Sternentstehung - Star Formation

Winter term 2020/2021

Henrik Beuther, Thomas Henning & Sümeyye Suri

03.11 Today: Introduction & Overview (Beuther)
10.11 Physical processes I (Beuther)
17.11 Physcial processes II (Beuther)
24.11 Molecular clouds as birth places of stars (Suri)
01.12 Molecular clouds (cont.), Jeans Analysis (Suri)
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------------ Christmas break -------------
12.01 Protostellar evolution (Beuther)
19.01 Pre-main sequence evolution & outflows/jets (Beuther)
26.01 Accretion disks I (Henning)
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09.02 High-mass star formation, clusters and the IMF (Suri)
16.02 Extragalactic star formation (Henning)
23.02 Examination week, no star formation lecture

Book: Stahler & Palla: The Formation of Stars, Wileys

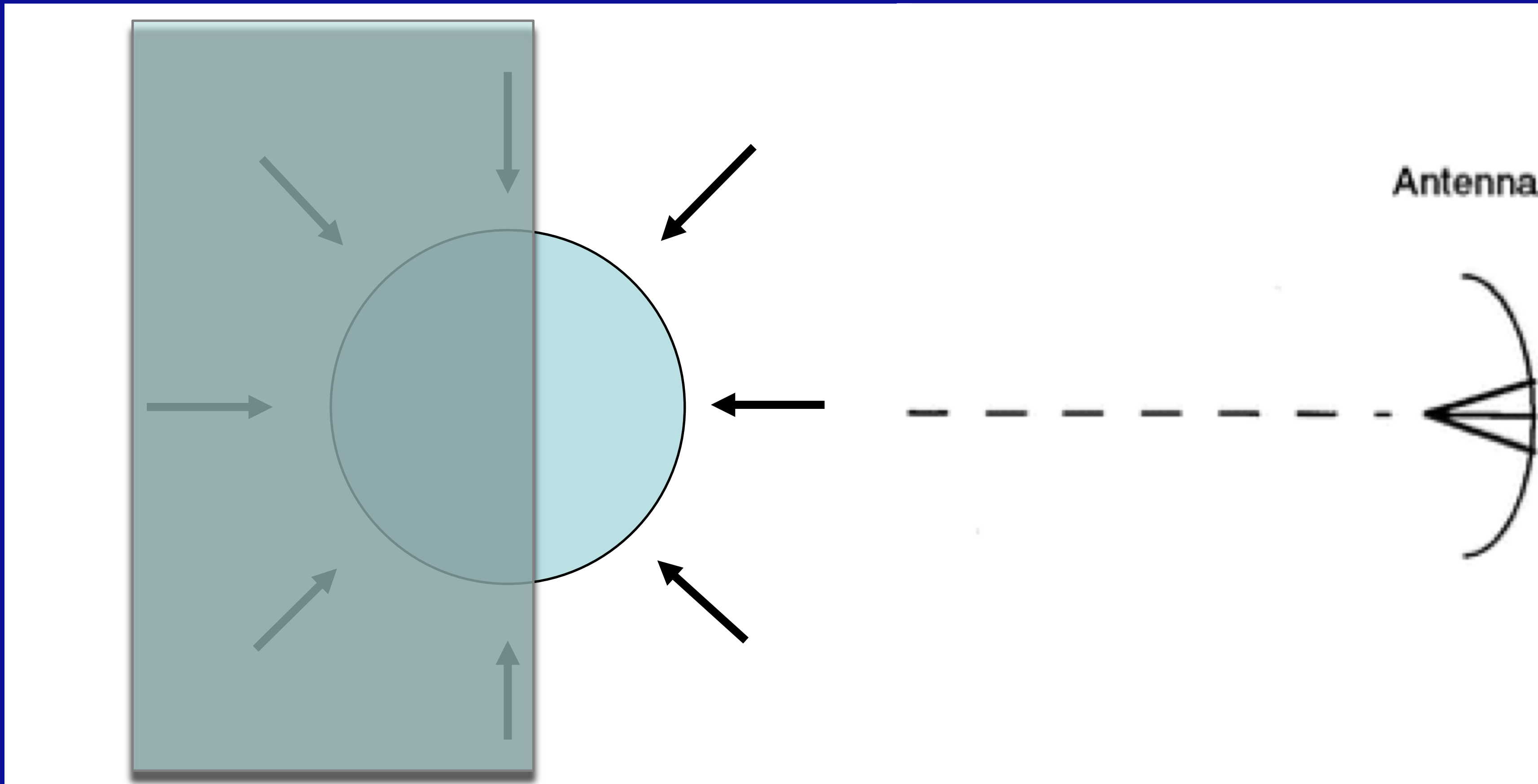
More Information and the current lecture files: http://www.mpia.de/homes/beuther/lecture_ws2021.html

beuther@mpia.de, henning@mpia.de , suri@mpia.de

Topics today

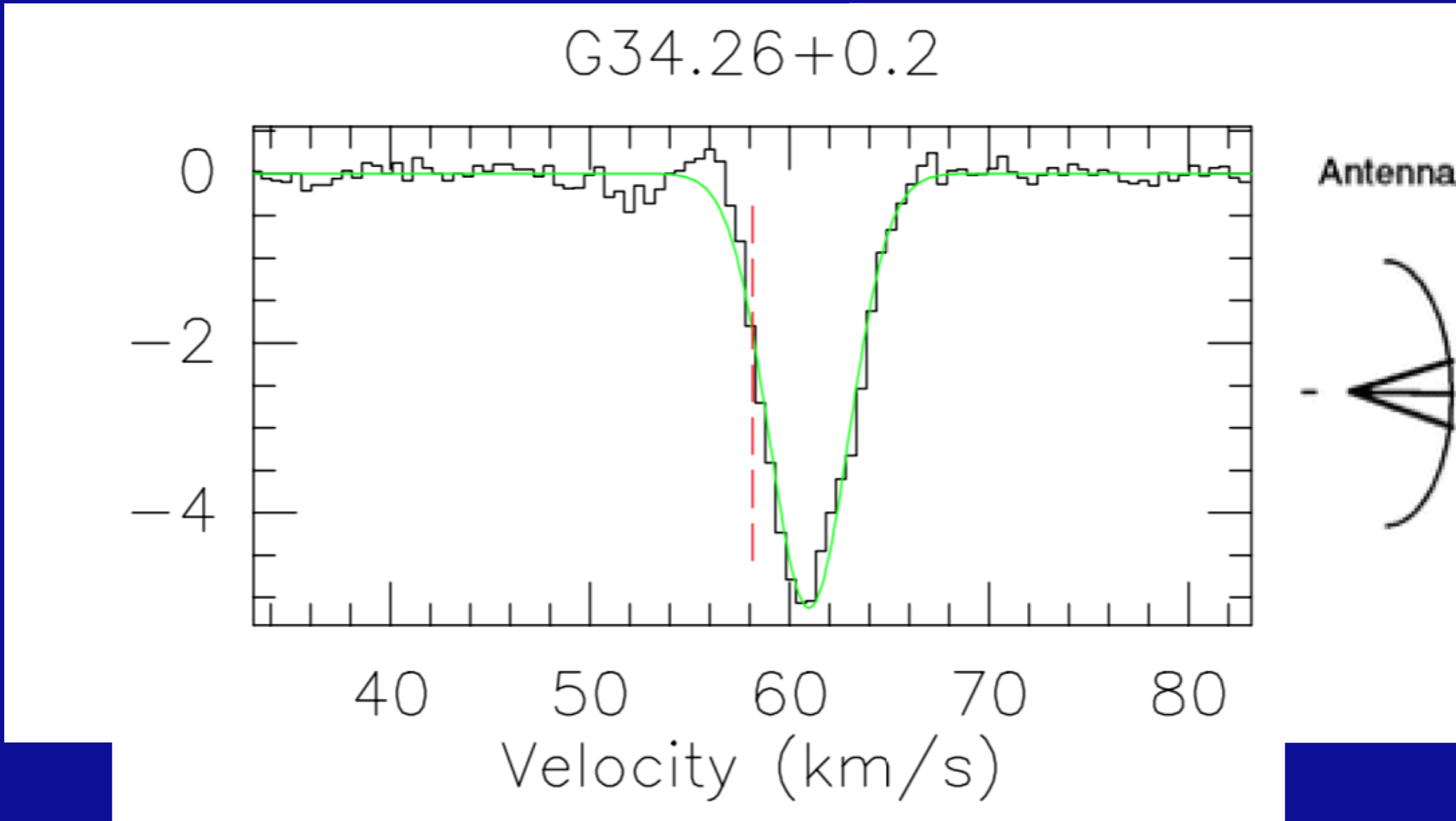
- Infall signatures
- The first core and accretion luminosity
- The protostellar envelope structure
- Protostellar evolution

Infall signatures I



Absorption against strong continuum source

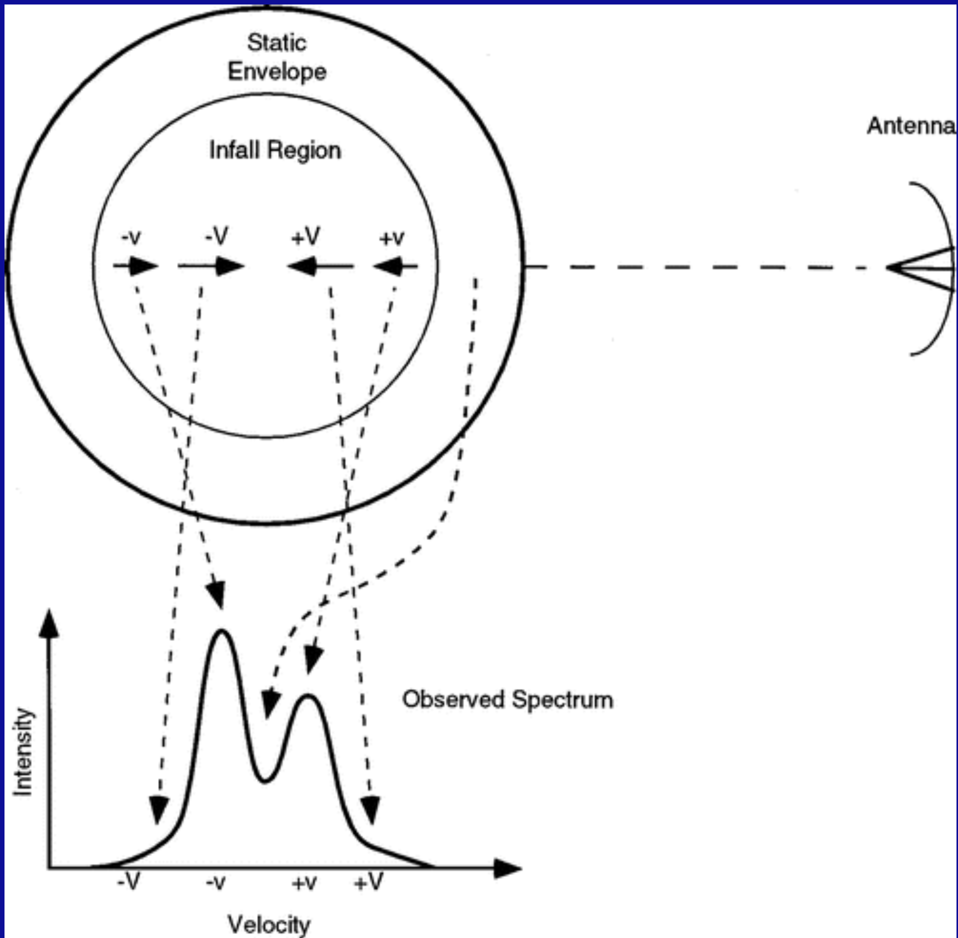
Infall signatures I

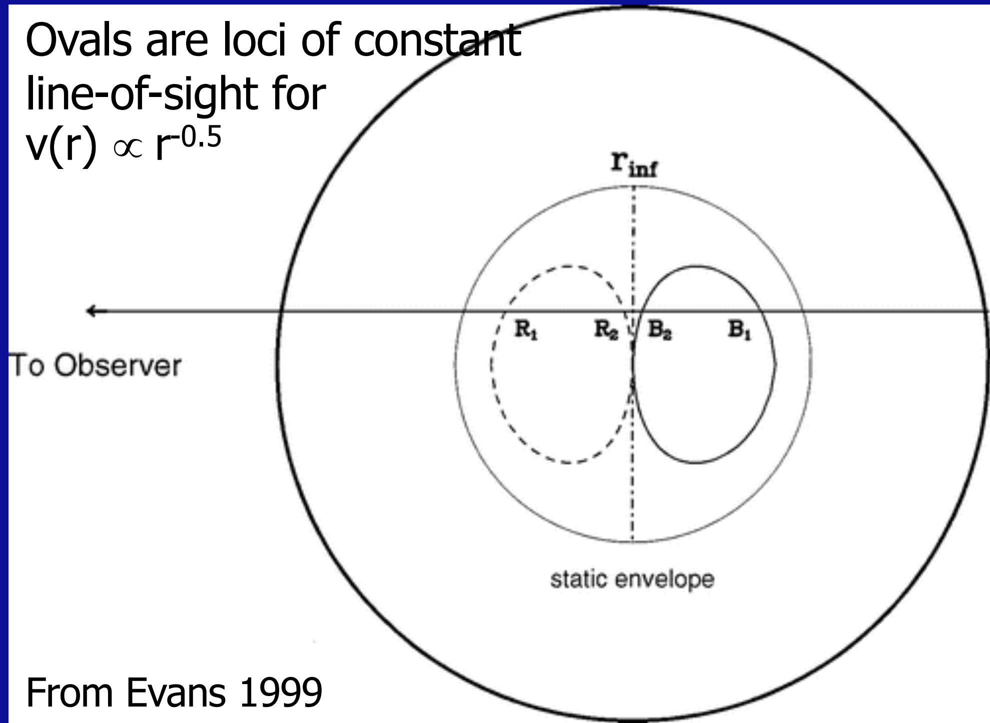


Absorption against strong continuum source

Wyrowski et al. 2016

Infall signatures II





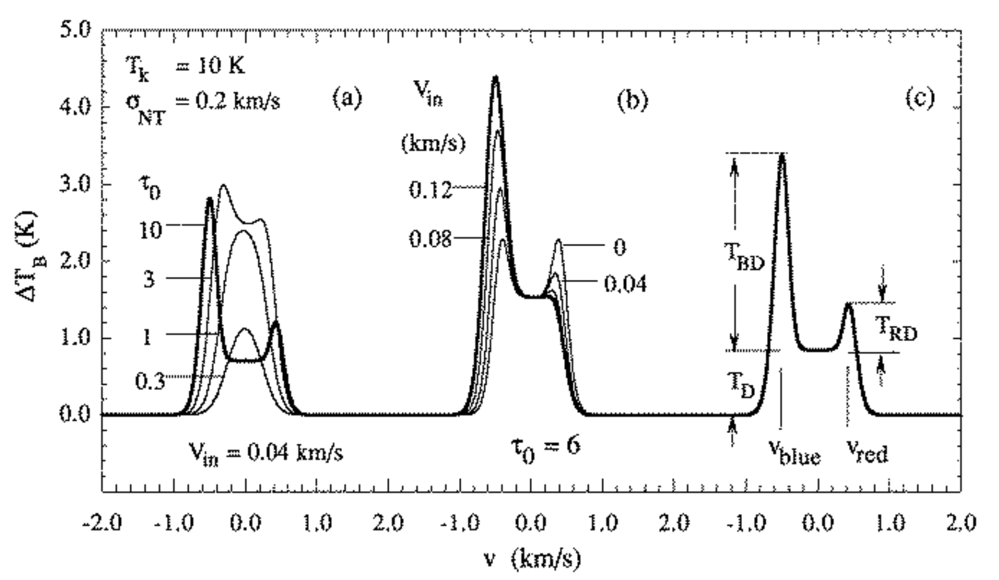
Ovals are loci of constant line-of-sight for $v(r) \propto r^{-0.5}$

From Evans 1999

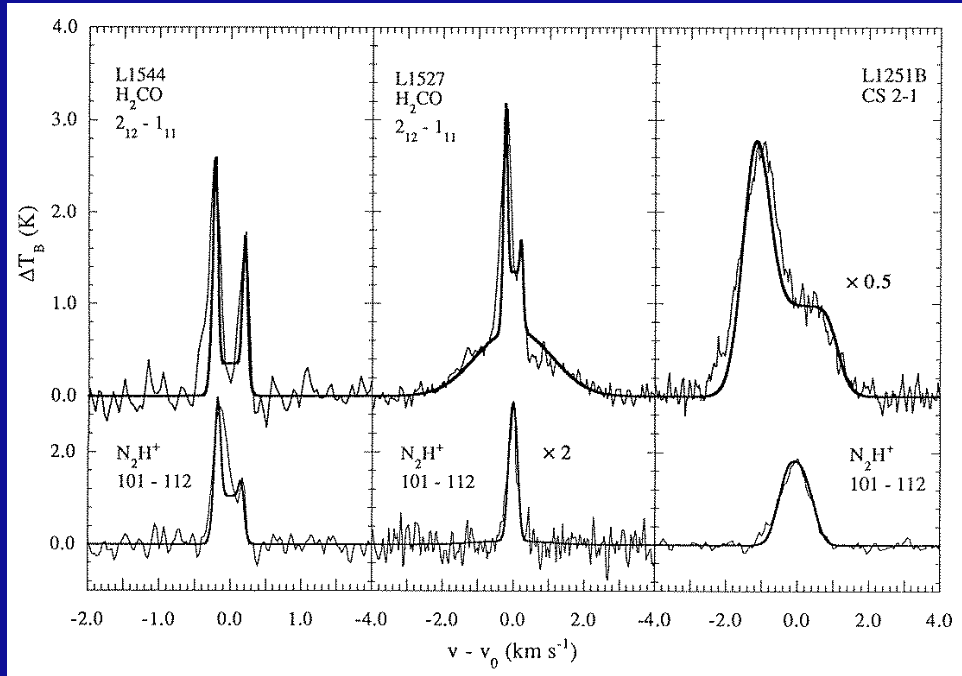
1. Rising T_{ex} along line of sight
2. Velocity gradient
3. Line optically thick
4. An additional optically thin line peaks at center

Infall signatures III

Models



Spectra and fits (Myers et al. 1996)



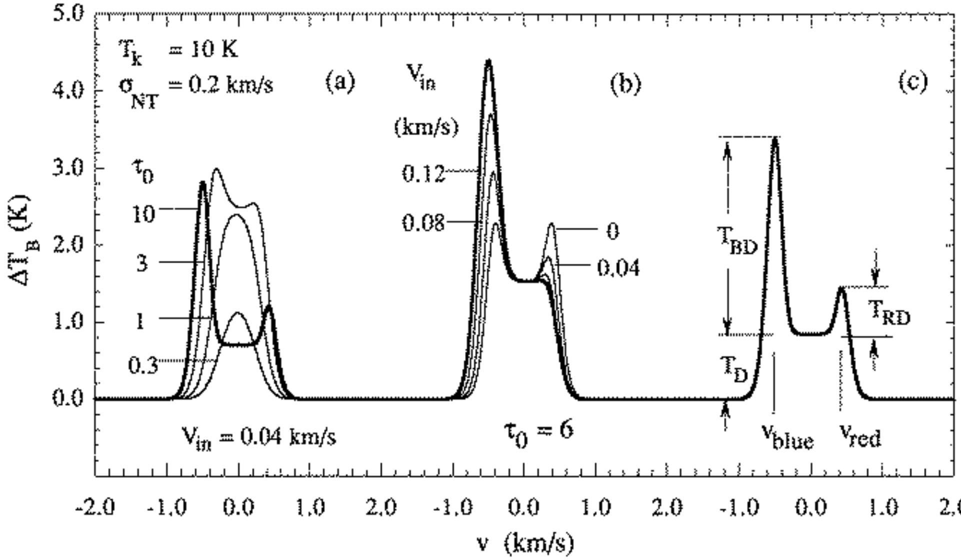
In model with two uniform regions along the line of sight, with velocity dispersion σ and peak optical depth τ_0 → infall velocity v_{in}:

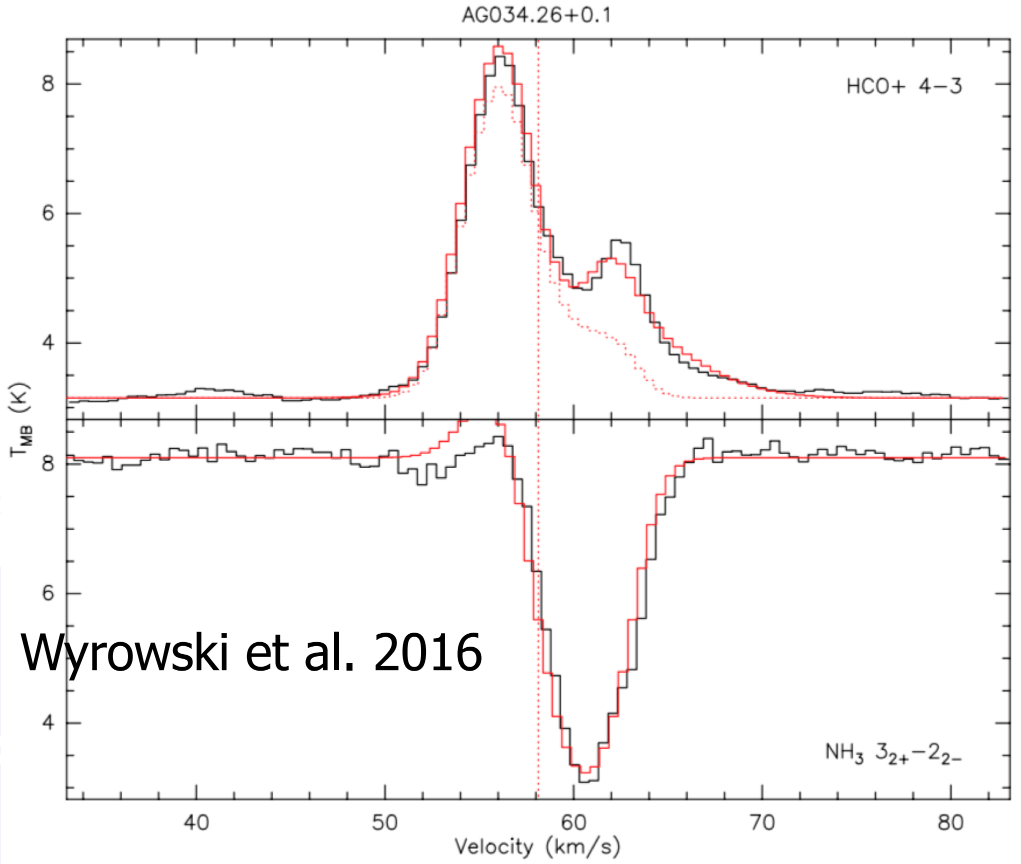
$$v_{in} \approx \sigma^2/(v_{red}-v_{blue}) * \ln((1+\exp(T_{BD}/T_D))/(1+\exp(T_{RD}/T_D)))$$

Low-mass regions → v_{in} usually of the order 0.1 km/s.
High-mass regions → V_{in} can exceed 1km/s → hence supersonic.

Infall signatures III

Models | Spectra and fits (Myers et al. 1996)





Wyrowski et al. 2016

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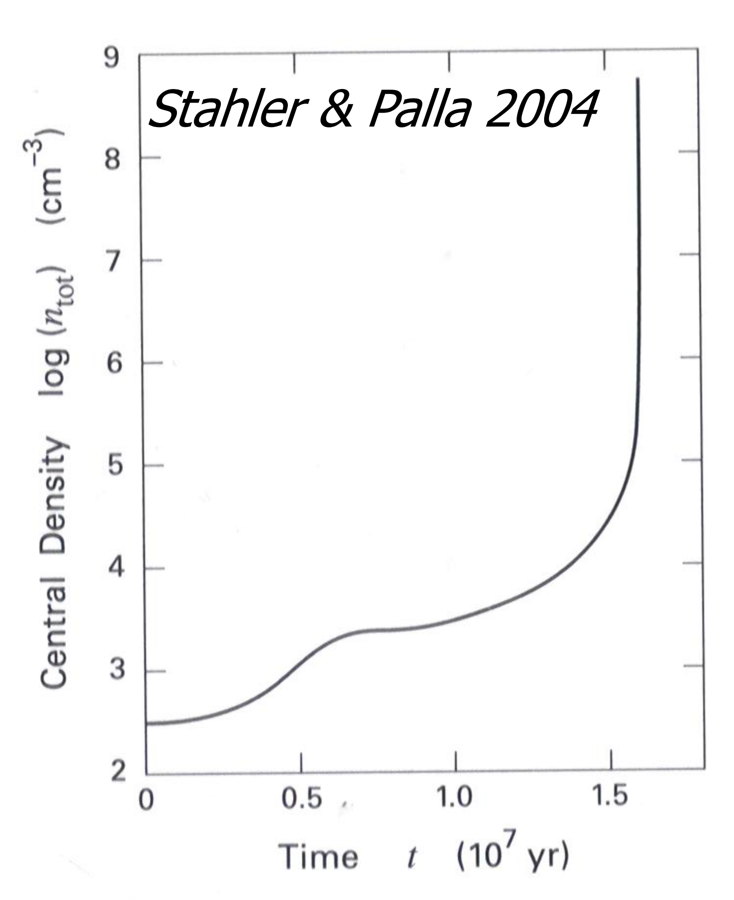
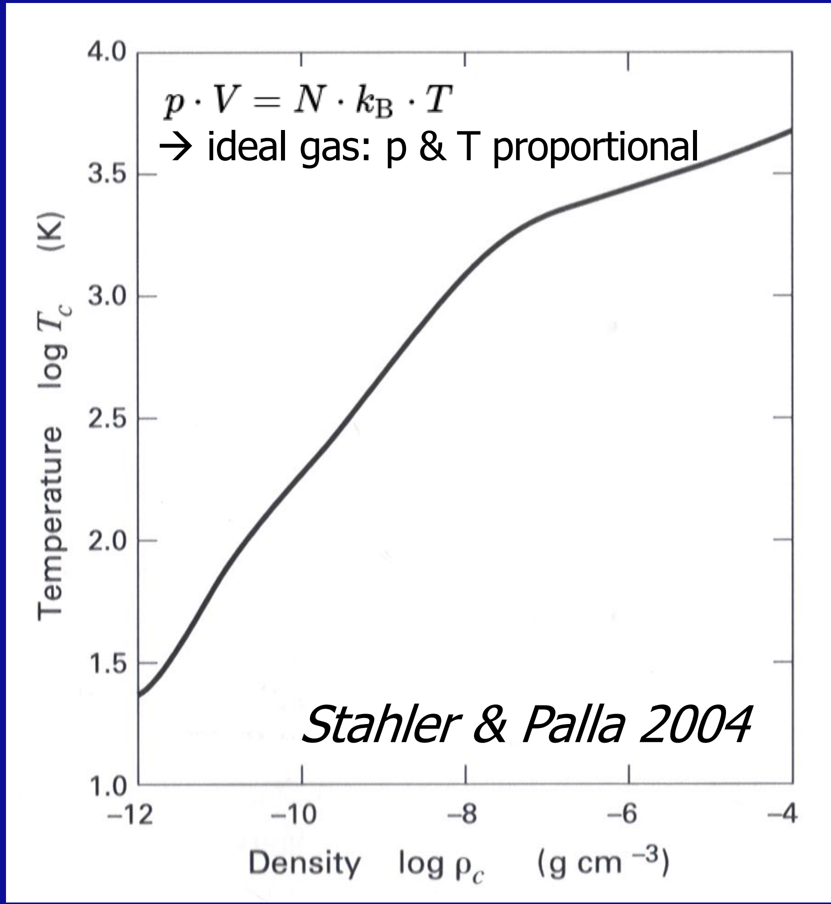
The first core I





- Contraction of core via ambipolar diffusion initially slow.

- Σ/B reaches critical threshold → contraction speeds up, high density → core becomes opaque → cooling less efficient → T & p rise.

- Interior still mainly molecular hydrogen → important for final collapse

The first core II

- Temperature estimate based on viral theorem:

$$2T + 2U + W + M = 0$$

$$W = -2U$$

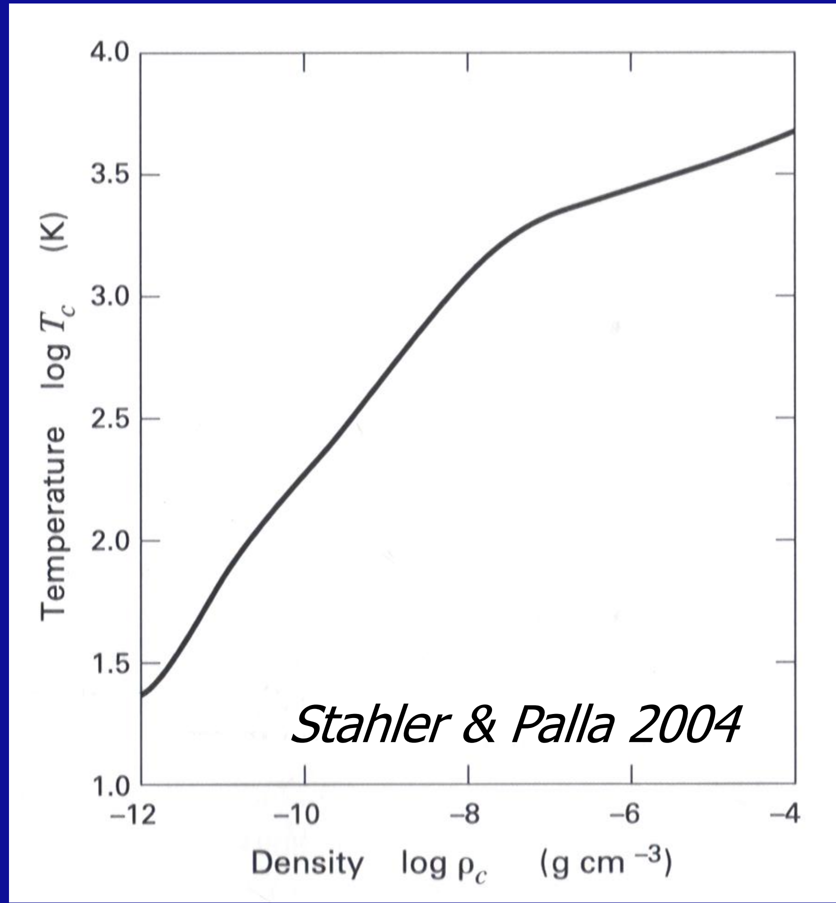
(kinetic & magnetic energy appr. as 0)

$$\Rightarrow -Gm^2/R = -3m\mathcal{R}T/\mu$$

$$\Rightarrow T = \mu Gm/(3\mathcal{R}\,R)$$

$$= 850K\,(m/0.05M_{sun})\,(R/5AU)^{-1}$$

→ significantly warmer than original core



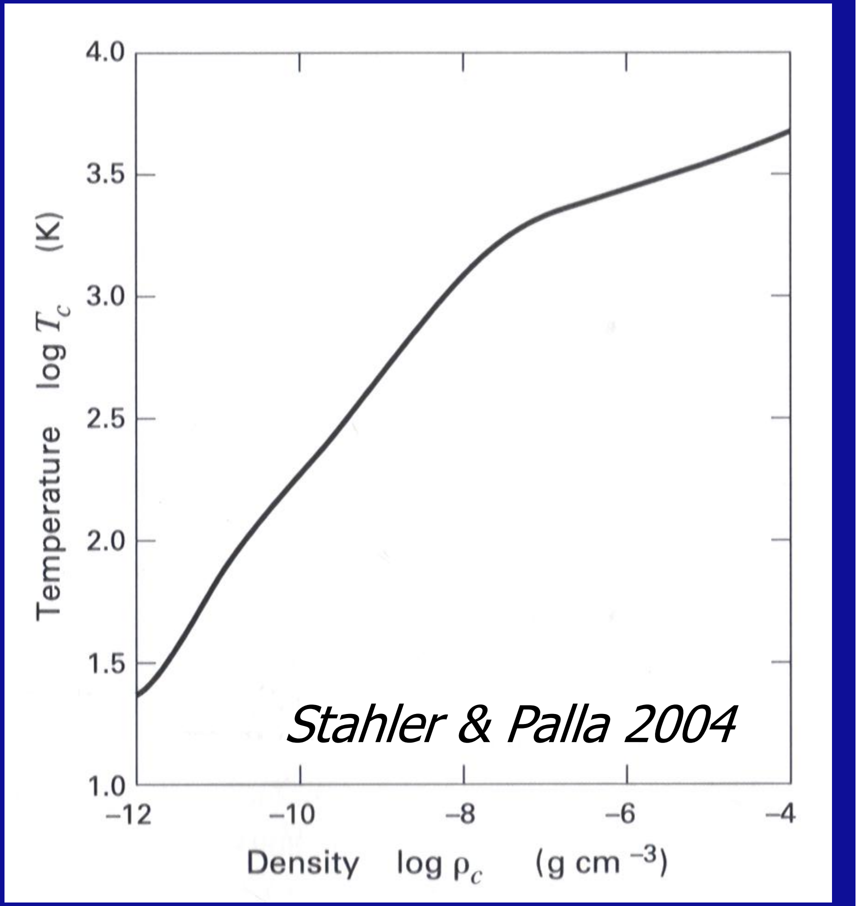
Stahler & Palla 2004

- Addition of mass and further shrinking:
  → soon 2000K reached
  → collisional dissociation of H_2 starts.

The first core III

- However:
  thermal energy per molecule at 2000K
  ~ 0.74eV
  compared to
  dissociation energy of H_2 of ~ 4.48eV

  → Even modest increase of dissociated H_2
  absorbs most grav. collapse energy
  → marginal increase in T & p

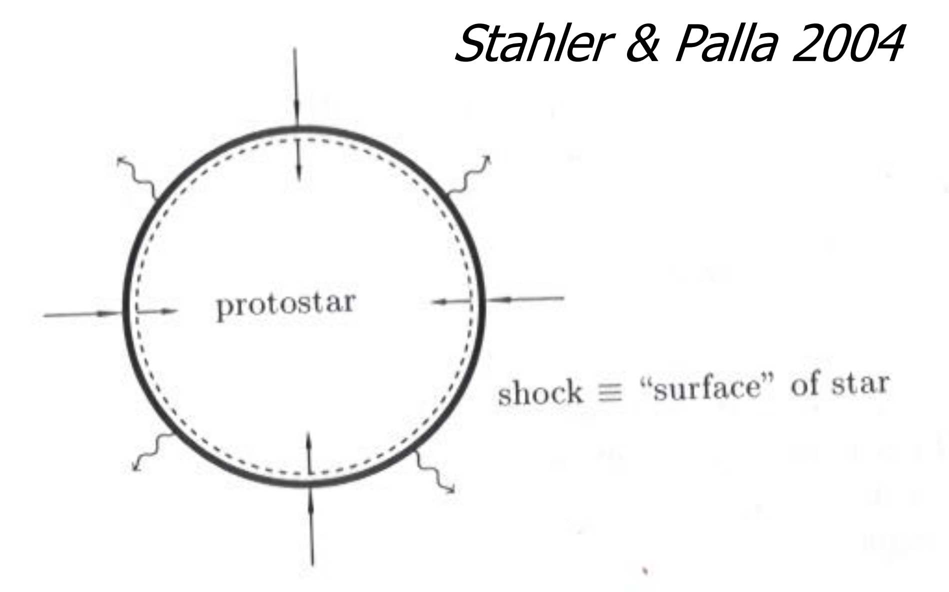


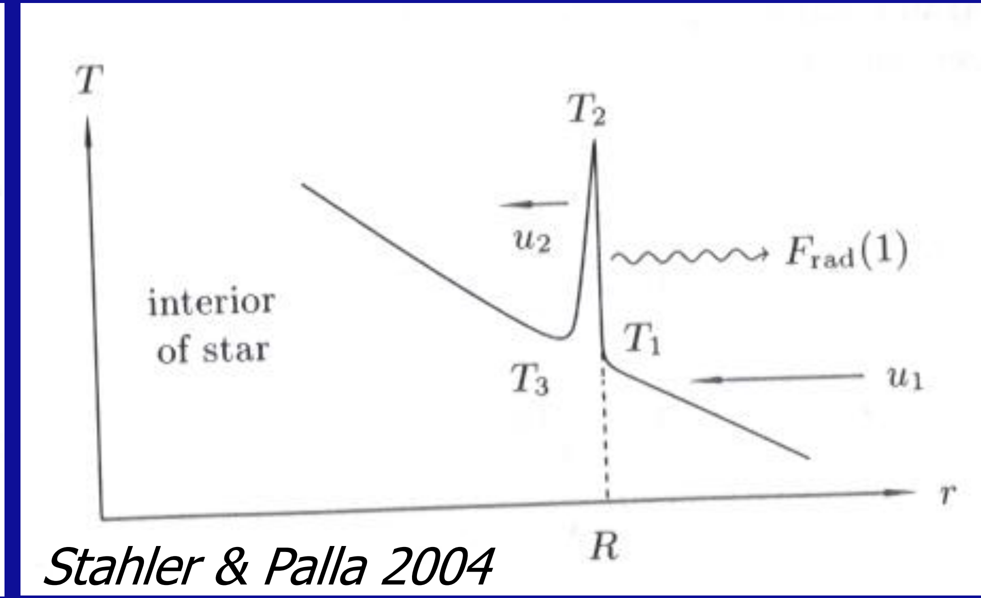
- Region of atomic H spreads outward

- Without significant T & p increase, the first core cannot keep equilibrium
  → Entire core becomes unstable → collapses and forms protostar
  → significant T & ρ increase → collisionally ionize most hydrogen
  → emerging protostar is now dynamically stable.

- A protostar of $0.1M_{sun}$ has radius of several R_{sun}, $T \sim 10^5$K and $\rho \sim 10^{-2}$g cm^{-3}

Accretion shock and Accretion luminosity





- Grav. energy released during accretion approx. by the grav. pot. GM_*/R_*

→ accretion luminosity of protostar: energy multiplied by accretion rate:

$$L_{acc} = GM_*/R_* \,(dM/dt)$$
$$= 61L_{sun}\ ((dM/dt)/10^{-5}M_{sun}/yr)\ (M_*/1M_{sun})\ (R_*/5R_{sun})^{-1}$$

- Additional luminosity from contraction and early nuclear fusion are negligable compare to L_{acc} for low- to intermediate-mass stars.
- Conventional definition of (low-mass) protostar:

"Mass-gaining star deriving most of its luminosity from accretion."

(However, caution for massive stars.)

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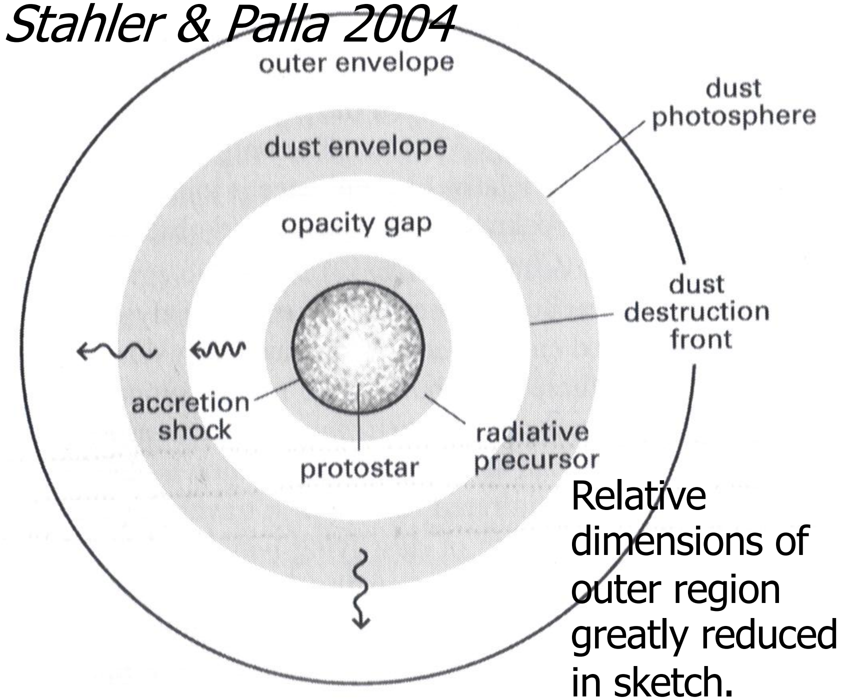
Protostellar envelope I

- Outer envelope optically thin.

- Infalling gas compressed
  → protostellar rad. trapped by high dust opacities.
  → Dust reradiates at FIR

→ Dust photosphere (a few AU for typical low-mass star) is effective warm radiating surface observable at MIR wavelengths

Stahler & Palla 2004



Relative dimensions of outer region greatly reduced in sketch.

- Rapid T increase in dust envelope → dust sublimation at T~1500K.

- Inside dust destruction front greatly reduced opacity
  → infalling gas transparent to protostellar radiation → opacity gap.

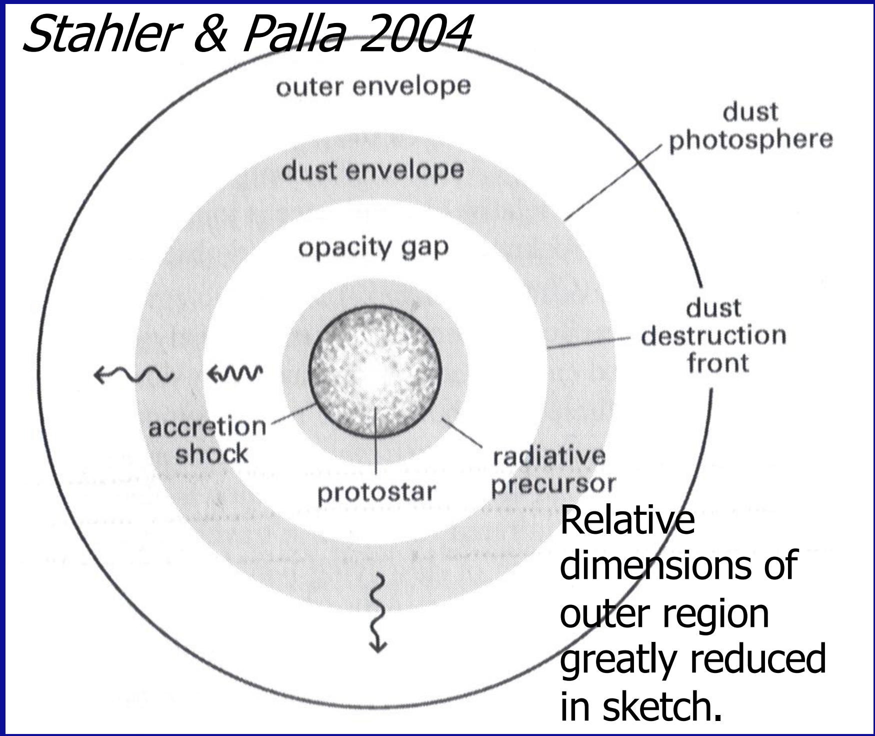
- Immediately outside the accretion shock, gas collisionally ionized
  → opacity increases again → so-called radiative precursor

Protostellar envelope II

- Difference in radiation from shocked "radiative precursor" and far-infrared radiation from dust photosphere

- In shock region gas approaches protostar ~ at free-fall speed:

$E_{kin} = 1/2mv_{ff}^2 = E_{grav} = GM_*m/R_*$
$\Rightarrow v_{ff} = \sqrt{2GM_*/R_*}$
$= 280$ km/s $(M_*/1M_{sun})^{1/2} (R_*/5R_{sun})^{-1/2}$

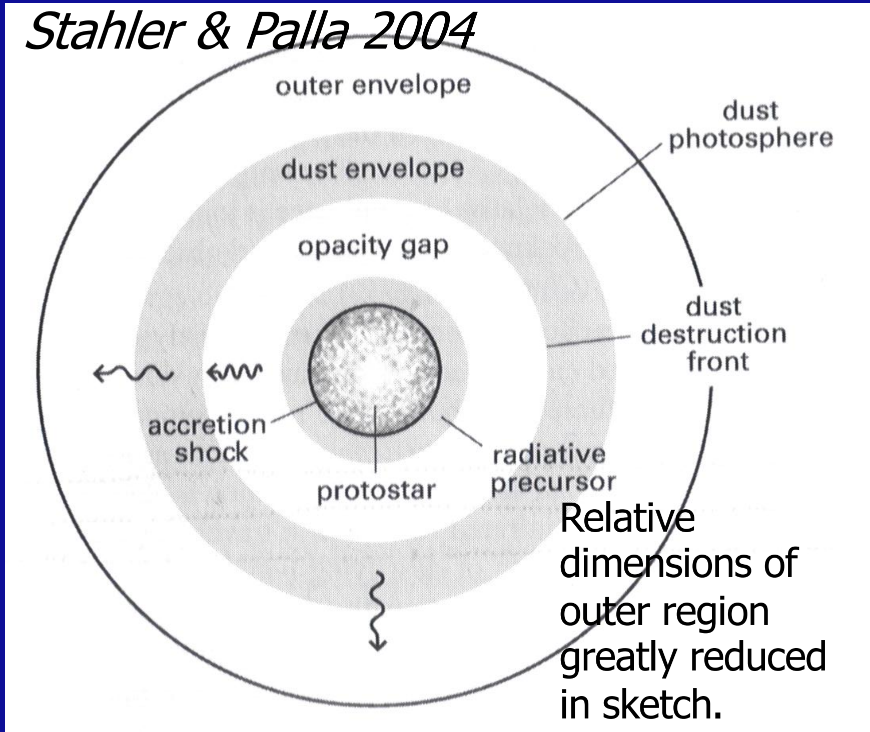


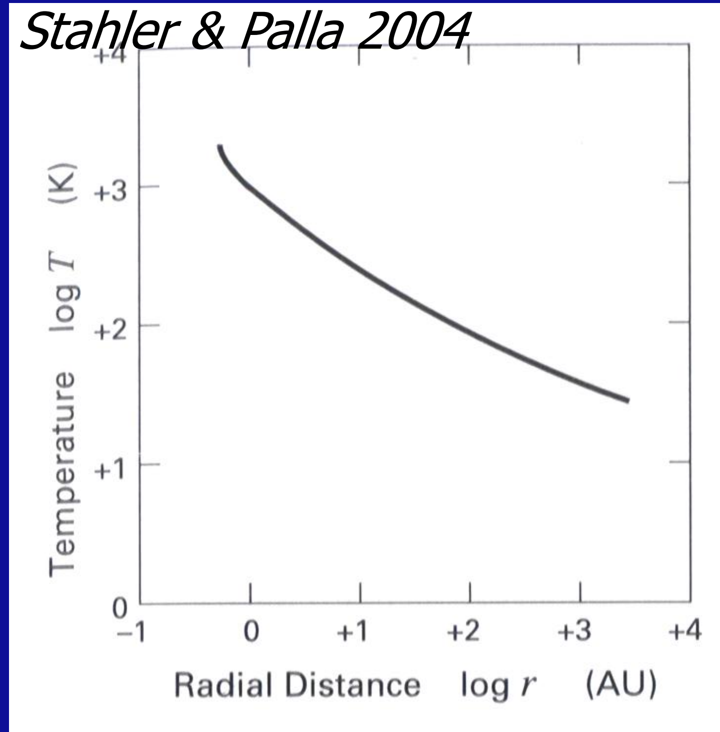
→ Immediate postshock temperature $>10^6$K, UV and X-ray regime
→ Postshock settling region opaque, quick temperature decrease
→ The surface of precursor radiates as ~ blackbody: Stephan-Boltzmann:

$L_{acc} \sim 4\pi R_*^2 \sigma_B T_{eff}^4$ Substituting L_{acc} $\Rightarrow T_{eff} \sim (GM_*(dM/dt)/4\pi R_*^3 \sigma_B)^{1/4}$
$\Rightarrow T_{eff} \sim 7300\text{K} ((dM/dt)/1\text{e-}5M_{sun}\text{yr}^{-1}) (M_*/1M_{sun})^{1/4} (R_*/5R_{sun})^{-3/4}$

→ Opacity gap is bathed in "optical emission" similar to main-sequence star. Very different to observable dust photosphere.

Temperatures and dimensions of envelope





- Temperature profile in optically thick dust envelope $T(r) \sim r^{-0.8}$
- Temperature profile in optically thin outer envelope $T(r) \sim r^{-0.4}$

- Typical dimensions for a $1M_{sun}$ protostar:

Outer envelope:	a few 100 to a few 1000 or 10^4 AU
Dust photosphere:	~ 10 AU
Dust destruction front:	~ 1 AU
Protostar:	~ 5 R_* ~ 0.02 AU

Topics today

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Protostellar evolution/Stellar Structure equations

- The protostellar evolution can be analyzed numerical similarly to stars.

→ Stellar Structure equations

- The used spatial variable is M_r, the mass within shells of radius r

$$M_r = {}_0\int^r 4\pi r^2 \rho \, dr$$

$$\Rightarrow \quad \partial r/\partial M_r = 1/(4\pi r^2 \rho) \qquad (1)$$

Hydrostatic equilibrium: $-1/\rho \, \mathrm{grad}(P) - \mathrm{grad}(\Phi_g) = 0$

$$\Rightarrow \quad \partial P/\partial r = -G\rho M_r/r^2 \qquad (2)$$

Combining (1) in (2), one gets

$$\Rightarrow \quad \partial P/\partial M_r = -GM_r/(4\pi r^4) \qquad (3)$$

Pressure obeys ideal gas equation: $P = \rho/\mu \, \mathcal{R}T$ (4)

(mean molecular weight μ depends on state of ionization and is function of T and ρ)

Protostellar evolution/Stellar Structure equations

- Thermal structure of opaque interior is described by diffusion equation

$$T^3\, \partial T/\partial M_r = -\, 3\kappa L_{int}/(256\pi^2 \sigma_B r^4) \qquad (5)$$

(mean opacity κ is again function of T and ρ)

- Spatial variation of internal luminosity L_{int} follows heat equation:

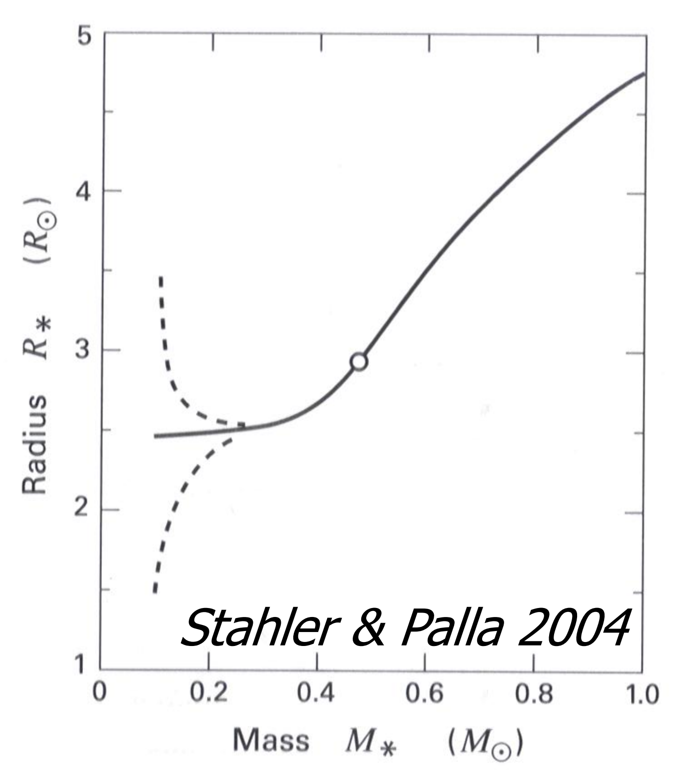
$$\partial L_{int}/\partial M_r = \varepsilon(\rho,T) - T\, \partial s/\partial t \qquad (6)$$

($\varepsilon(\rho,T)$ rate of nuclear energy release; $s(\rho,T)$ is the entropy)

(For a mono-atomic gas, the entropy is: $s(\rho,T) = \mathcal{R}/\mu \ln(T^{3/2}/\rho)$)

- Using adequate boundary conditions, one can now follow numerically the protostellar evolution.

Mass-radius relation



- Initial size unknown → quickly converges

  - Initially large → low infall vel. → low L_{acc} → low $s(M_r)$ → initial decrease of R_*
  - Opposite effect for very small initial state.

- Adding additional infalling mass shells → protostar can be described by entropy profile $s(M_r)$ (reflects conditions at accretion shock)

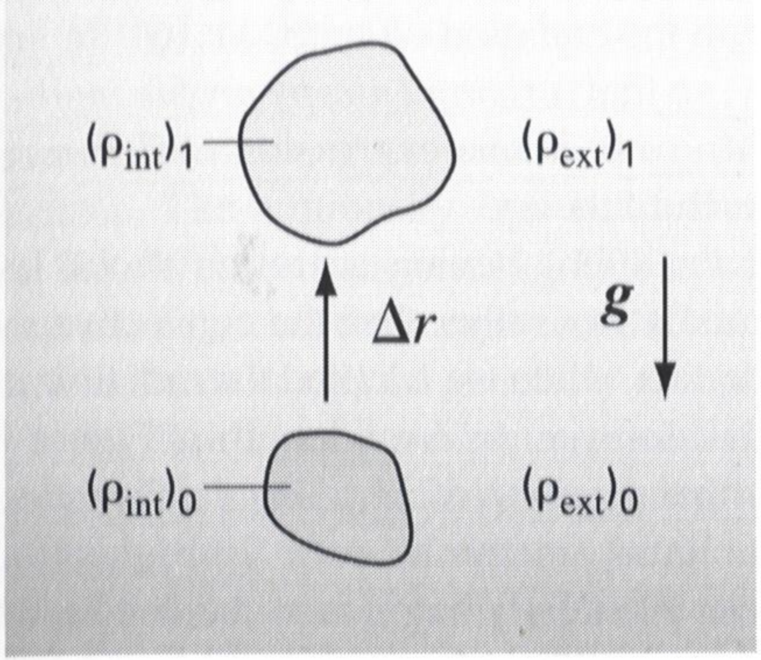
- s represents heat content of each added mass shell → increase of $s(M_R)$ causes a swelling of the protostar.

- In the absence of nuclear burning, an increasing $s(M_r)$ arises naturally because with rising M_*, the velocity of the infalling gas and hence the accretion shock and L_{acc} increases.

  → Protostellar radius increases with time.

Convection I

Stahler & Palla 2004

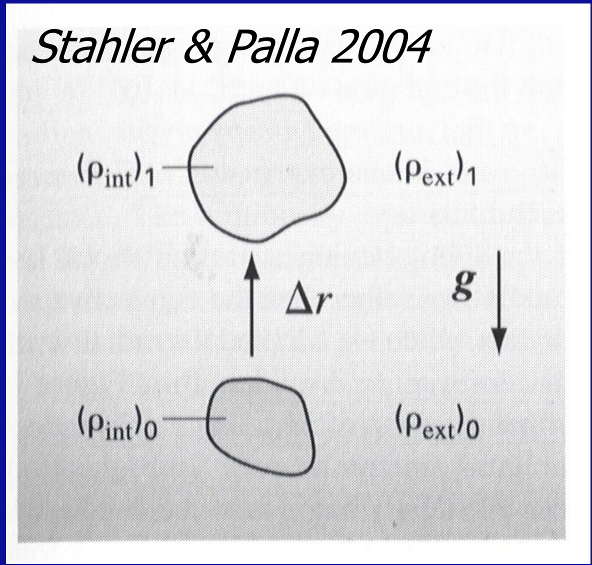


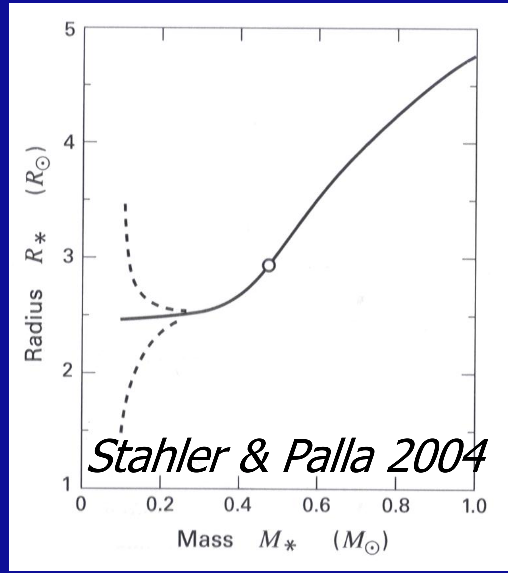
- Displace parcel outward. P_{ext} decreases.
  → parcel expands and $(\rho_{int})_1 < (\rho_{int})_0$

- **<u>Question:</u>**
  - If $(\rho_{int})_1 < (\rho_{ext})_1$ parcel gets buoyant
    → convection starts and becomes important for heat transfer.
  - If $(\rho_{int})_1 > (\rho_{ext})_1$ parcel sinks back down → star remains radiatively stable.

- If parcel displacement very quick → heat loss is negligable
  → its specific entropy s stays the same.
- In the absence of nuclear burning protostar has rising entropy profile $s(M_r)$ with $\partial s/\partial M_r > 0$ → $(s_{int})_0 = (s_{int})_1 < (s_{ext})_1$
- However, $(P_{int})_1 = (P_{ext})_1$ and for ordinary gases $(\partial\rho/\partial s)_P < 0$,
  i.e. → density falls with increasing entropy at constant pressure.
  → $(\rho_{int})_1 > (\rho_{ext})_1$ for a rising entropy profile.
  → $\partial s/\partial M_r > 0$ implies radiative stability.

Convection II

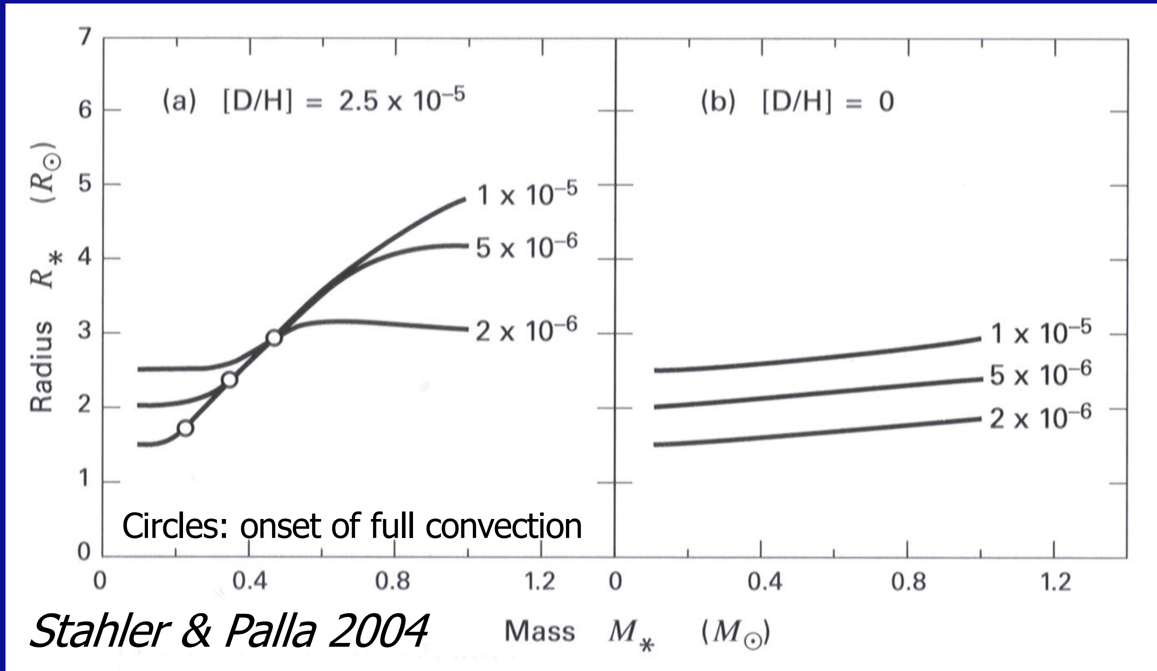




- However, M_*/R_* rises fast → interior T increase → Nuclear reactions start (at ~0.3M_{sun} deuterium burning at ~10^6K).
  - → entropy profile turns $\partial s/\partial M_r < 0$
  - → too much energy for radiative transport in opaque interior
  - → convection starts

- $\partial s/\partial M_r < 0$ → parcels are underdense ($(\rho_{int})_1 < (\rho_{ext})_1$) and hot.
  → heat transfer to surrounding → denser/cooler parcels travel down again.
  → Protostellar interior is well mixed and provides its own deuterium to center for further fusion processes.
- Convection is local phenomenon, some regions can be convective whereas others remain radiatively stable.

Deuterium burning

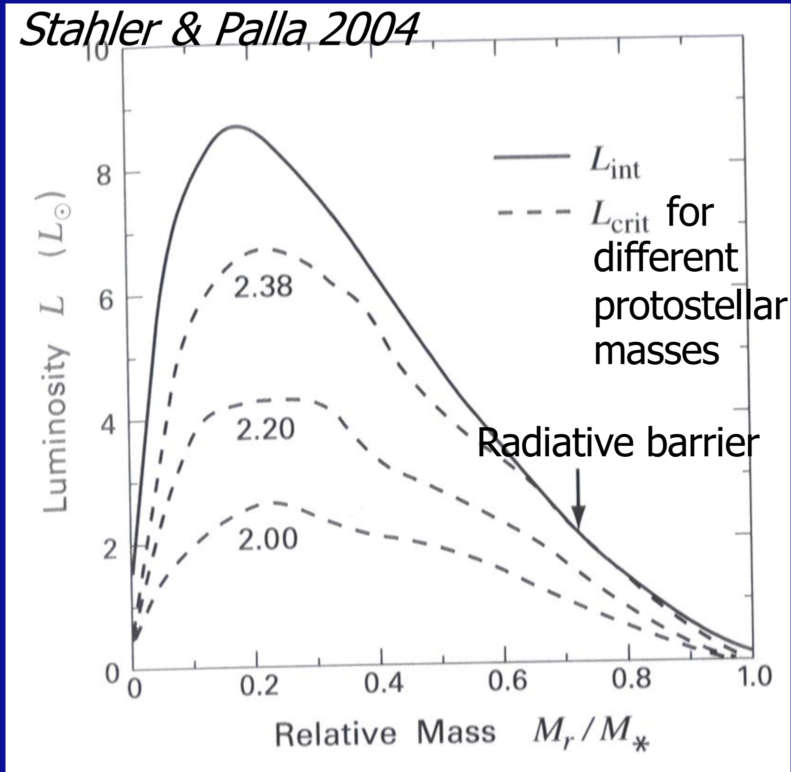


- $^2H + ^1H \rightarrow ^3He + \Delta E$ with $\Delta E \sim 5.5$ MeV, important from 10^6K
- Protostellar size depends also on accretion but D-burning more important.
- The deuterium burning is very temperature sensitive:
  Increase of T → more deuterium burning → more heat
  → increase of protostellar radius ($L_{acc} = G(dM/dt)M_*/R_*$) → lower T again
    → Deuterium burning acts as kind of thermostat keeping protostellar core at that evolutionary stage at about 10^6K.

- Steady supply by new deuterium from infalling gas via convection necessary to maintain thermostat.

Radiative stability again

What happens for Protostars gaining more than 1-2M_{sun} of mass?

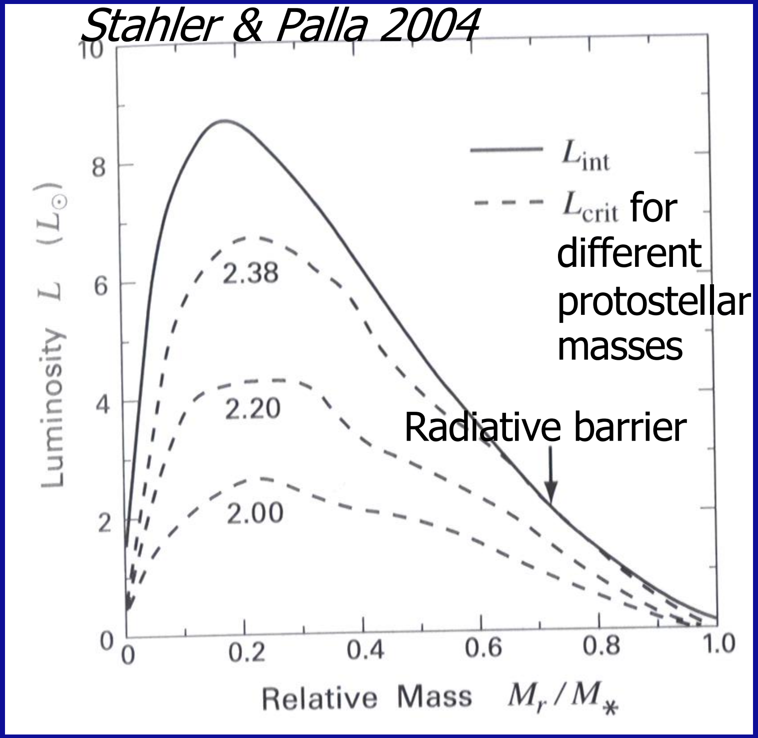


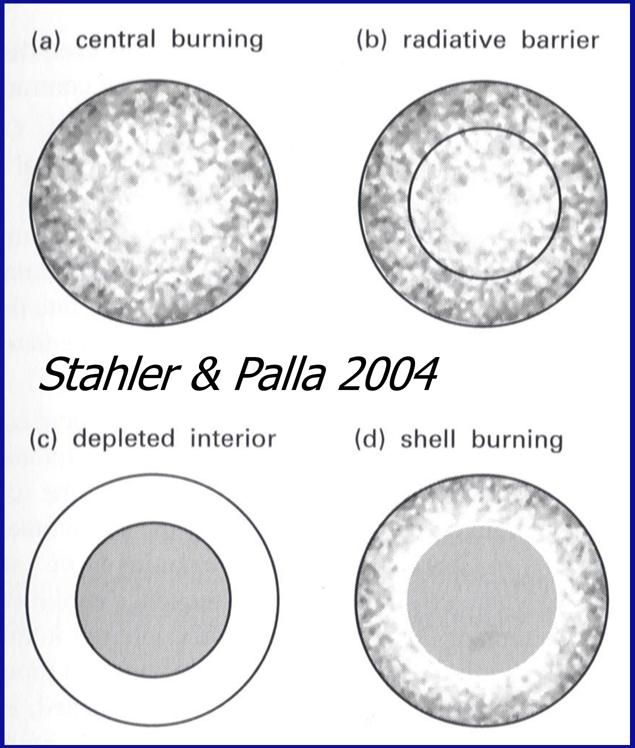
- The critical luminosity L_{crit} is the maximum value to be carried by radiative diffusion. It depends on opacity of gas/plasma.
- Continuum opacity from free-free emission (Kramers-law opacity) scales

$\kappa_{ff} \propto \rho T^{-7/2}$ → strong decrease with T

- And one finds: $L_{crit} \propto M_*^{11/2} R_*^{-1/2}$
  → For growing protostars, L_{crit} rises sharply surpassing interior luminosity.
  → Convection then disappears and protostar gets radiative barrier.

Deuterium shell burning I

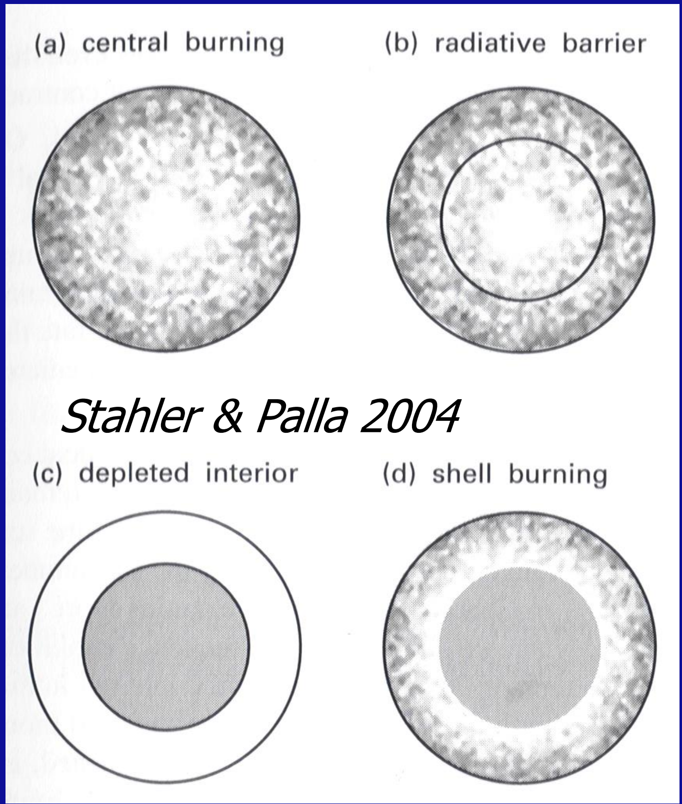


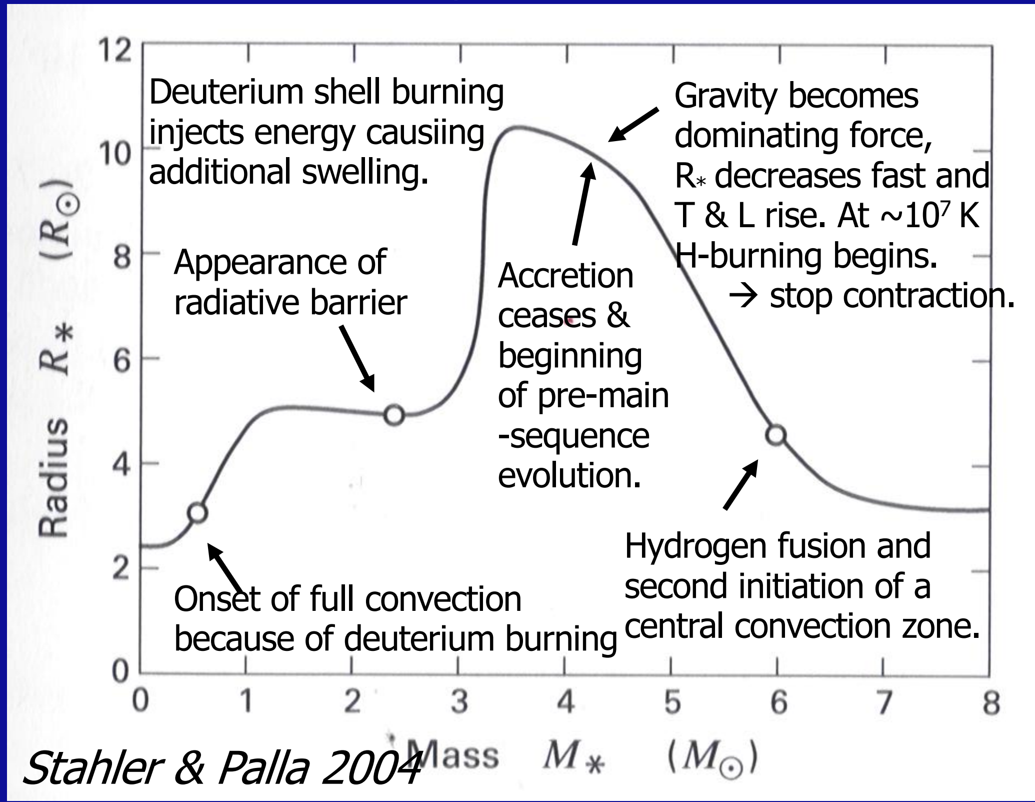


- Radiative barrier → no new deuterium to center & deut. consumed rapidly.
- Interior luminosity L_{int} declines below L_{crit}
  → convection disappears in whole interior volume.

- Deuterium accumulates in mantle outside radiative barrier.
- No internal fuel → R_* does not change much anymore
  → M_*/R_* rises more quickly, and temperatures increase rapidly.
- Base of deuterium shell reaches 10^6K, deuterium shell burning starts and convection occurs in this shell structure.

Deuterium shell burning II





- Deuterium shell burning is accompanied by structural change of protostar.
- The shell burning injects heat and rises the entropy s of the outer layers.
  → further swelling of the protostellar radius
- Adding even more mass, the inevitable rise of L_{crit} drives the radiative barrier and the associated burning layer and convection zone outward.
  → The protostar ($>\sim 2M_{sun}$) is then almost fully radiatively stable.
- The previous scaling relation for L_{crit} should now apply to interior luminosity, and one finds: $L_{int} \sim 1L_{sun} (M_*/1M_{sun})^{11/2} (R_*/1R_{sun})^{-1/2}$

Summary

- The “first core” contracts until temperatures are able to dissociate H_2 to H.

- H-region spreads outward, T and P not high enough to maintain equilibrium, further collapse until H gets collisionally ionized. The dynamically stable protostar has formed.

- Accretion luminosity. Definition of low-mass protostar can be “mass-gaining object where the luminosity is dominated by accretion”.

- Structure of the protostellar envelope.

- Stellar structure equations: follow numerically the protostellar and then later the pre-main sequence evolution.

- Convection and deuterium burning.

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