AY 20 Fall 2010

STAR FORMATION and PRE-MAIN SEQUENCE EVOLUTION

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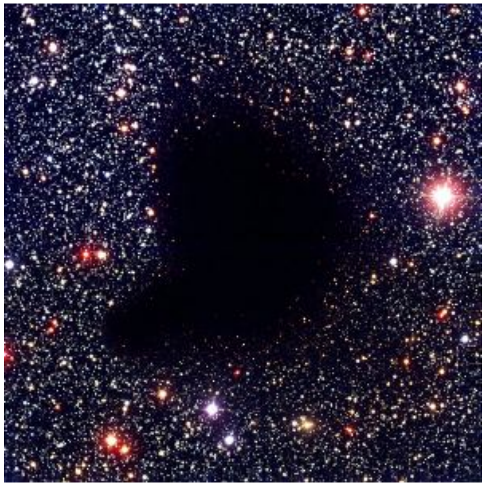
Reading: Carroll & Ostile, Chaper 12.2 and 12.3

From the last class: **Jeans criteria**

Barnard 68: dark nebula



The collapse conditions are set from the balance between the gas pressure (i.e. temperature) and the cloud gravity (i.e. density)

Virial Theorem

$$2K + U = 0$$

$2K > U$ Expansion

$2K < U$ Collapse

Sir James Jeans (1877-1946)

The derivation: see previous lesson (Carroll, 12.2)

Jeans mass

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

Jeans length

$$R_J = \left(\frac{15kT}{4\pi G\mu m_H \rho_0}\right)^{1/2}$$

From the last class: **Free-fall collapse**

If $M_c > M_J$ the core collapses. The cloud is optically thin and the gravitational energy is radiated away.

Hydrostatic equilibrium

$$\rho_0 \frac{d^2 r}{dt^2} = -G\frac{M_c \rho_0}{r^2} - \cancel{\frac{dP}{dr}} \xrightarrow[\text{collapse}]{\text{Isothermal}} \frac{d^2 r}{dt^2} = -G\frac{M_c}{r^2}$$

Free-fall

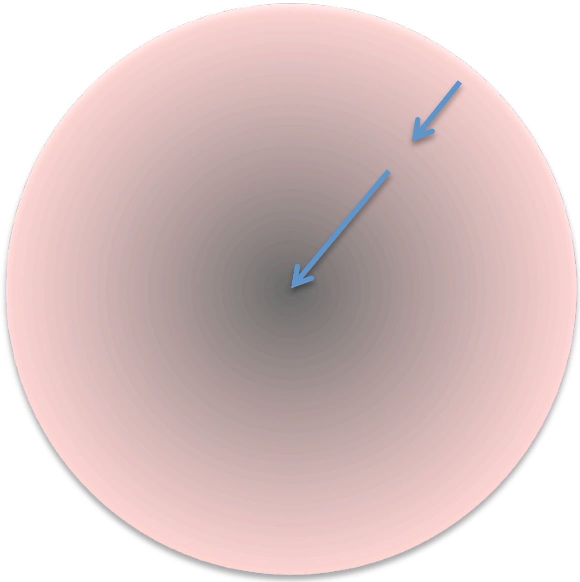
$$\boxed{t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2} = \left(\frac{\pi^2}{8}\frac{R_c^3}{GM_c}\right)^{1/2} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2}}$$

Homologous collapse

Typical numbers for the free-fall time scale

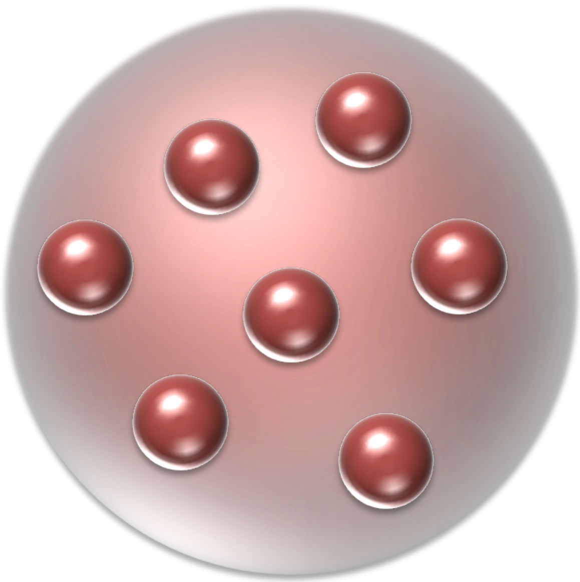
T = 10 K, M_c=1 Msun, R_c=0.1 pc, $\rho=10^{-17}$ kg m^{-3} :: **$t_{ff} \approx 4 \times 10^5$ yr**

From the last class: **Fragmentation of the collapsing could**



If the core density is not uniform, e.g., larger in the center, then the central part collapses faster than the outer part: INSIDE-OUT collapse

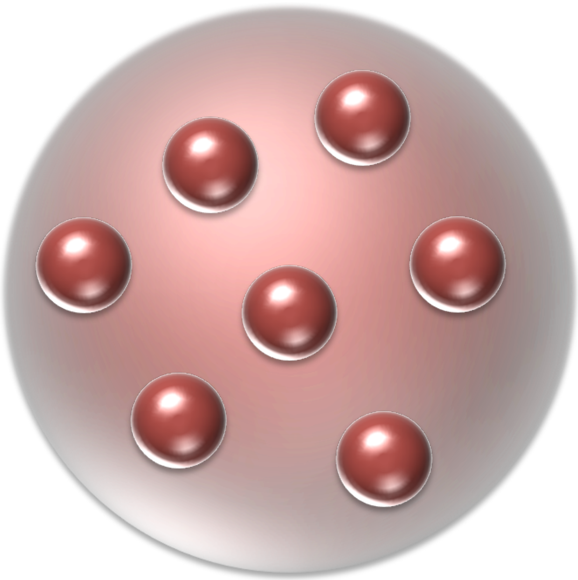
From the last class: **Fragmentation of the collapsing could**



During the collapse, T remain constant (10-100 K) and the density increases with time. These to facts imply that M_J decreases with time. The collapsing cloud can fragment.

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2}\left(\frac{3}{4\pi\rho_0}\right)^{1/2}$$

From the last class: **Adiabatic collapse stops the fragmentation**



As the density increases ($\rho > 10^{-10}$ kg m^{-3}) the core becomes more optically thick to the released gravitational radiation, the temperature starts to increase and the collapse becomes more adiabatic

$\frac{dP}{dr} < G\frac{M_c \rho_0}{r^2}$ The collapse slows down

$T \propto \rho^{\gamma - 1}$ The temperature increases

$$M_J = \left(\frac{5kT}{G\mu m_H}\right)^{3/2} \left(\frac{3}{4\pi\rho_0}\right)^{1/2} \propto \rho^{(3\gamma - 4)/2}$$

For mono atomic gas (i.e. H), γ=5/3 $M_J \propto \rho^{1/2}$

During free-fall: $M_J \propto \rho^{-1/2}$

This leads to a minimum mass of 0.2-0.5 Msun

Formation of a protostar: qualitative description of a spherical collapse

- 1 Msun cloud, initially follows the isothermal free-fall collapse with $t_{ff} \approx 10^5$ yr
- At $\rho \approx 10^{-10}$ kg m^{-3}, the cloud becomes more optically thick (due to the dust opacity) and the collapse more adiabatic (temperature increases)
- The gas pressure increases and the collapse slows down.
- The gravitational energy is converted into heat and radiated away as a b-b radiation.
- The core is *nearly* in hydrostatic equilibrium at a radius of about 5 AU. This is a protostar
- We can define a surface at $\tau = 2/3$ (as for the stellar surface), and an effective temperature $T_{eff}=T(\tau = 2/3)$. The stellar surface is “cold” <1000 K and rich of dust which dominates the opacity

$$L = 4\pi R^2 \sigma T_{eff}^4$$

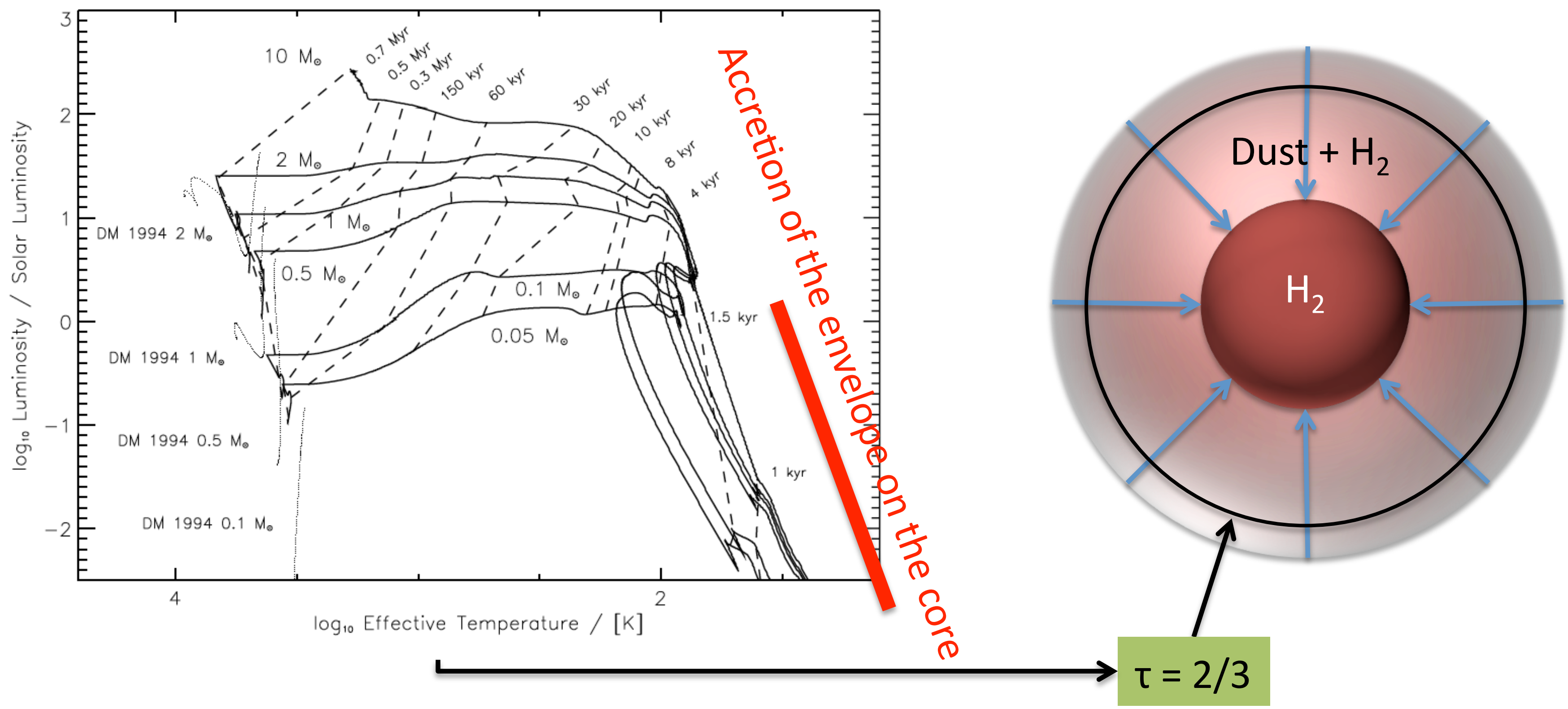
- The temperature increases toward the center of the protostar.
- A density increase toward the center leads to an INSIDE-OUT collapse, the core collapse becomes adiabatic before the collapse of the envelope.
- The envelope still collapses on a free-fall time scale and this can produce a shock front where the material falls on the core

We can follow the evolution of a protostar on the (theoretical) H-R diagram, i.e., plotting Log(L/Lsun) Vs Log(T_{eff})

Evolution of a protostar: theoretical evolutionary tracks – 1 Msun

The luminosity during the protostellar phase is provided by the accretion luminosity, the release of gravitational energy, and, in the last phase, by the Deuterium burning

H_2 core : 1000-1500 K < T
Dusty envelope : T < 1000 – 1500 K

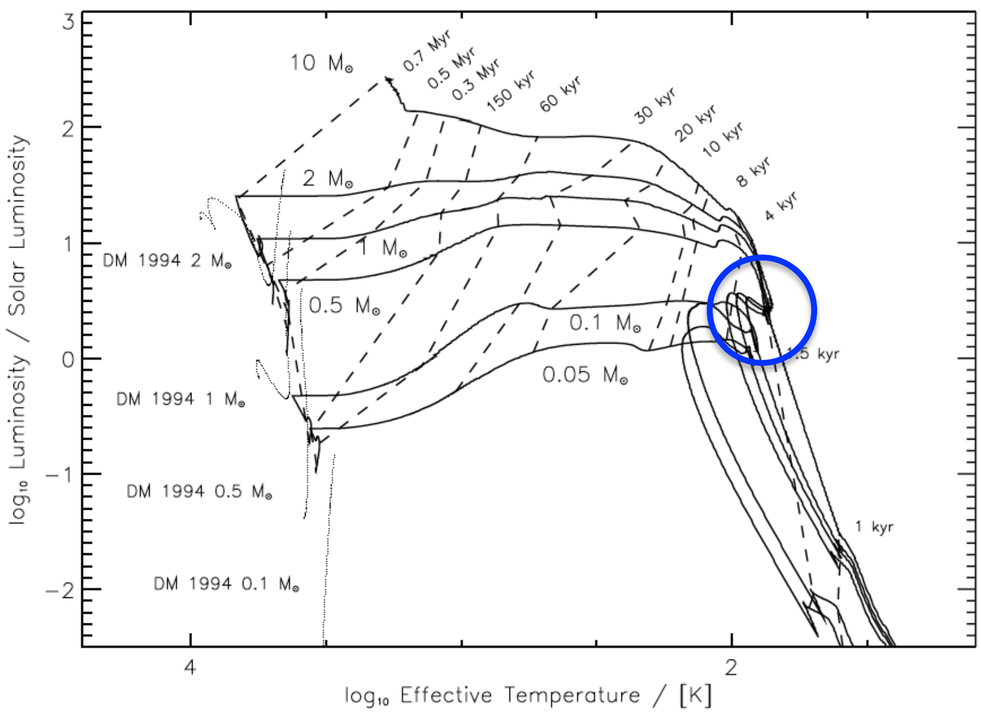


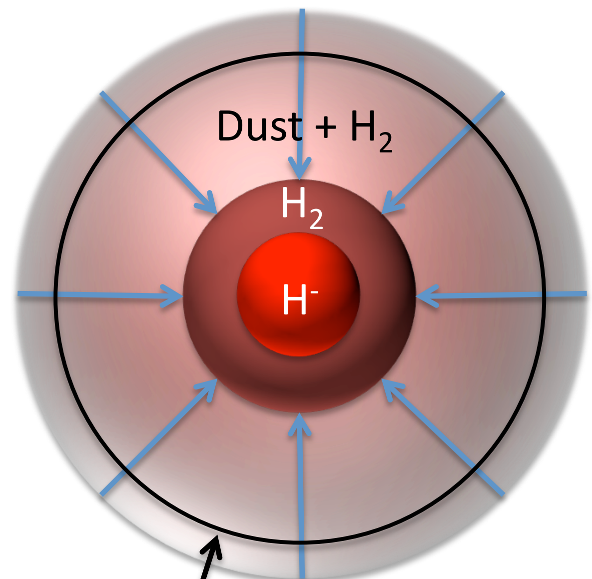
Suggested reading: Wuchterl & Tscharnuter, 2003, A&A, 398, 1081

Evolution of a protostar: theoretical evolutionary tracks

The luminosity during the protostellar phase is provided by the accretion luminosity, the release of gravitational energy, and, in the last phase, by the Deuterium burning

Formation of H^- core when T > 1800-2000 K.
H_2 shell : 1000-1500 K < T <1800-2000 K
Dusty envelope : T < 1000 – 1500 K





τ = 2/3

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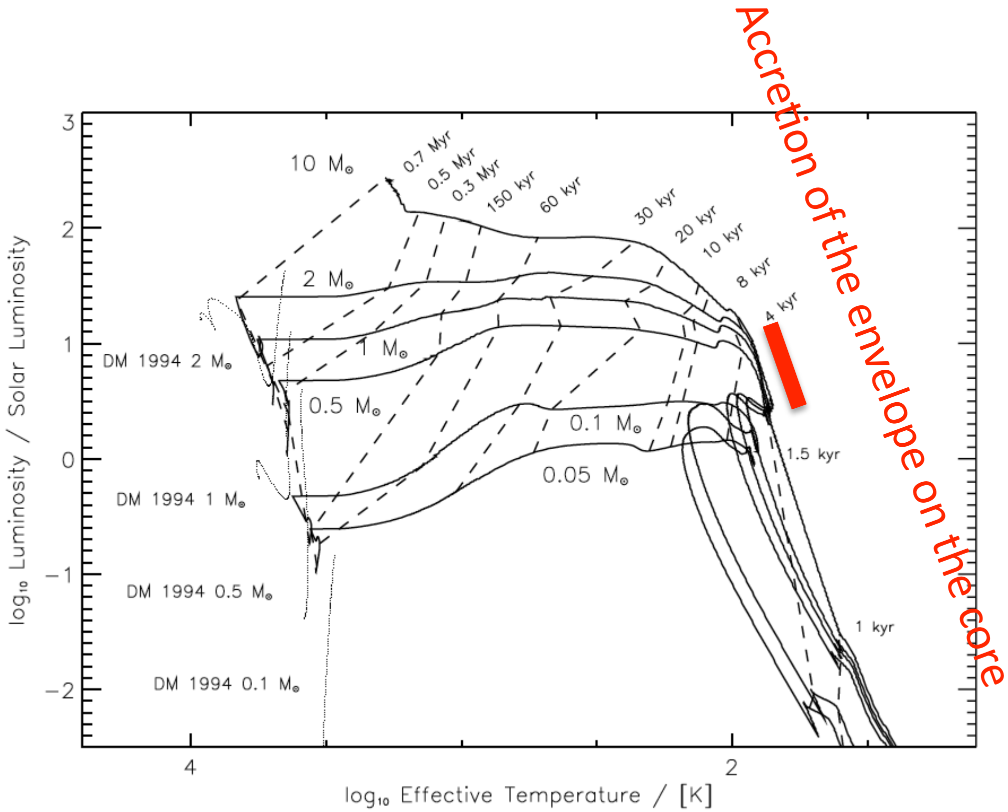
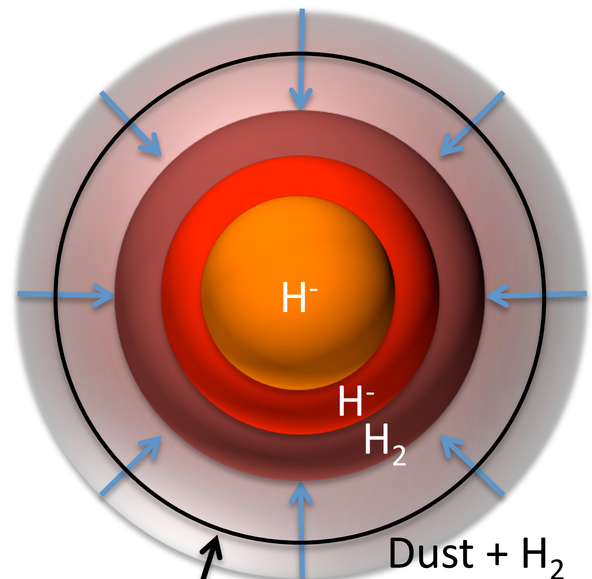


$T > 10^4$ K, He is ionized
Formation of H^- core when T > 1800-2000 K.
H_2 shell : 1000-1500 K < T <1800-2000 K
Dusty envelope : T < 1000 – 1500 K



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Evolution of a protostar: theoretical evolutionary tracks

The luminosity during the protostellar phase is provided by the accretion luminosity, the release of gravitational energy, and, in the last phase, by the Deuterium burning

The material in the envelope is depleted and the Accretion luminosity decreases
$T > 10^5$ K, all gas is ionized
Formation of H^- core when $T > 1800$-2000 K.
H_2 shell : 1000-1500 K < T <1800-2000 K
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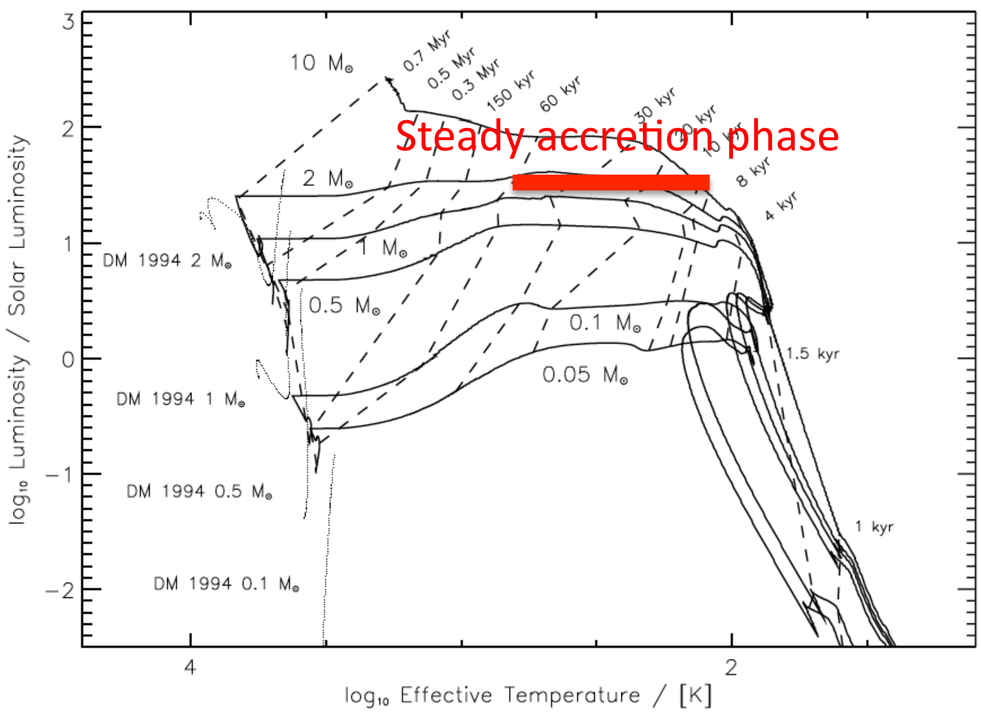

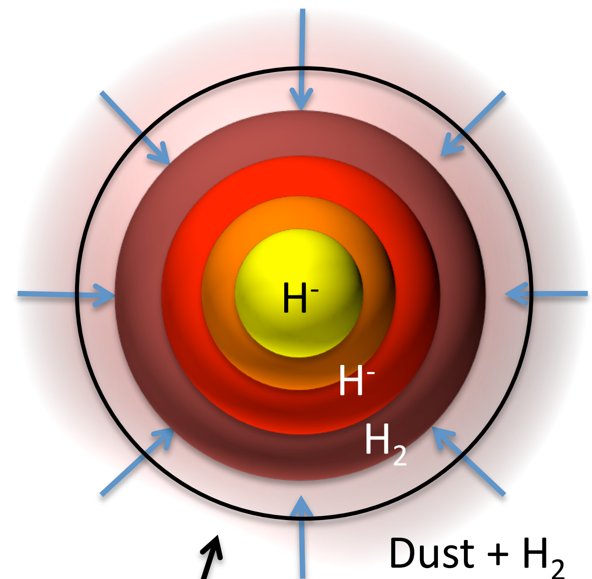

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The luminosity during the protostellar phase is provided by the accretion luminosity, the release of gravitational energy, and, in the last phase, by the Deuterium burning

When Teff > 1000-1500 K, the dust evaporate and the radius decreases to the size of the hydrostatic core
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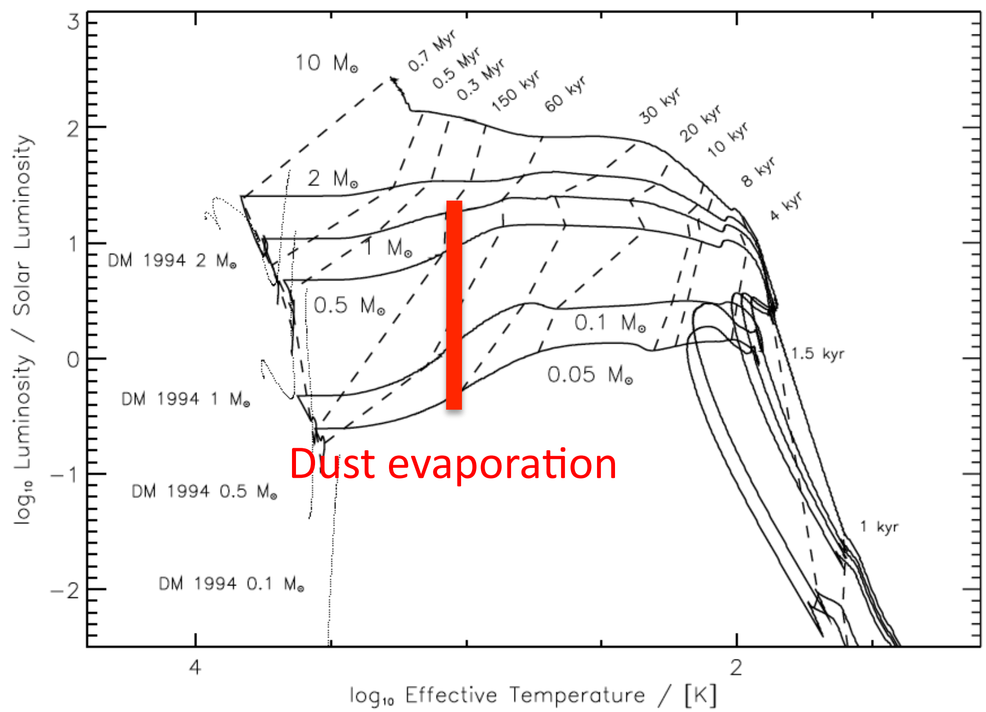

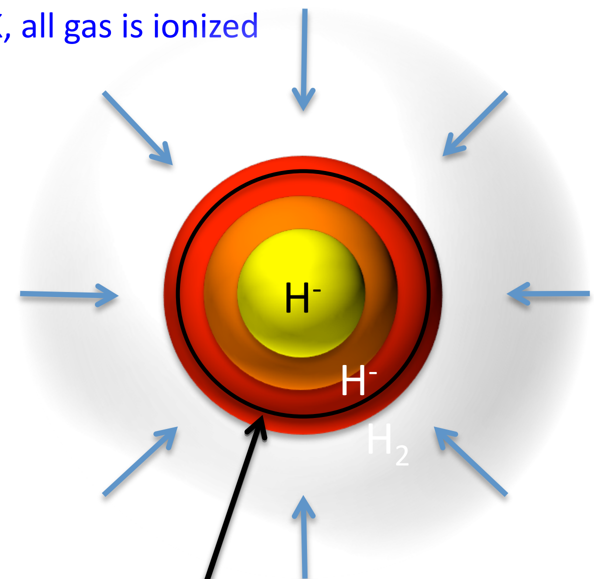

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Evolution of a protostar: theoretical evolutionary tracks

The luminosity during the protostellar phase is provided by the accretion luminosity, the release of gravitational energy, and, in the last phase, by the Deuterium burning

D burning (^2H +p -> $^3He+\gamma$) provides 60% of the total luminosity.
The envelope is convective. The protostar might be completely convective. Opacity due to H^-
When Teff > 1000-1500 K, the dust evaporate and the radius decreases to the size of the hydrostatic core
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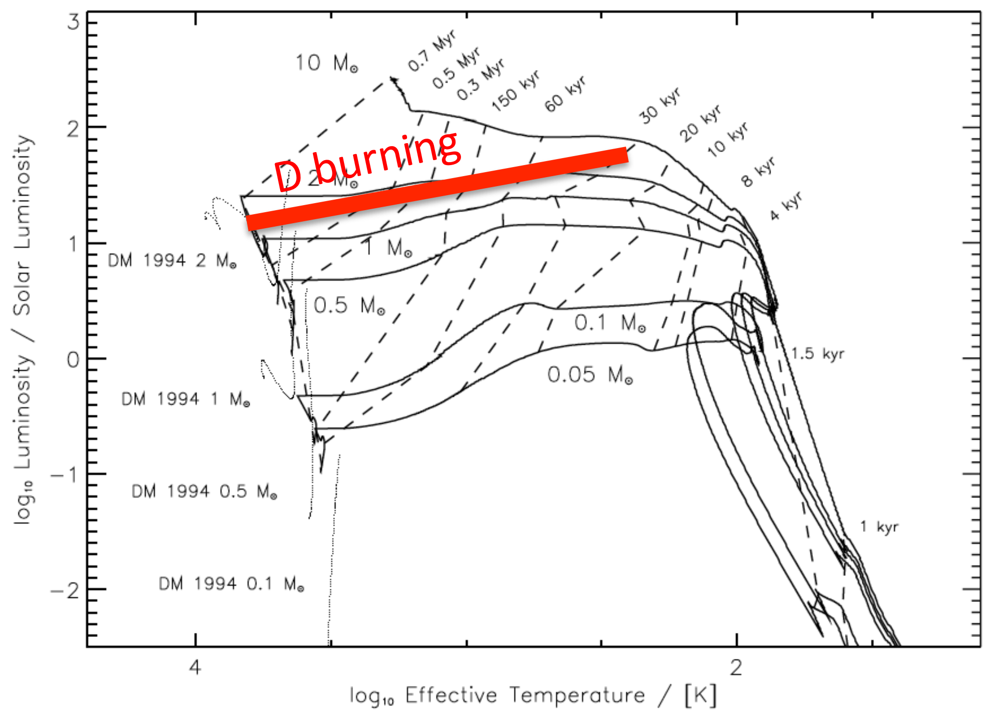

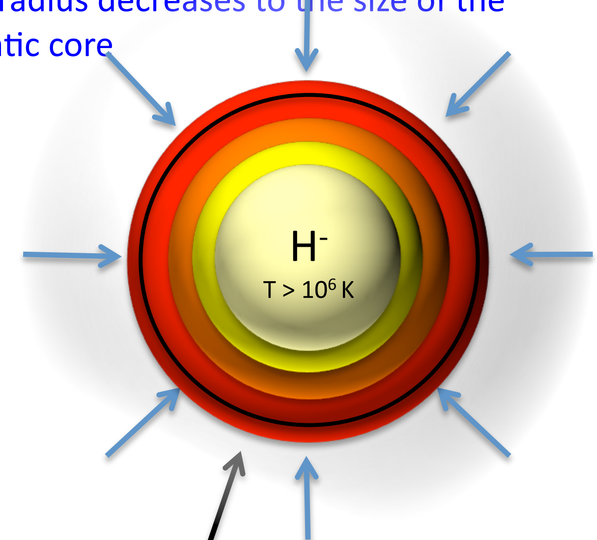

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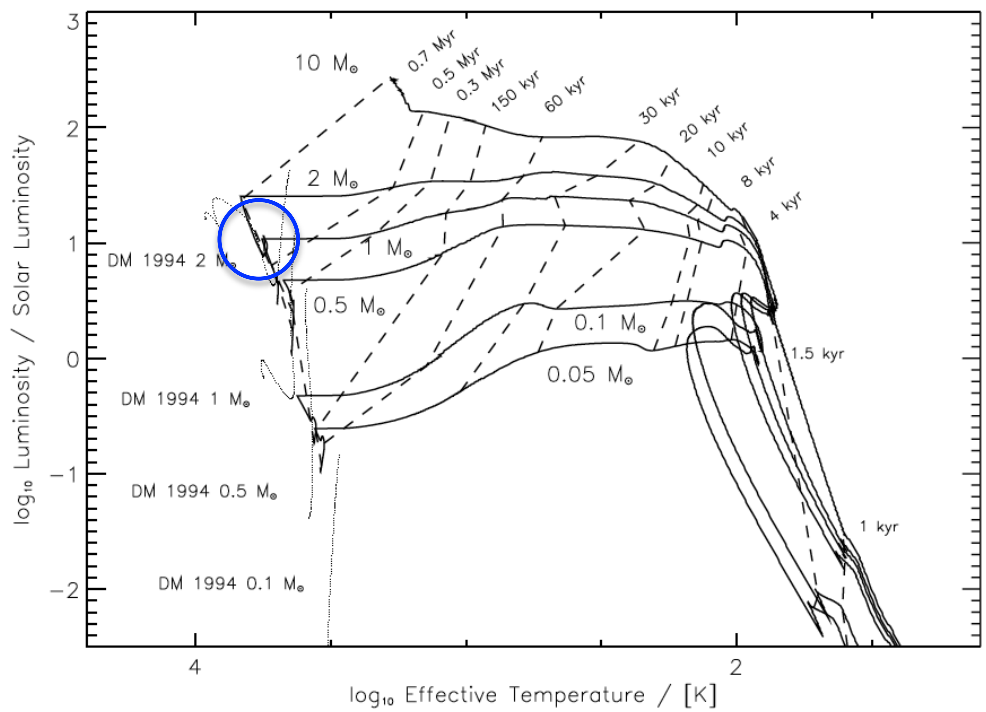
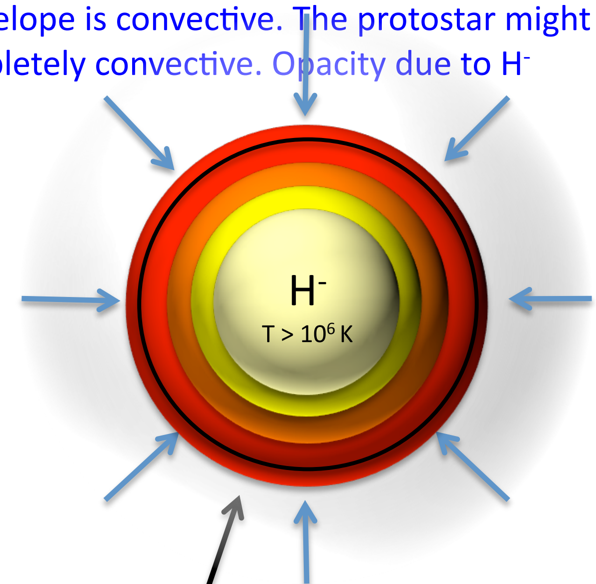


Deuterium burn-out in the central core. T and L decrease slightly.
D burning (^{2}H +p -> ^{3}He+γ) provides 60% of the total luminosity.
The envelope is convective. The protostar might be completely convective. Opacity due to H$^-$
...



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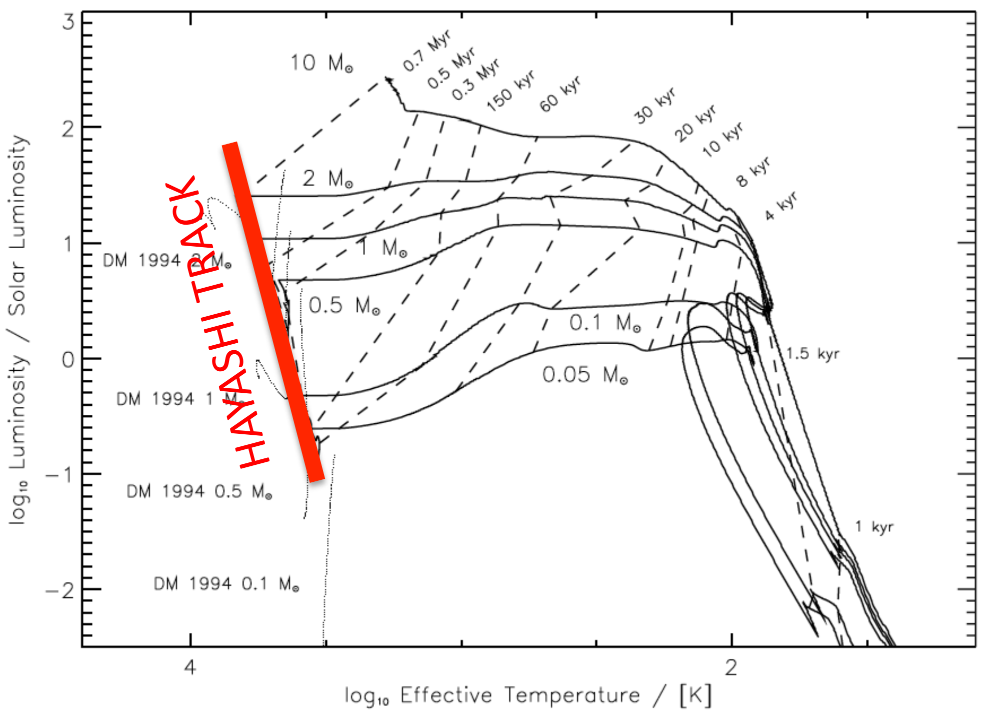
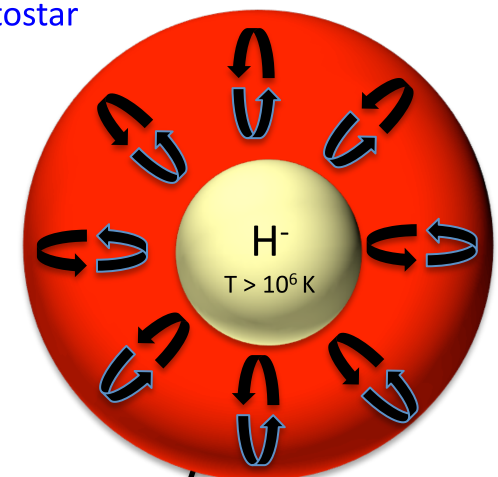


Quasi-static premain-sequence phase.
The envelope is convective. The protostar might be completely convective. The thickness of the convective layer depends on the stellar mass.
The convection limits the amount of energy lost by the protostar



$\tau = 2/3$

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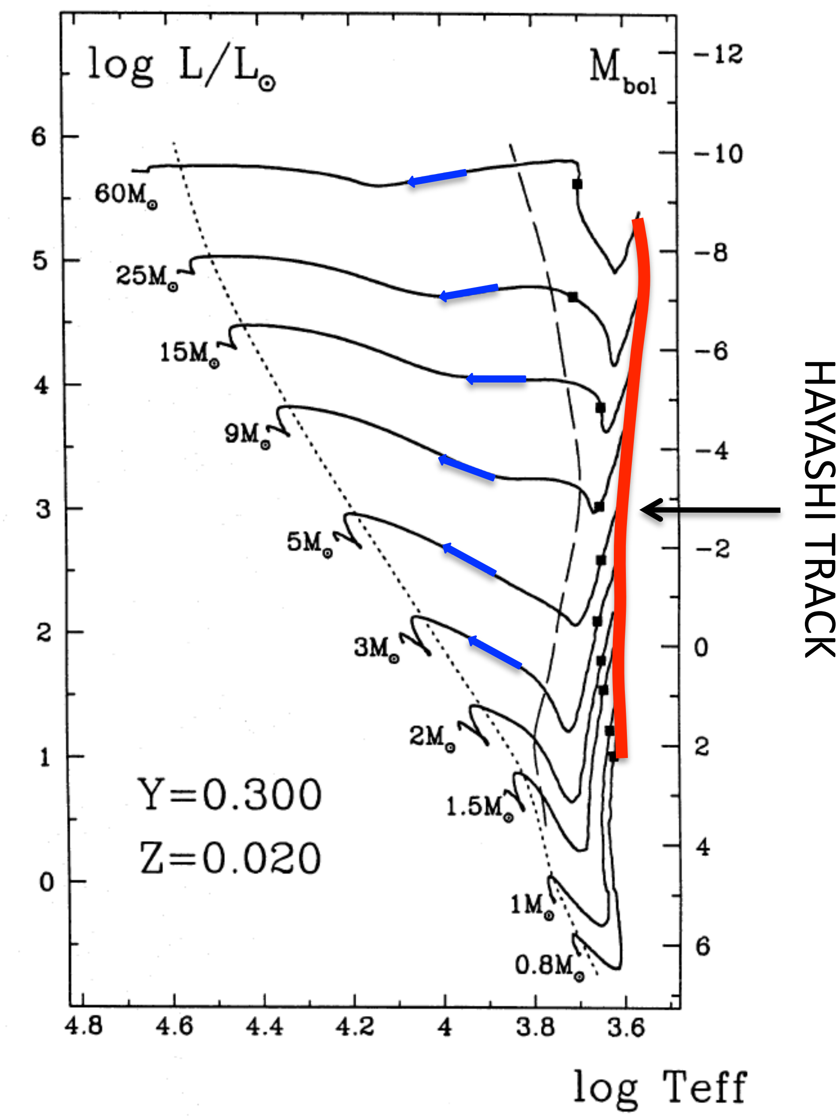
Evolution of a protostar: HAYASHI track



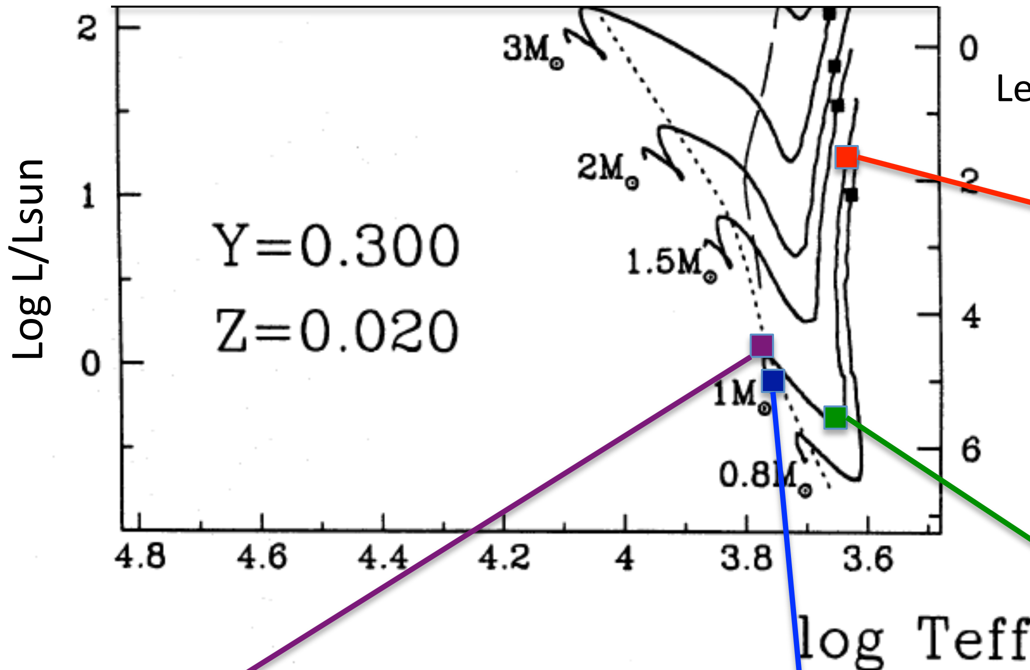
- The protostar stops contracting
- Evolve on Kelvin-Helmholtz time scale

$$t_{KH} = \frac{\Delta E_g}{L_{sun}} \approx 10^7\, yr >> t_{ff} \approx 10^4\, yr$$

- the propostars can be convective or radiative, depending on the mass

Left of HAYASHI track	Right of HAYASHI track
The core structure is in equilibrium, i.e., the luminosity can be transported out by convection or radiation	The core structure is unstable. Free fall evolution in not hydrodynamic equilibrium

Evolution of a protostar: HAYASHI track and Zero-age main sequence



Let's follow the evolution of a 1 Msun protostar:

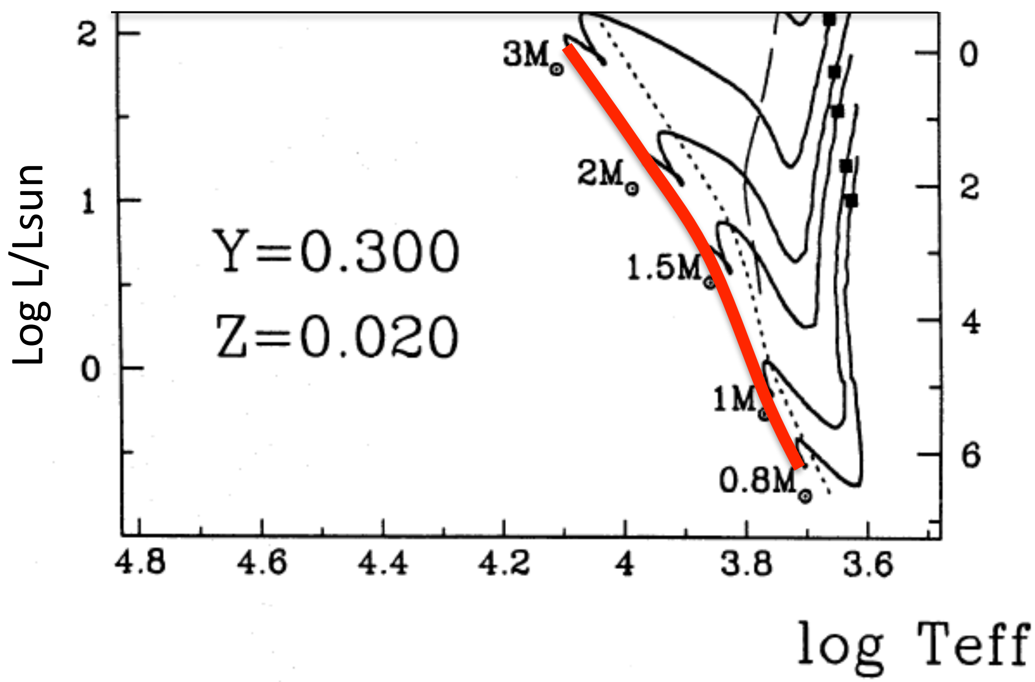
Deuterium burning continue but it is not very effective is slowing down the collapse. The opacity is dominated by H^- and the star remains fully convective for about 1Myr

As the core temperature increases, the gas becomes ionized and the opacity decreases. The core becomes radiative and more energy is released in the envelope. The luminosity starts to rise again. The temperature increases and nuclear reactions start: PP I (H+H-> 2H+..,2H+H->3He+..) and CNO

The energy released in the CNO forces the core to expand. The gravitational luminosity becomes negative and the total luminosity decreases slightly.

When the C is exhausted, the core contract again and the temperature reaches 10^7 K. PP I chain stars. The protostar has reached the zero-age main sequence.

Evolution of a protostar: Zero-age main sequence



Time to reach the main sequence goes as 1/Mstar

1 Msun = 4 x 10^7 yr (very close to the t_{KH})
3 Msun = 7 x 10^6 yr
9 Msun = 3 x 10^5 yr
15 Msun = 1 x 10^4 yr

Hydrogen burning, star is in hydrostatic equilibrium. Stellar life time on the main sequence is set by the Hydrogen Burning "lifetime"

For the Sun is $t_n \approx 10^{10}$ yr

Kelvin-Helmholtz
From Hayashi to main sequence

$$t_{KH} = \frac{3}{10}\frac{GM_*^2}{R_*}\frac{1}{L_*} \approx 10^7\,yr$$

Free-fall
To reach the Hayashi track

$$t_{ff} = \left(\frac{3\pi}{32}\frac{1}{G\rho_0}\right)^{1/2} \approx 4\times 10^5\,yr$$

$t_n >> t_{KH} >> t_{ff}$ → Most stars are observed on the main sequence

Brown Dwarfs

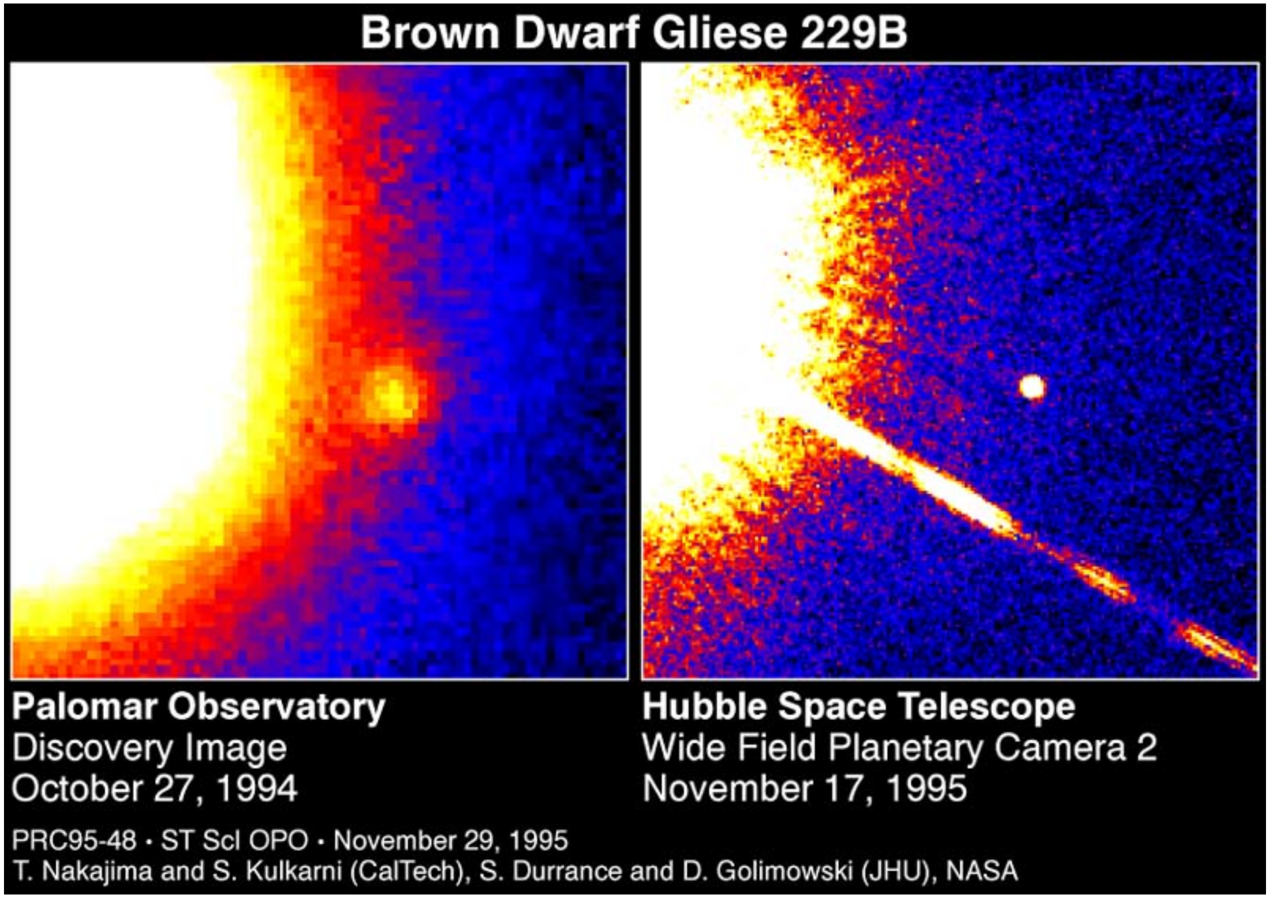
Below 0.08 Msun – No stable nuclear reactions
0.002 Msun < Mstar < 0.08 Msun : Brown dwarfs
High opacity, low temperature: the core is fully convective
Energy sources: gravitational collapse, perhaps Deuterium burning (10^5 – 10^6 yr), NO H burning

Recall: PP I chain – D Burning most easily initiated in pre-main sequence phase

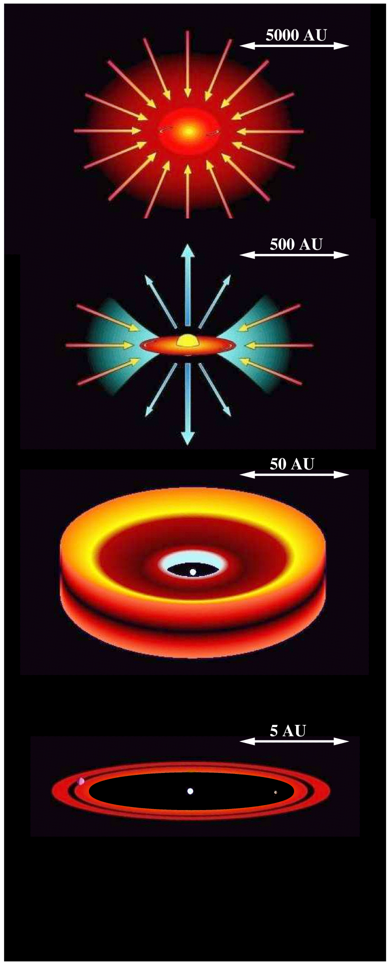
$$^1_1H + ^1_1H \rightarrow ^2_1H + e^+ + \nu_e$$
$$^2_1H + ^1_1H \rightarrow ^3_2He + \gamma$$
$$^3_2He + ^3_2He \rightarrow ^4_2He + 2\,^1_1H$$

EXAMPLE: Gliese229B

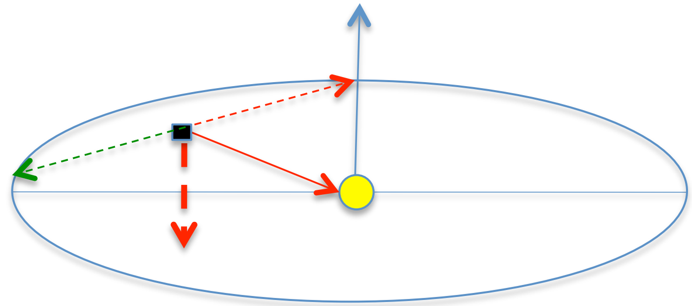
Distance = 5.8 pc
Mass = 20-50 M_J
0.02-0.05 Msun
T_{eff} = 950 K !



Circumstellar disks and planetary systems



- Molecular cores rotate.
- The angular momentum is conserved during the collapse $\vec{L} = \vec{r} \times \vec{p} = \vec{r} \times m\vec{v}$
- The cloud rotate faster and flattens



- Collapse impeded when the centripetal force (v^2/r) is balanced by the gravitational force. If the core is in rigid rotation

Measured observing velocity gradients in dense cores

$$R_c \approx 50 \times \left(\frac{\omega_c}{10^{-14}\,s^{-1}}\right)^2 \left(\frac{M_*}{1M_{sun}}\right)^3 AU$$

Suggested reading: Hueso & Guillot (2005)

- disk carries most of the angular momentum

R=0.1 pc, M=1 Msun, v = 1 km s^{-1}

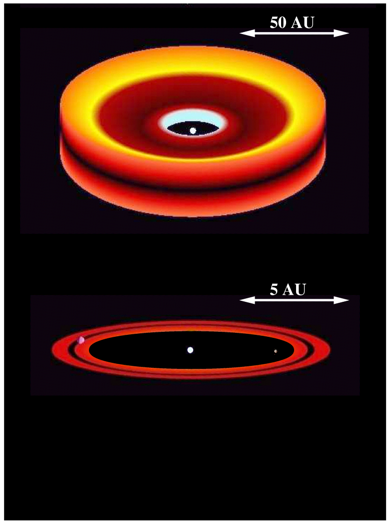
R=1 Rsun, M=1 Msun

$$m_i v_i r_i = m_f v_f r_f$$

$$v_f = v_f r_f / r_i \approx 5 \times 10^6 \; km/s$$

Untenable for star!

Circumstellar disks and planetary systems



$$R_c \approx 50 \times \left(\frac{\omega_c}{10^{-14}\, s^{-1}} \right)^2 \left(\frac{M_*}{1 M_{sun}} \right)^3 AU$$

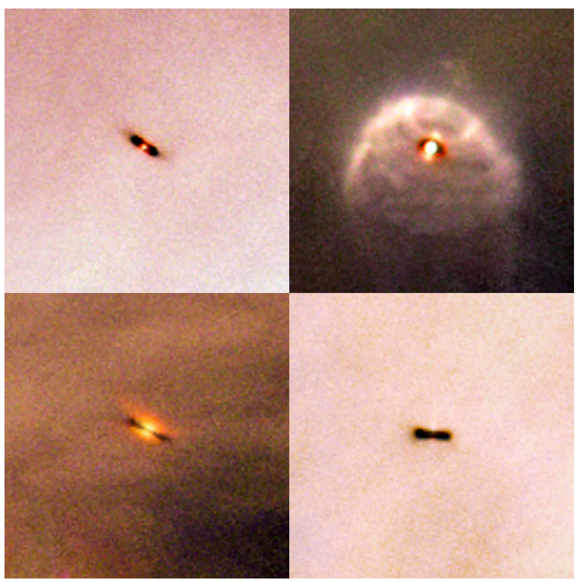
Comparable to the size of the Solar System

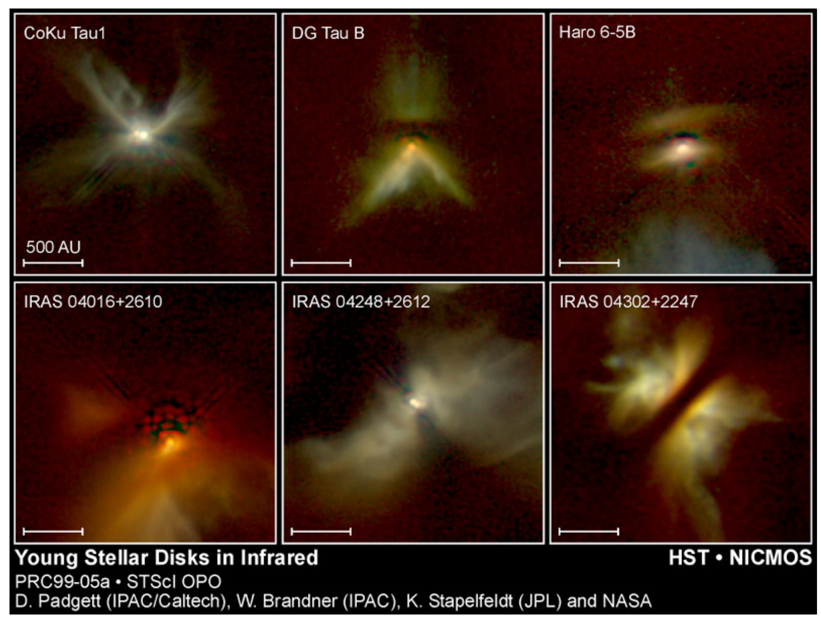
• disk is accreting on the central star at a rate of $10^{-7/-8}$ Msun/yr.
The disk is dispersed after ~ 10-30 Myr ~ t_{KH}
• Dust particles grow from 10^{-8} m (ISM) to 10^{6} m (planets) !

Observational evidences: R~150 AU, d~150 pc (i.e. Taurus), θ~1”

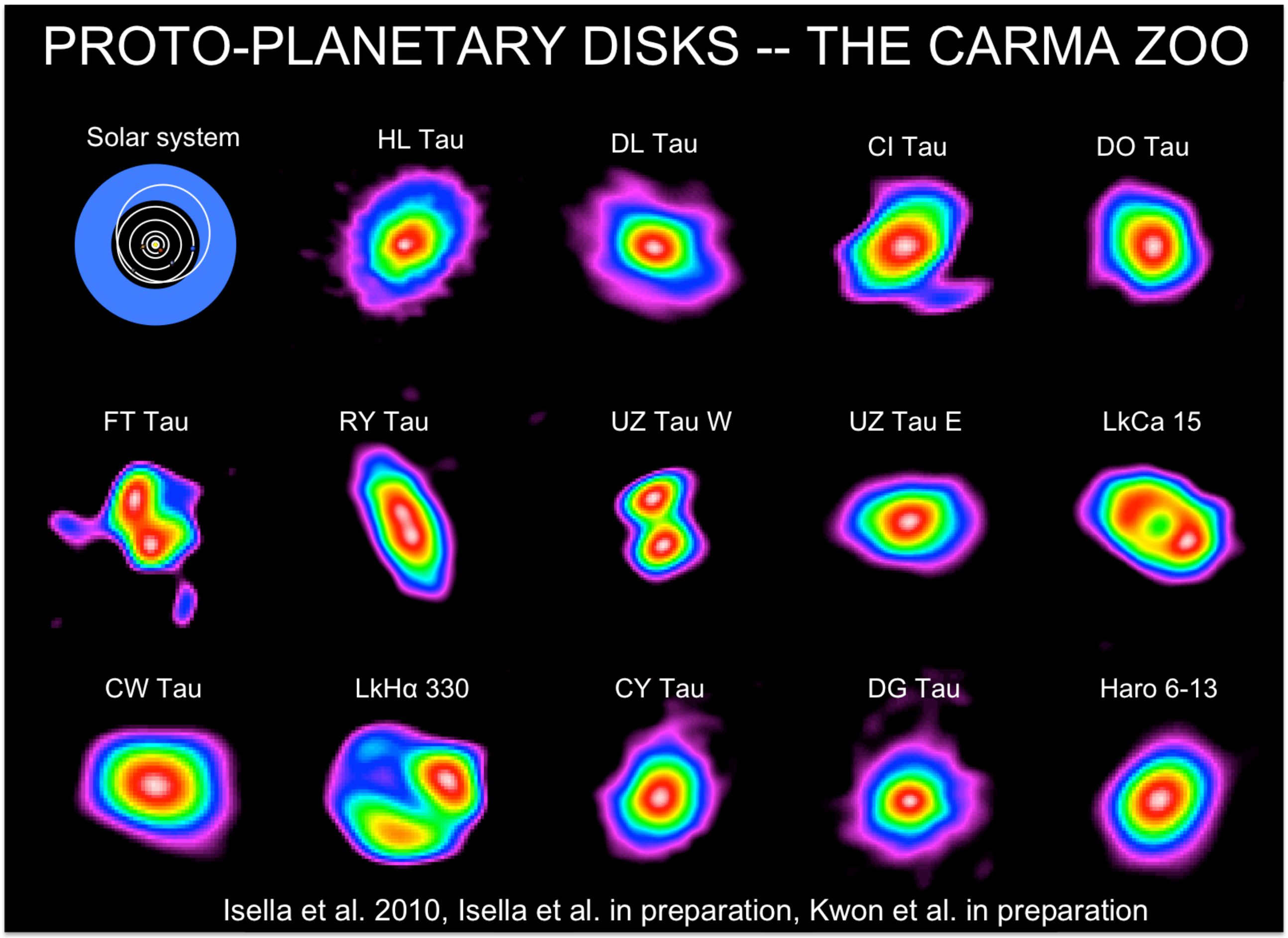
HST Images – disks in the Orion and Taurus

.. But in the optical we see only the disk surface!!





Observing protoplanetary disks at millimeter-wavelengths



At λ>1mm the disk emission is optically thin. We can see the disk interior !

But we need huge telescopes, since $D=\lambda/\theta$ > 200 m to get θ<1"

We can use interferometers like CARMA