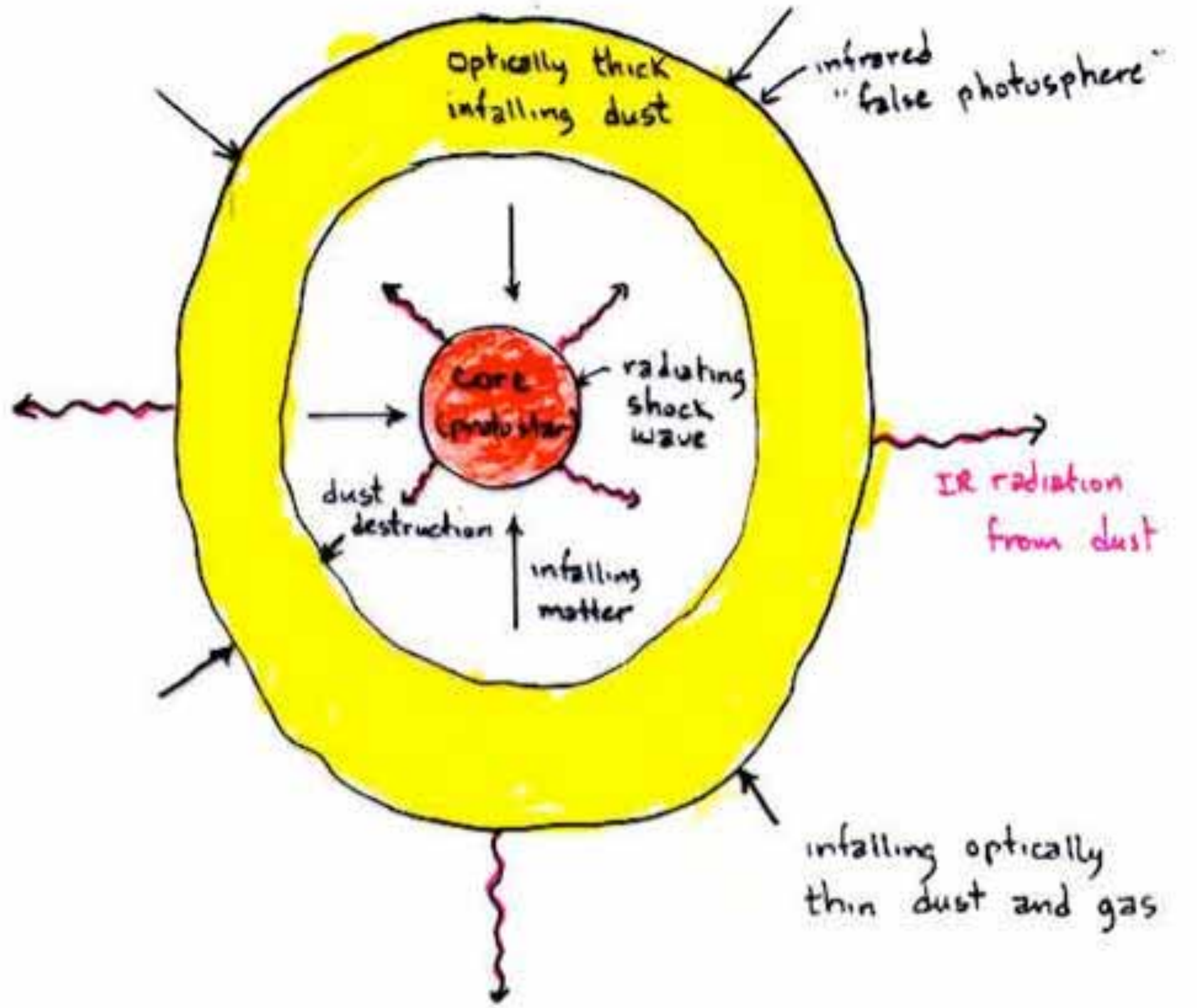
Fragmentation



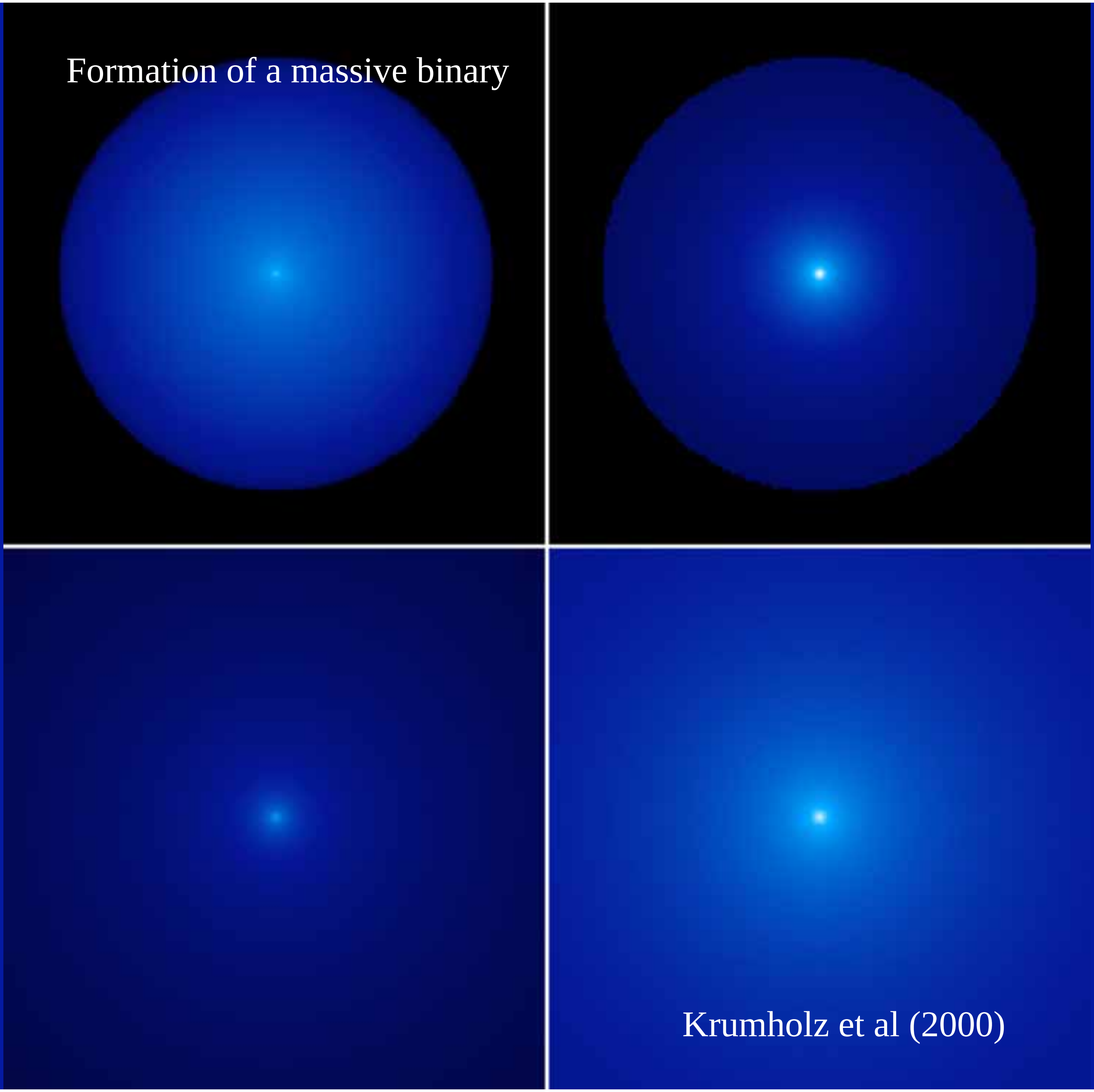
Complications:

Rotation

Magnetic fields



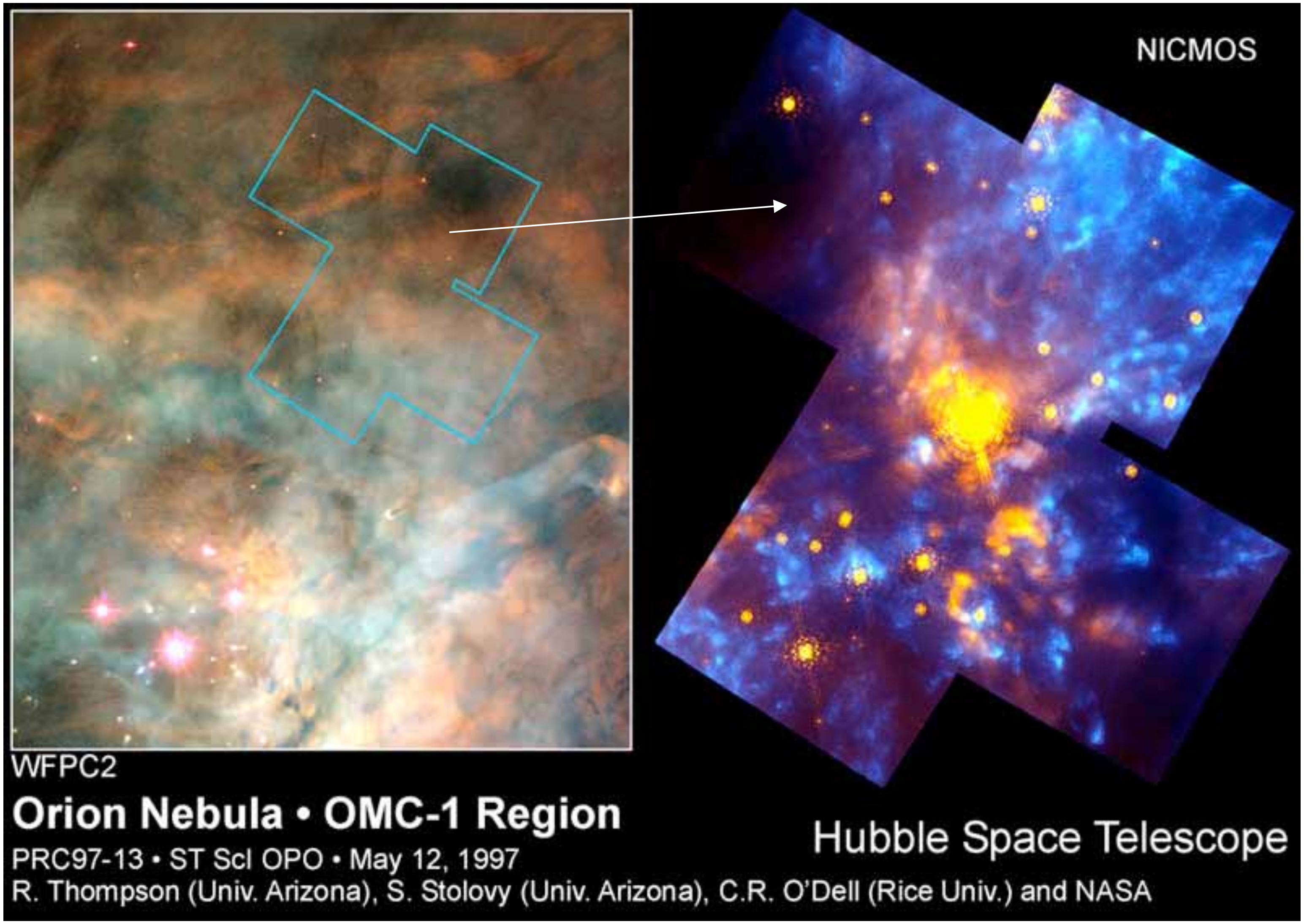
Star formation
inefficient. Uses
~5-20% of gas


Formation of a massive binary
Krumholz et al (2000)

500 solar mass cloud makes 1250 stars
2.6 ly across 285,000 years
Mathew Bate et al

http://www.astro.ex.ac.uk/people/mbate/Cluster/cluster3d.html

Power of observing in the infrared



LH 95
A Stellar
Nursery in the
Large Magellanic
Cloud (HST)

The star formation region N11B in the LMC taken by WFPC2 on the NASA/ESA Hubble Space Telescope

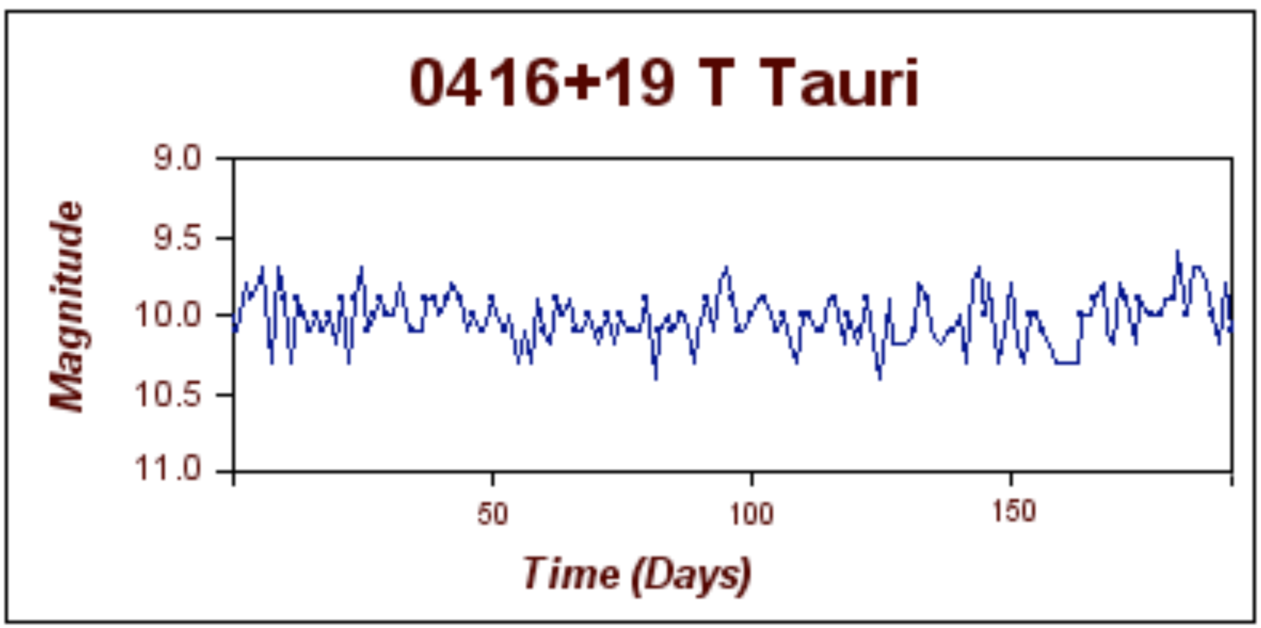
T-Tauri Stars

T-Tauri – in Taurus close to the Pleaides

T-Tauri discovered by John Hind in 1852 as a 10th magnitude star.
A faint nebula was subsequently discovered nearby ("Hind's nebula").
Both the star and nebula had variable brightness. The nebula was a "reflection" nebula, shining from the reflected light of T-Tauri.

By 1861 the nebula disappeared from view and by 1890 T-Tauri itself had faded to 14th magnitude, about the limit of telescopes then.
A faint nebula at the site of T-Tauri itself was observed at that time,

Over the next 10 – 20 years, T-Tauri brightened back to 10th magnitude and its local nebula became invisible against the glare. T-Tauri has remained at about 10th magnitude since (but varies).

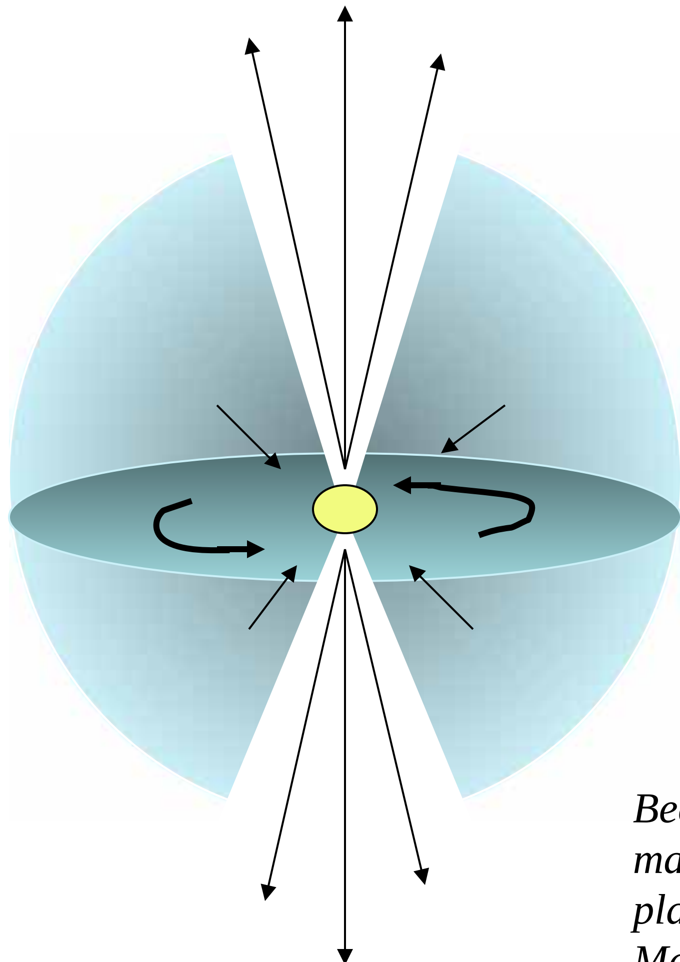


T-Tauri - about 400 ly away at the edge of a molecular cloud.
FOV here is 4 ly at the distance of T-Tauri http://apod.nasa.gov/apod/ap071213.htm

T-Tauri Stars

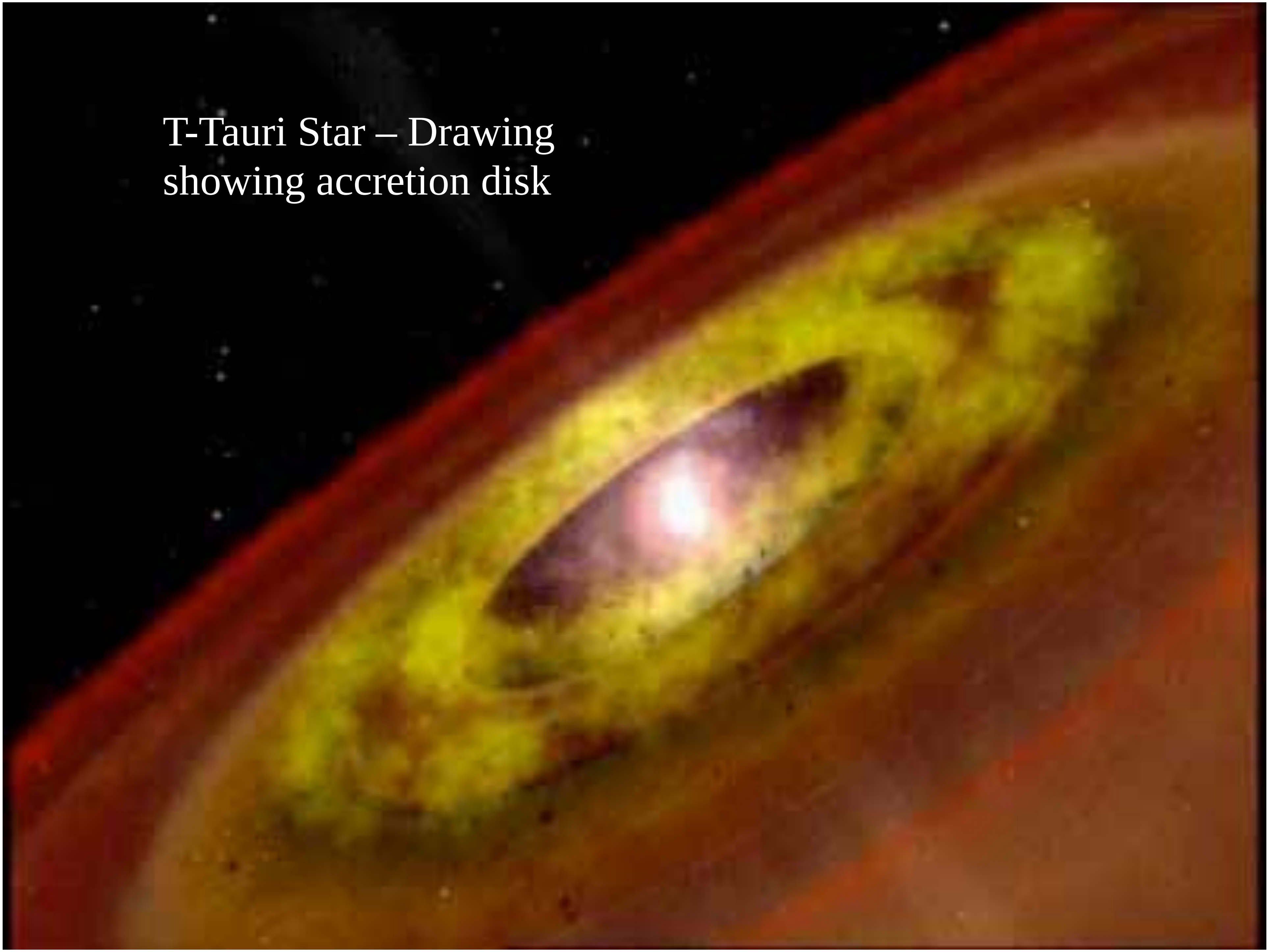
- Short lived phase in life of stars under 2 solar masses. Heavier stars evolve quicker and start burning by the time the star is visible. Above 2 solar masses the objects evolve rapidly and are rarely seen - "Herbig Ae and Be stars".
- Accretion disks and jets are common features
- Emission and absorption lines
- Powered by gravitational contraction, not nuclear burning
- May be forming planetary systems
- High lithium abundance
- Embedded in dense, dusty regions
- Can be highly variable

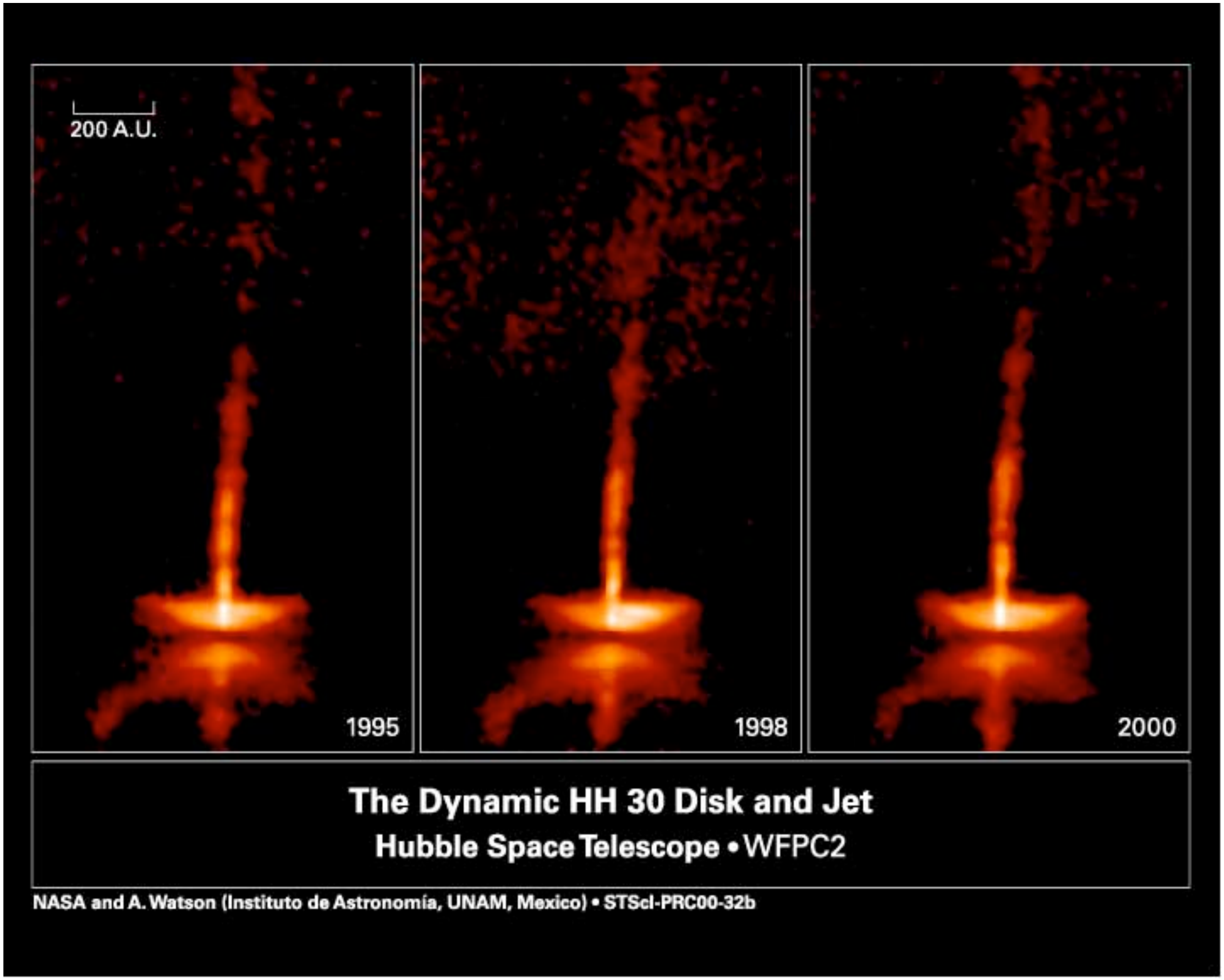
When the star first becomes visible it may still be surrounded by the gas and dust from which it formed. Often jets are seen.



Because of rotational support matter hangs up in the equatorial plane forming an "accretion disk". Matter first rains down on the poles, but then later reverses direction in a strong collimated outflow called a "jet".

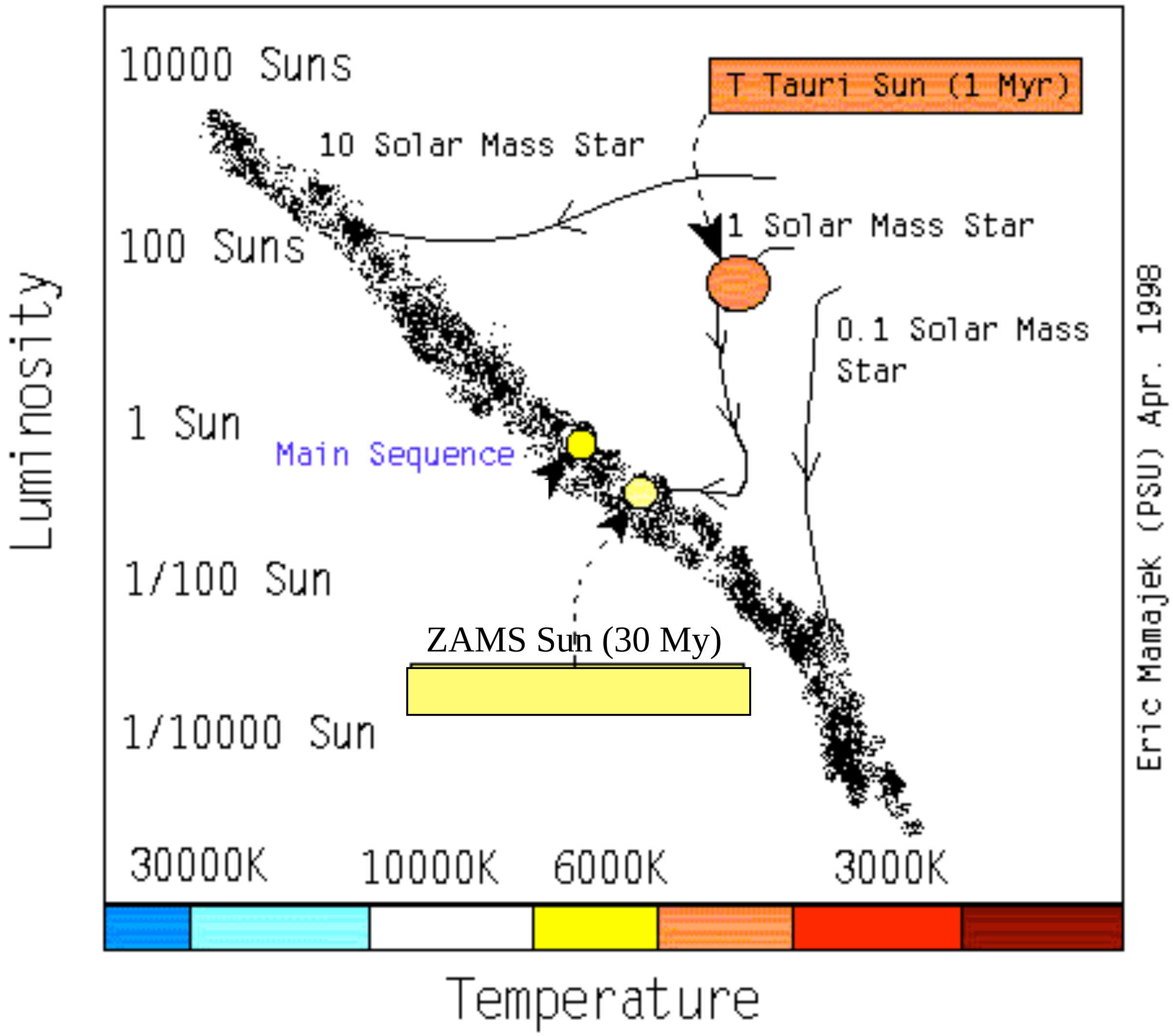
Protoplanetary disks orbit over half of T-Tauri stars.
This shows 5 such stars in the constellation Orion.
Picture using HST - field is about 0.14 ly across
http://en.wikipedia.org/wiki/T_Tauri_star


T-Tauri Star – Drawing
showing accretion disk



30” west of the brightest point in Hind’s nebula is a disk-jet system, Herbig-Haro 30. At the center of this is probably another T-Tauri like star.

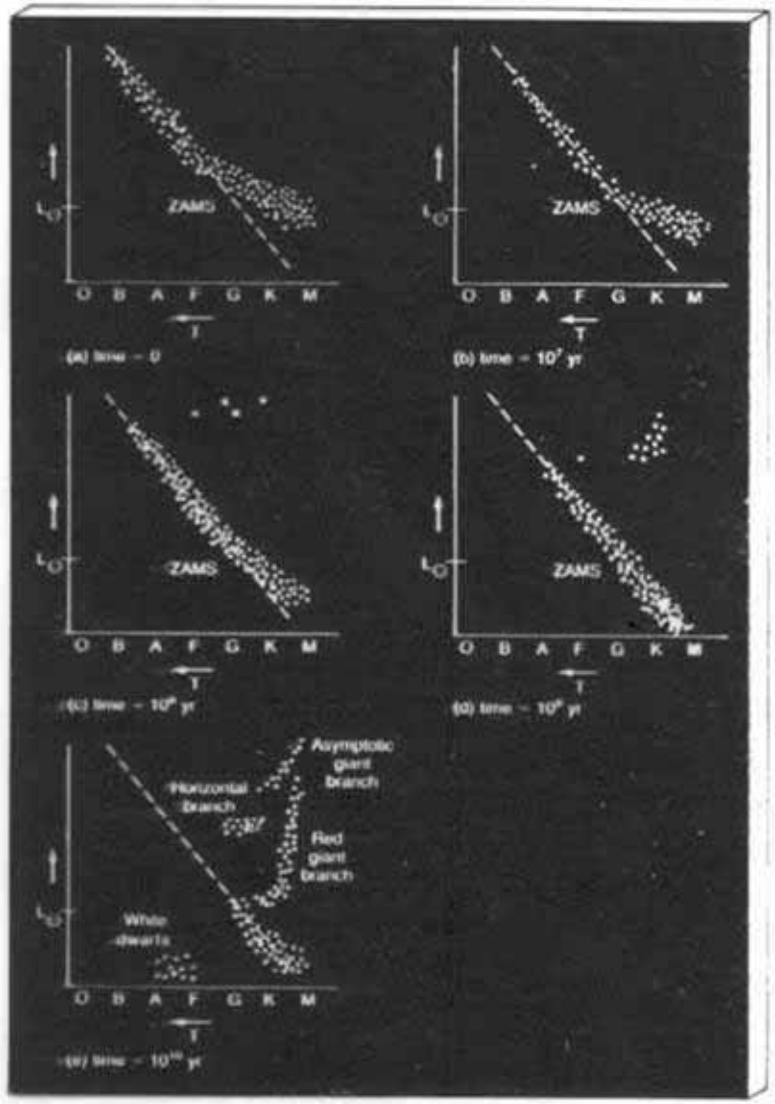
Hertzsprung-Russell Diagram



Protostars start off with very large radii because they begin as contracting clouds of gas. They additionally have high luminosities because they are fully convective (more about this later) and able to transport the energy released by gravitational contraction efficiently to their surface.

Most of the time is spent close to the main sequence.

TM 22-4 HR evolution of hypothetical cluster



$\tau_{KH} \propto \frac{M^2}{RL}$

$L \propto M^3$

$R \uparrow$ with M

$\therefore \tau_{KH} \downarrow$ as $M \uparrow$

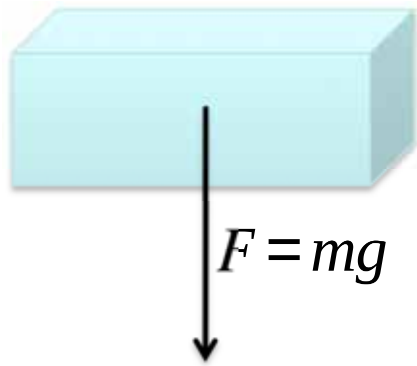
Stellar Interiors - Kinds of Pressure

Pressure is force *per unit area*

$$\text{Pressure} = \frac{\textit{Force}}{\textit{Area}}$$

$$g = \frac{GM_{earth}}{R_{earth}^2} = 980 \text{ cm s}^{-2}$$

Mass 100 gm
Area 100 cm^2



Area 10 cm^2

$$P = \frac{mg}{A} = \frac{(100)(980)}{100} \qquad = \frac{(100)(980)}{10}$$

980 dyne cm^{-2} 9800 dyne cm^{-2}

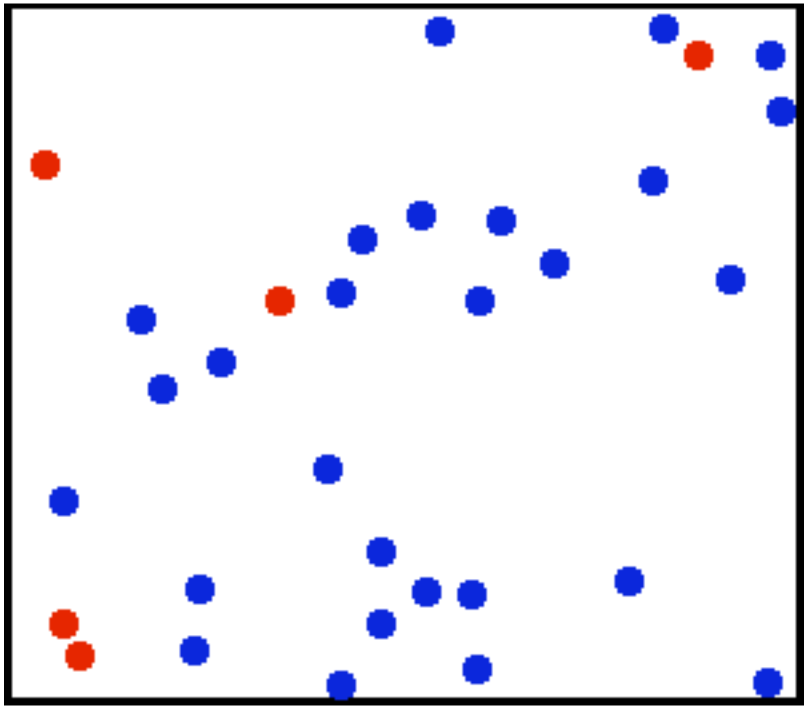
For a gas, pressure is defined as

$$P = \frac{1}{3} \int n(p) v \, p \, dp$$

where *n(p) dp* is the number density (per cm^3) of particles having momentum between *p* and *p+dp*, and *v* is their speed.

Pressure thus has units

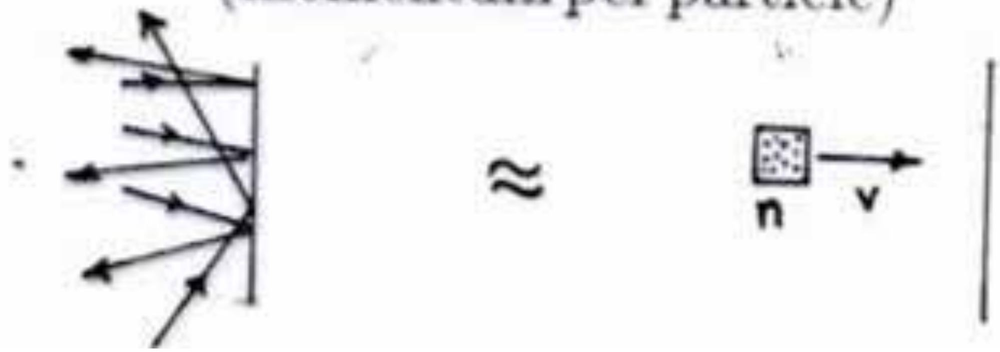
$$\frac{1}{cm^3} \frac{cm}{s} \frac{gm \; cm}{s} = \frac{gm \, cm}{cm^2 \, s^2} = \frac{dyne}{cm^2}$$



http://intro.chem.okstate.edu/1314f00/laboratory/glp.htm

Qualitatively

$$P \sim (\text{number density})(\text{mean velocity})(\text{momentum per particle})$$



Each particle delivers a "kick" = 2 $m\, \Delta v_x$ *where* Δv_x is the change in x-velocity

Approximate this with a group of particles n in one cubic cm all moving to the right with $v_x = v$. The particle flux then = n times v and each particle imparts momentum of roughly mv

$$P \approx (mv)(nv) = n\,m\,v^2$$

IDEAL GAS PRESSURE

- Due to thermal motion of particles such as electrons, atoms, and ions. Particles are assumed to only interact during their collisions.

Qualitatively

$$P \sim (n)(v)(mv) = nmv^2 \sim nkT$$

nb units

$$\frac{\text{gm cm}^2}{\text{cm}^3\,\text{s}^2} = \frac{\text{gm cm}}{\text{s}^2}\,\frac{1}{\text{cm}^2}$$

$$= \frac{\text{dyne}}{\text{cm}^2}$$

$$\left(\text{also } = \frac{\text{dyne cm}}{\text{cm}^3} = \frac{\text{erg}}{\text{cm}^3}\right)$$

In fact,

$$\boxed{P = nkT}$$

where n is the total number of particles per cm^{-3} (both ions and electrons) and T is the temperature in Kelvins. For pure unionized H I, $n = N_A.\rho$. In general,

$$P_{ideal} = \underbrace{8.31 \times 10^7}_{N_A k}\, \rho T F \text{ dyne cm}^{-2}$$

$N_A = 6.023 \times 10^{23}\ \text{gm}^{-1}$
$k = 1.38 \times 10^{-16}\ \text{erg K}^{-1}$

where F = 1 for pure H I, 2 for pure ionized hydrogen (H II), and 1.69 for a mixture of 75% H and 25% He, both completely ionized.

Example: *What is the pressure of a fully ionized gas composed of 75% H and 25% He at a temperature of 10^7 K and a density of 100 g cm^{-3} (similar to solar center when the sun was born)?*

In each cm^3 of gas there are 75 gm of hydrogen and 25 gram of helium.

In 75 gm of hydrogen there are

$$\frac{75\text{ gm}}{m_{proton}} = 75\ \mathrm{N}_A = 75 \times 6.02 \times 10^{23} = 4.52 \times 10^{25} \text{ protons}$$

In 25 gram of helium there are (the helium nucleus weighs approximately 4 m_{proton})

$$\frac{25\text{ gm}}{4m_{proton}} = 6.25\ \mathrm{N}_A = 6.25 \times 6.02 \times 10^{23} = 3.76 \times 10^{24} \text{ helium nuclei}$$

In addition, each hydrogen contributes to the ionized plasma 1 electron and each helium contributes two

$$N = 4.52 \times 10^{25} + \overbrace{4.52 \times 10^{25}}^{\text{electrons}} + 3.76 \times 10^{24} + \overbrace{2(3.76 \times 10^{24})}^{\text{electrons}}$$

$$= 1.02 \times 10^{26} \text{ particles per cm}^3$$

continued…

$$P = nkT = \left(\frac{1.02\times10^{26}}{\text{cm}^3}\right)\overbrace{\left(\frac{1.38\times10^{-16}\ \text{erg}}{\text{K}}\right)}^{\text{k}}\left(10^7\ \text{K}\right)$$

$$= 1.40\times10^{17}\ \text{dyne cm}^{-2} \qquad \frac{\text{erg}}{\text{cm}^3} = \frac{\text{dyne cm}}{\text{cm}^3}$$

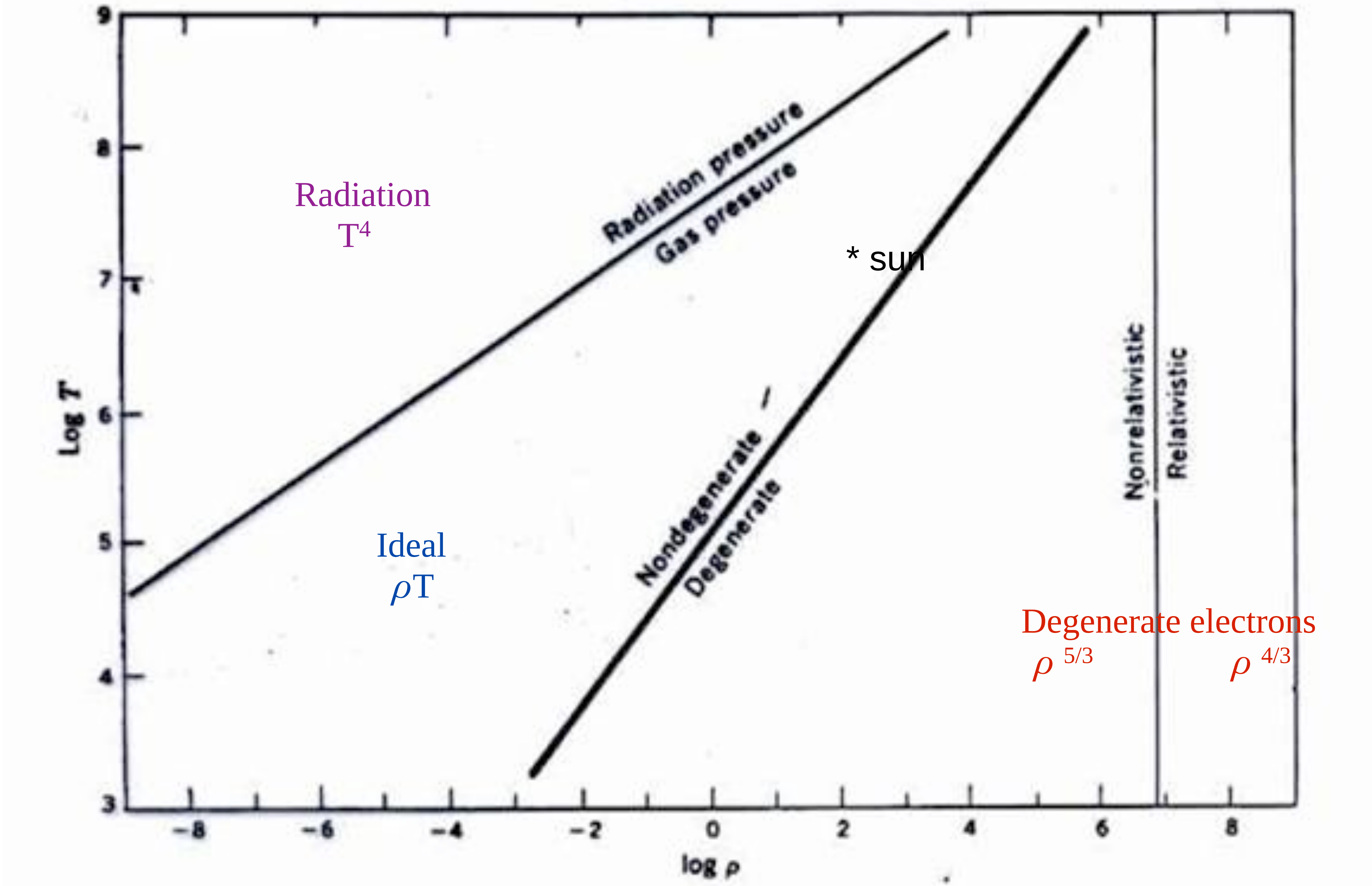
But it is easier and just as accurate to use the formula

$$P = 8.31\times10^7\,\rho T F$$

$$= \left(8.31\times10^7\right)(100)\left(10^7\right)(1.69)$$

$$= 1.40\times10^{17}\ \text{dyne cm}^{-2}$$

Most main sequence stars have pressures that are dominantly ideal gas pressure



DEGENERACY PRESSURE

Pressure due entirely to the Uncertainty Principle

Suppose one packs as many electrons with momentum p into a volume, V, as are quantum mechanically allowed ("Pauli exclusion principle")

$$\Delta x \cdot p \approx h$$

Each pair of electrons occupies a cell of size ~ $(\Delta x)^3$, but Δx ~ h/p

Number of cells in volume V $= \dfrac{V}{(\Delta x)^3} = \dfrac{Vp^3}{h^3}$

Number of electrons, N, in volume V = $\dfrac{2Vp^3}{h^3}$

Number of electrons per unit volume $n_e = \dfrac{N}{V} = \dfrac{2p^3}{h^3}$

So, $p_F \sim \left(\dfrac{n_e h^3}{2}\right)^{1/3}$

This is commonly called the "Fermi Momentum"

http://en.wikipedia.org/wiki/Electron_degeneracy_pressure

http://en.wikipedia.org/wiki/Pauli_exclusion_principle

DEGENERACY PRESSURE

Now the pressure

$$P \sim n_e \, p_F \, v = n_e p_F \frac{mv}{m} = \frac{n_e \, p_F^2}{m}$$

$$\sim \frac{n_e}{m} \left(\frac{n_e \, h^3}{2} \right)^{2/3}$$

$$P_{deg} \sim \frac{h^2 \, n_e^{5/3}}{2^{2/3} \, m}$$

The contribution of electrons, when present, is much larger than from neutrons or protons because of the 1/m

As n_e goes up the speed of each electron rises

$$p_F = m_e v \approx \left(\frac{n_e h^3}{2}\right)^{1/3} \quad \text{more accurately} \quad \left(\frac{3}{8\pi} n_e h^3\right)^{1/3}$$

$$v = \frac{1}{m_e}\left(n_e\left(\frac{3h^3}{8\pi}\right)\right)^{1/3} \qquad n_e \approx \frac{1}{2}\rho N_A$$

for elements other than H

$$v = \left(\frac{3\rho N_A h^3}{16\pi m_e^3}\right)^{1/3} \approx 2\ x\ 10^{10}\left(\frac{\rho}{10^6 \text{ gm cm}^{-3}}\right)^{1/3} \text{cm s}^{-1}$$

At around 10^7 gm cm^{-3} the electrons will move close to the speed of light.

$$\text{"}non-relativistic\text{"}\text{ degeneracy pressure} = \mathrm{P}_{NRD}$$

$$\mathrm{P}_{NRD} \sim \frac{n_e p_F^2}{m_e} = \frac{n_e \left(\frac{n_e h^3}{2} \right)^{2/3}}{m}$$

$$= \frac{h^2}{2^{2/3} m_e} n_e^{5/3}$$

A more accurate calculation gives

$$\mathrm{P}_{NRD} = \frac{1}{20} \left(\frac{3}{\pi} \right)^{2/3} \frac{h^2}{m_e} n_e^{5/3}$$

http://scienceworld.wolfram.com/physics/ElectronDegeneracyPressure.html

For charge neutrality, number of electrons = number of protons and for pure hydrogen, $n_e = N_A \rho$.

For other compositions, $n_e = N_A \rho Y_e$ where $(Y_e)^{-1}$ is the number of electrons per atomic mass unit in the neutral atom. E.g., $Y_e = 1$ for hydrogen, 0.5 for ^{4}He, ^{12}C, etc, and 0.88 for 75% H and 25% He.

usually where P_{deg} is important $Y_e = 0.5$

Then

$$P_{deg}^{NR} = 1.00 \times 10^{13} (\rho Y_e)^{5/3} \text{ dyne cm}^{-2}$$

$\rho \lesssim 10^7 \frac{g}{cm^3}$

Note that the degeneracy pressure depends only on the density and not on the temperature

RELATIVISTIC DEGENERACY PRESSURE

The above remains true only so long as v of the electrons remains << c. As v approaches c

$$P_{deg} \sim (n_e)(c)(p) \sim n_e^{4/3}$$

$(p \propto n_e^{1/3})$

and in fact

$$P_{deg}^R = 1.24 \times 10^{15}(\rho Y_e)^{4/3}\,\mathrm{dyne\,cm^{-2}}$$

$\rho \gtrsim 10^7\ \mathrm{g/cm^3}$

Once the electrons move near the speed of light, the pressure does not increase as rapidly with density as before.

RADIATION PRESSURE

Because electromagnetic radiation (light) carries energy, it also carries momentum. In general, for non-relativistic motion ($v << c$), momentum = (2)(kinetic energy)/(velocity), e.g., $2(1/2mv^2)/v = mv = p$. For photons the relation is a little different.

$$p = E/c = h\nu/c$$

THE "PRESSURE" OF SUNLIGHT

From the sun, at the earth's orbit (1AU), we receive a flux of radiation

$$\phi = \frac{L}{4\pi d^2} = \frac{L_\odot}{4\pi(AU)^2}$$

$$= 1.37 \times 10^6 \text{ erg cm}^{-2} \text{ s}^{-1}$$

This corresponds to a momentum flux, or pressure of

$$P = \frac{\phi}{c} = \frac{(1.37\times10^6)}{(3.00\times10^{10})} \frac{\text{erg} \qquad (\text{s})}{\text{cm}^2 \text{s} \ (\text{cm})}$$

$$= 4.57\times10^{-5} \frac{\text{dyne}}{\text{cm}^2} \quad \text{since (dyne)(cm)} = \text{erg}$$

(1 square meter (10^4 cm^2) would be accelerated 0.46 cm/s^2 if it weighed 1 gm)

1997 Comet Hale Bop

The pressure is then

$$
\begin{aligned}
P &\sim \text{(number flux)(momentum per photon)} \\
&= \left(\frac{\text{E flux}}{\text{energy per photon}}\right)\text{(momentum per photon)} \\
&= \left(\frac{\sigma T^4}{h\nu}\right)\left(\frac{h\nu}{c}\right) \\
&= \frac{\sigma}{c} T^4
\end{aligned}
$$

In fact the correct expression is

$$\boxed{P_{rad} = \frac{4\sigma}{3c} T^4 = \frac{1}{3} a T^4}$$

where $a = 7.56 \times 10^{-15}$ dyne cm^{-2} (K)$^{-4}$. $= \frac{4\sigma}{c}$

IN SUMMARY

There are 3 kinds of pressure:

- Ideal gas pressure ($\propto \rho$ and T)
- Radiation pressure ($\propto T^4$)
- Degeneracy pressure ($\propto \rho^n$) $4/3 < n < 5/3$

The *total* pressure is given by

$$P_{tot} = P_{ion} + P_{rad} + P_e$$

Except in neutron stars, P_{ion} is ideal. P_e can be quite complex (semidegenerate, semirelativistic) which can lead to some difficult math (Fermi integrals) which we will not consider.

Most main sequence stars have pressures that are dominantly ideal gas pressure