Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning & Jonathan Henshaw

18.10 Today: Introduction & Overview (Beuther)
25.10 Physical processes I (Beuther)
08.11 Physcial processes II (Beuther)
15.11 Molecular clouds as birth places of stars (Henshaw)
22.11 Molecular clouds (cont.), Jeans Analysis (Henshaw)
29.11 Collapse models I (Beuther)
06.12 Collapse models II (Henning)
13.12 Protostellar evolution & prep-main sequence (Beuther)
20.12 Outflows/jets (Beuther)
10.01 Accretion disks I (Henning)
17.01 Accretion disks II (Henning)
24.01 High-mass star formation, clusters and the IMF (Henshaw)
31.01 Extragalactic star formation (Henning)
07.02 Planetarium@HdA, outlook, questions (Beuther)
13.02 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_ws2223.html

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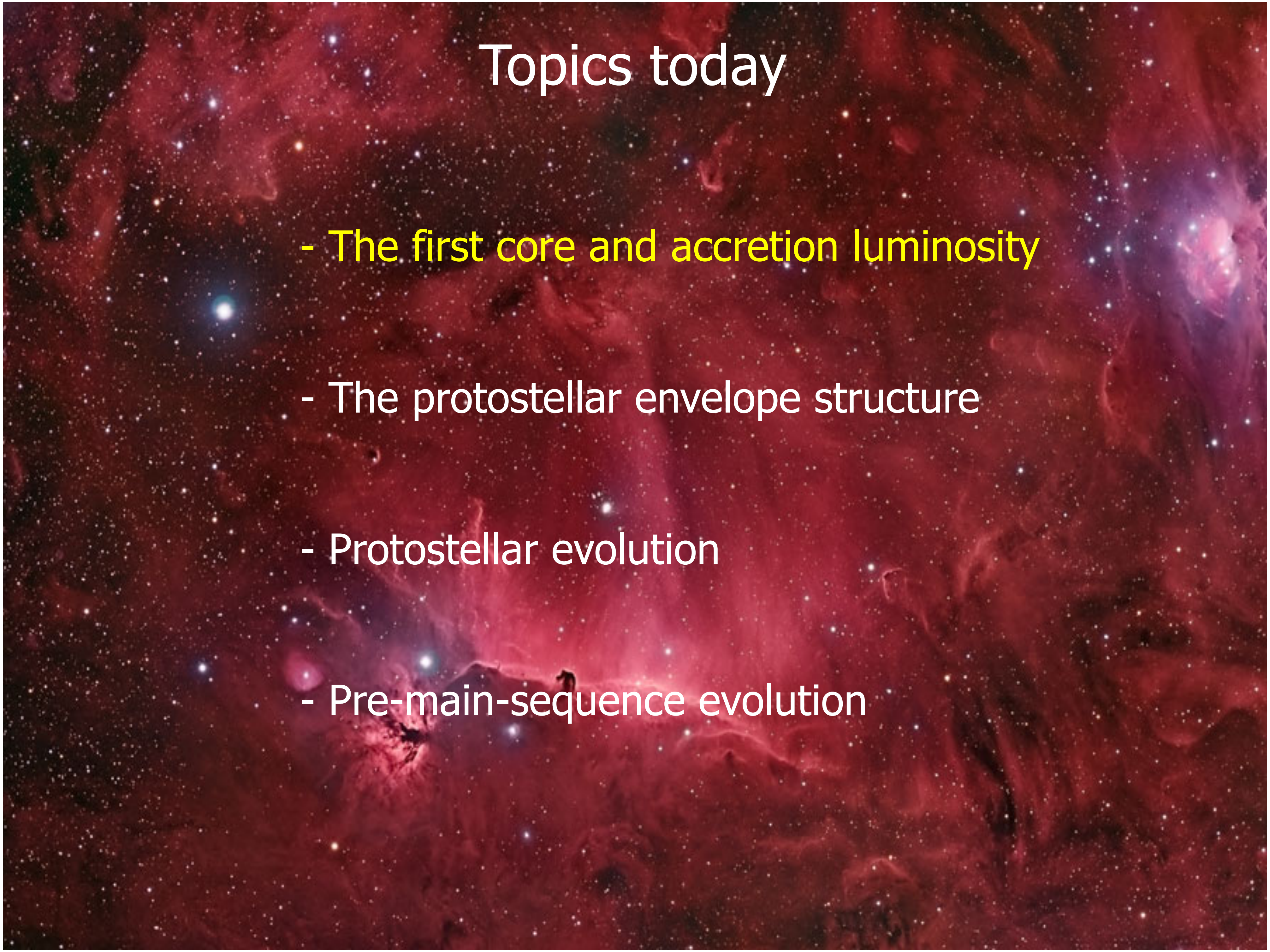
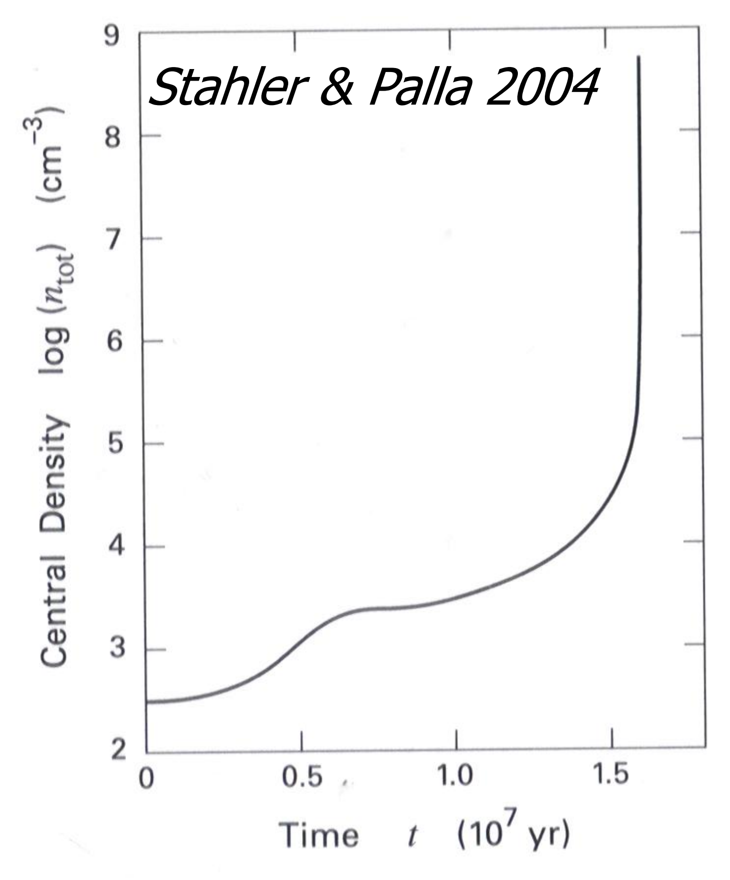
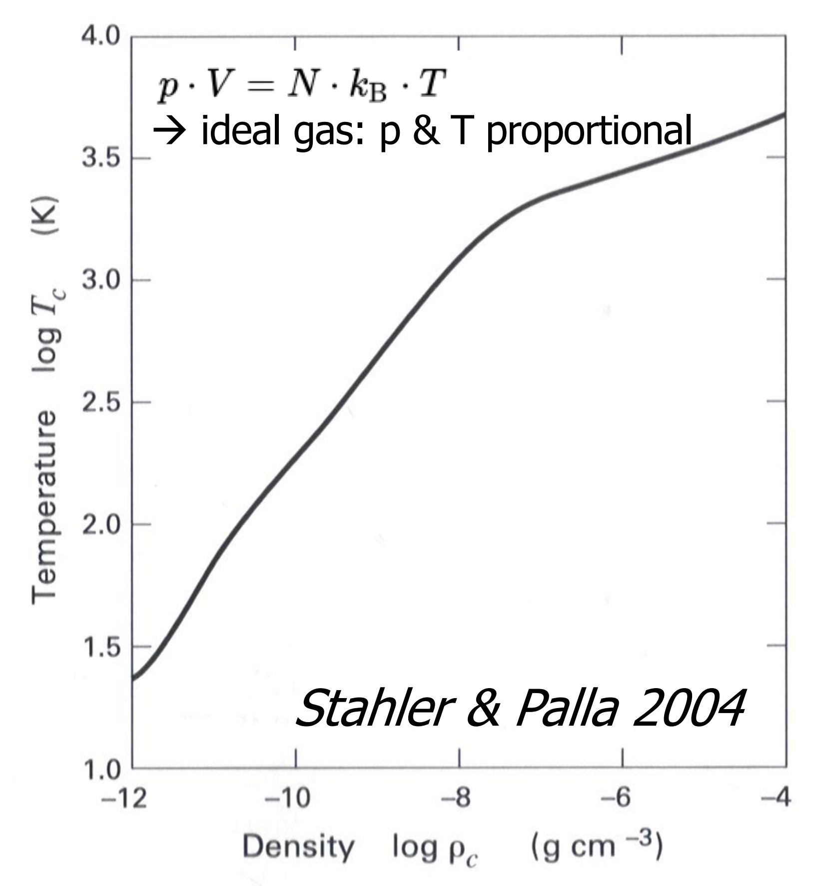
Topics today



- The first core and accretion luminosity
- The protostellar envelope structure
- Protostellar evolution
- Pre-main-sequence evolution

The first core I


Stahler & Palla 2004


$p \cdot V = N \cdot k_B \cdot T$

→ ideal gas: p & T proportional

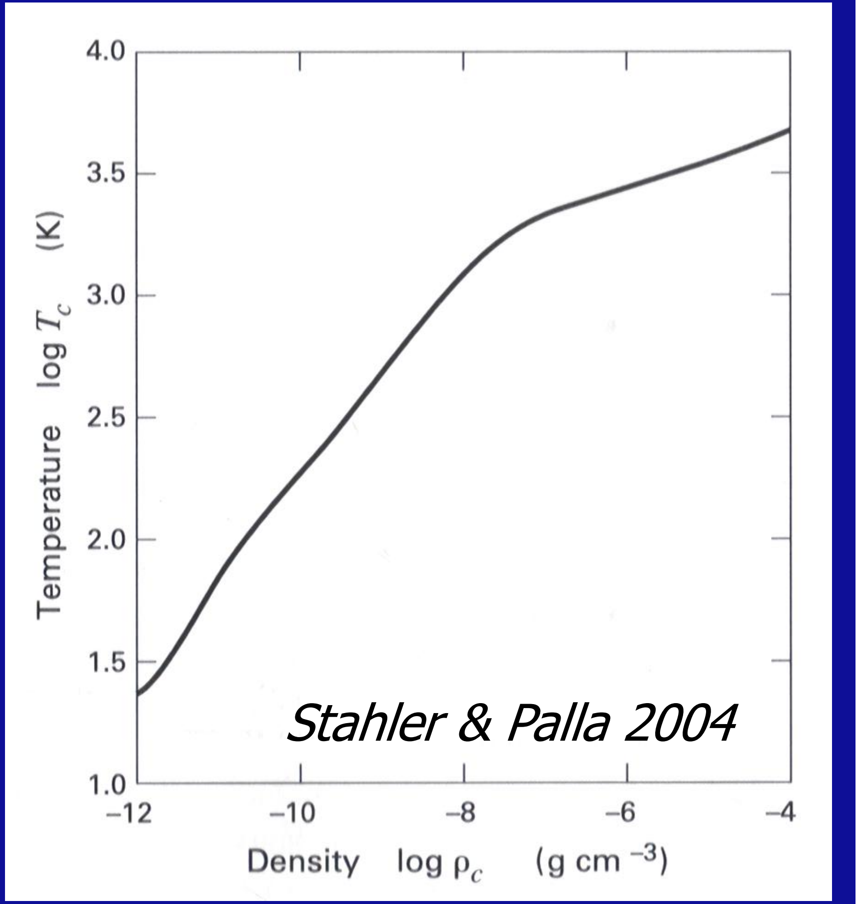
Stahler & Palla 2004

- 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



Stahler & Palla 2004

- Temperature estimate based on viral theorem:

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

$$W = -2U$$

(kinetic & magnetic energy appr. as 0)

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

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

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

→ significantly warmer than original core

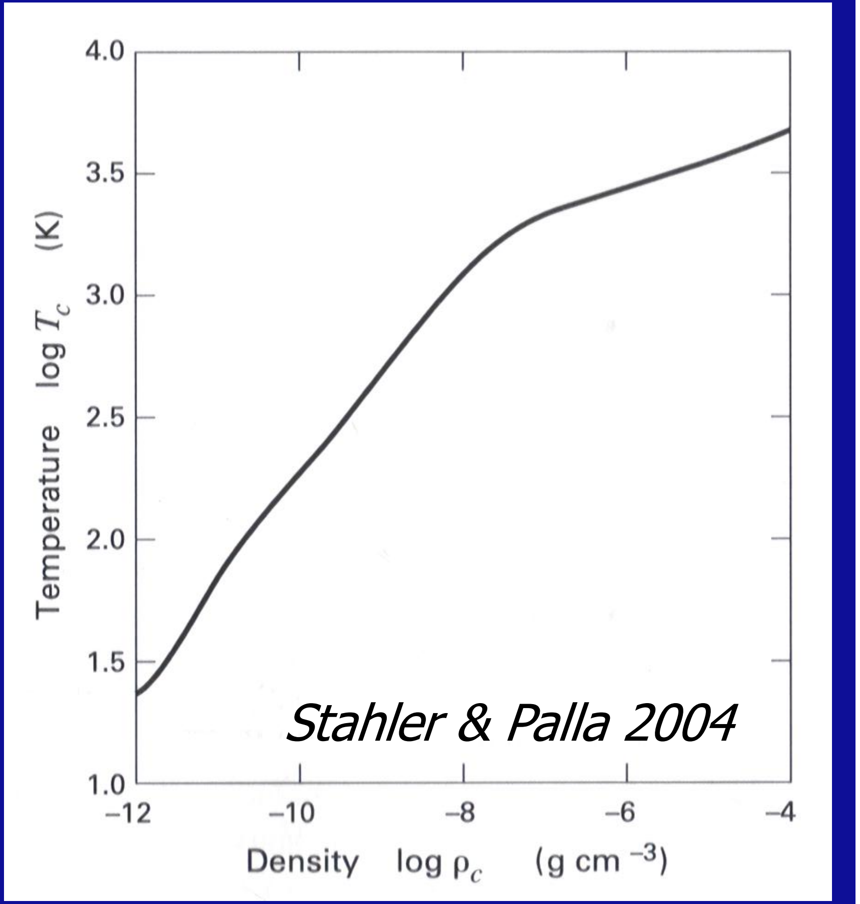
- Addition of mass and further shrinking:
  → soon 2000K reached
  → collisional dissociation of H_2 starts.

The first core III

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

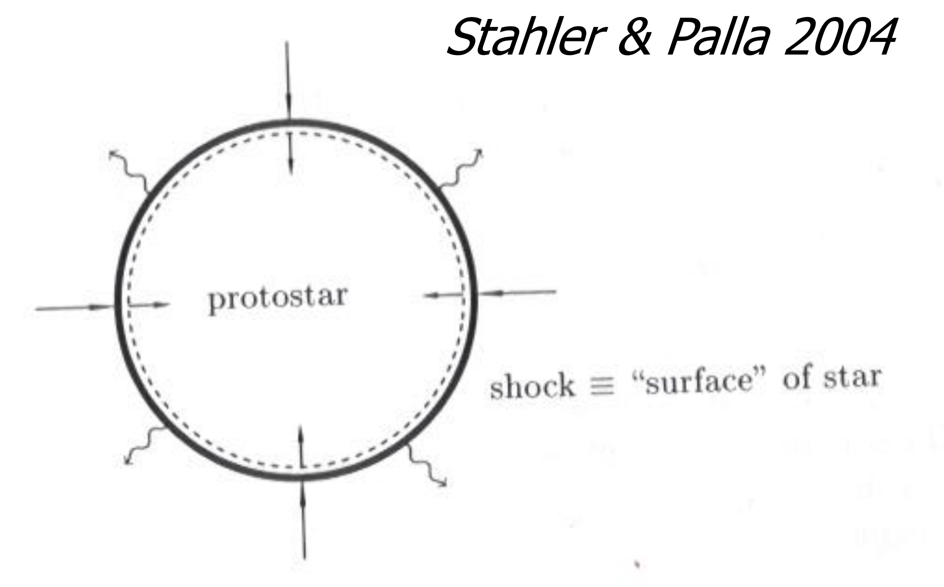
- Region of atomic H spreads outward

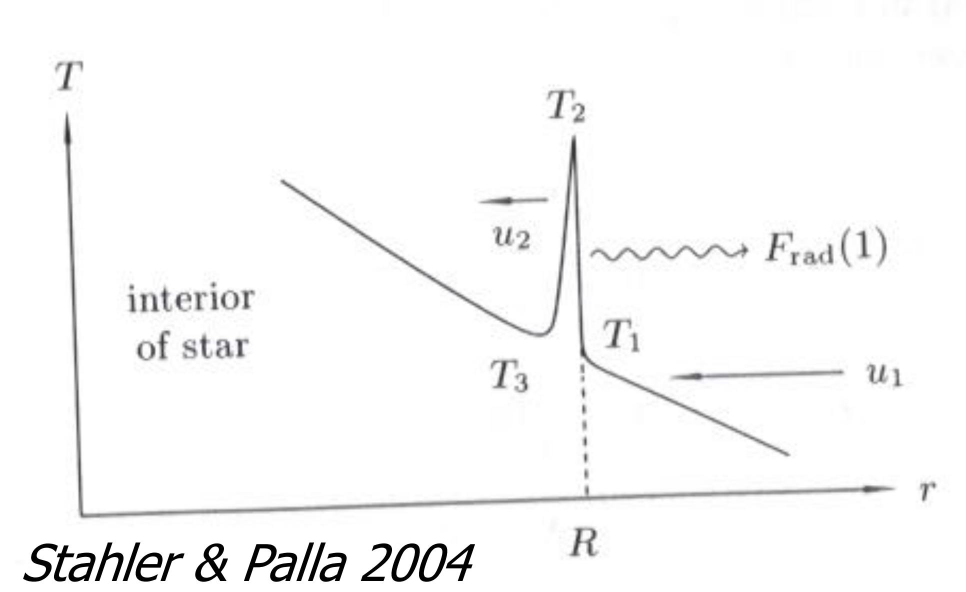


- Without significant T & p increase, the first core cannot keep equilibrium
  → Entire core becomes unstable → collapses and forms protostar
  → significant T & ρ increase → collisionally ionize most hydrogen
  → emerging protostar is now dynamically stable.

- 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_*

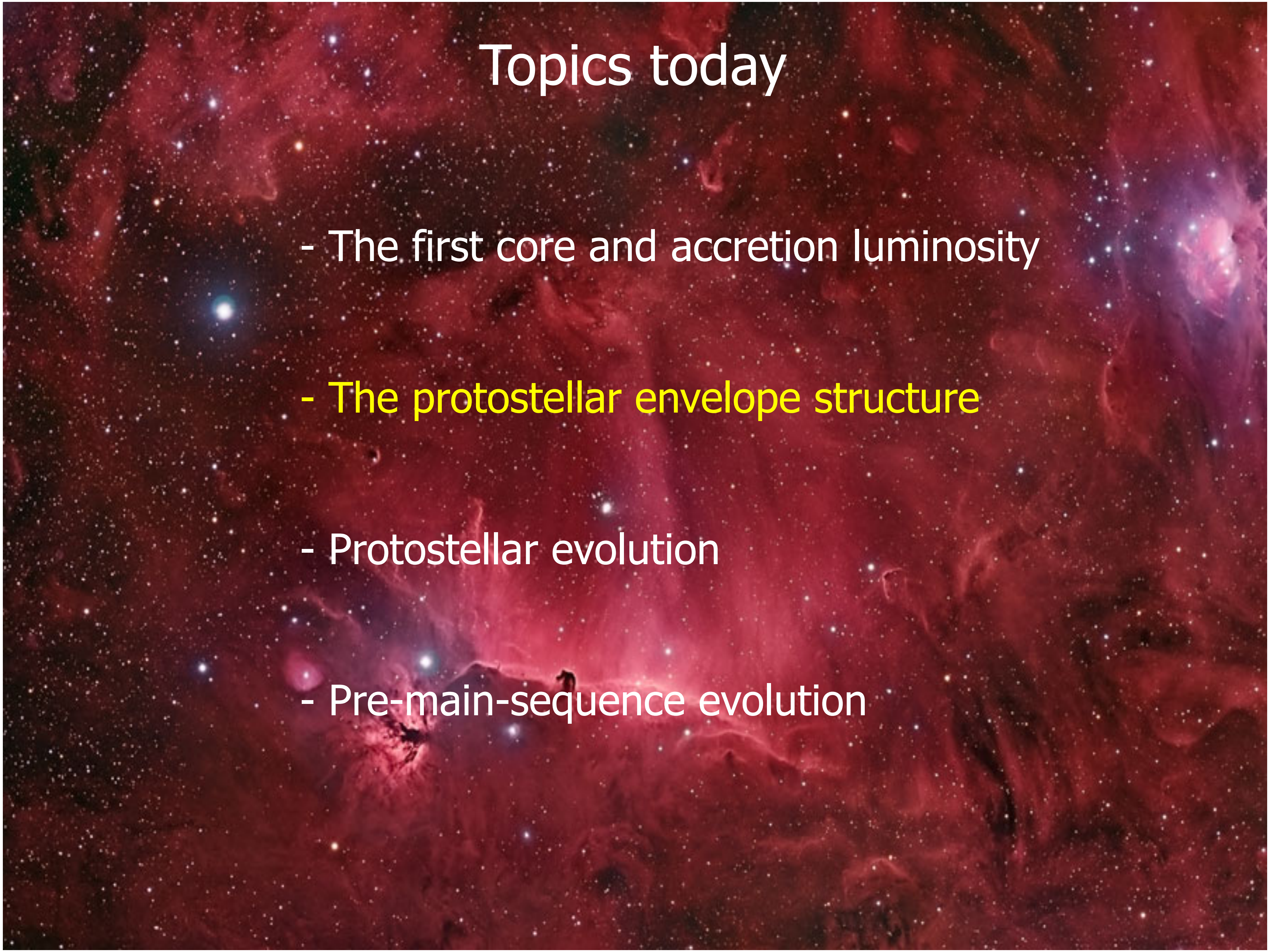
→ accretion luminosity of protostar: energy multiplied by accretion rate:

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

- 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.)



Topics today

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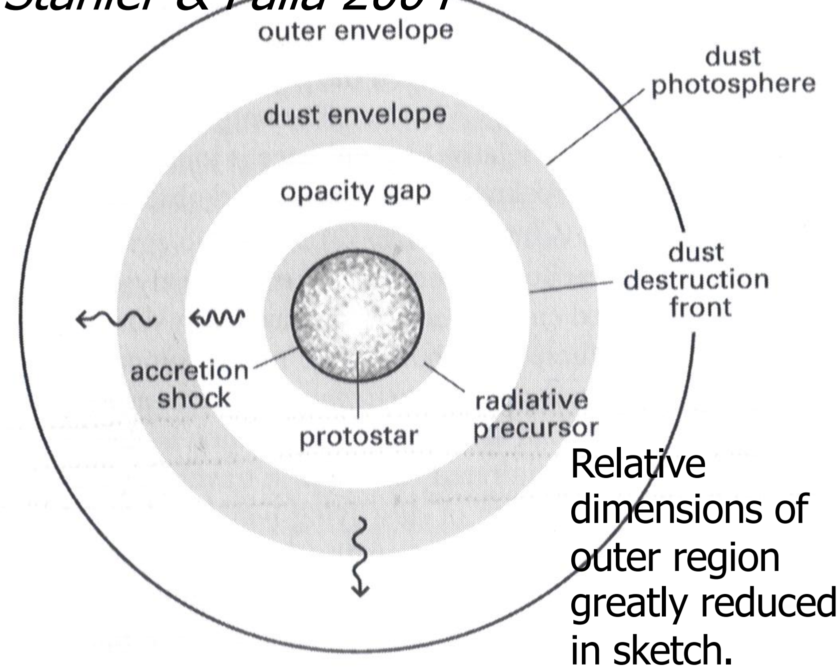
Protostellar envelope I

- Outer envelope optically thin.

- Infalling gas and dust 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

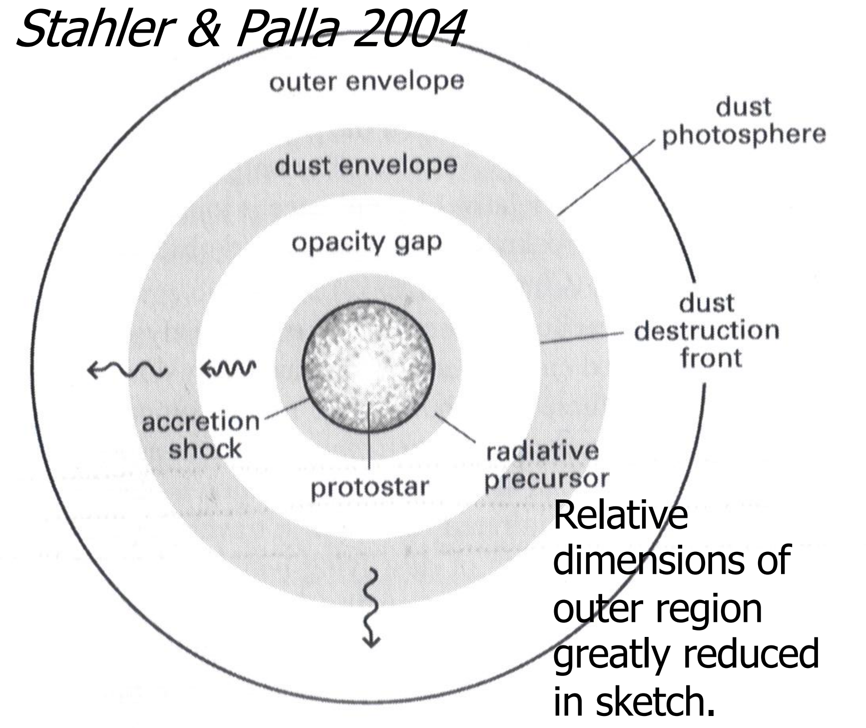
- In shock region gas approaches protostar ~ at free-fall speed:

$E_{kin} = 1/2mv_{ff}^2 = E_{grav} = GM_*m/R_*$

$=> v_{ff} = \sqrt{2GM_*/R_*}$

$= 280 \text{ km/s } (M_*/1M_{sun})^{1/2} (R_*/5R_{sun})^{-1/2}$

Stahler & Palla 2004



Relative dimensions of outer region greatly reduced in sketch.

→ Immediate postshock temperature $>10^6$K, UV and X-ray regime

→ Postshock settling region opaque, quick temperature decrease

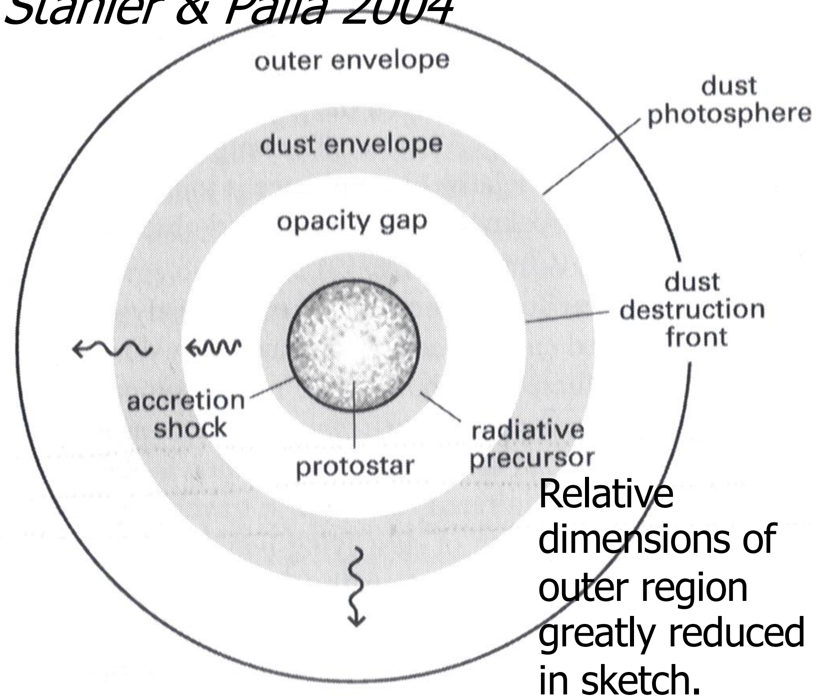
→ The surface of precursor radiates as ~ blackbody: Stephan-Boltzmann:

$L_{acc} \sim 4\pi R_*^2 \sigma_B T_{eff}^4$ Substituting L_{acc} $=> T_{eff} \sim (GM_*(dM/dt)/4\pi R_*^3 \sigma_B)^{1/4}$

$=> T_{eff} \sim 7300\text{K } ((dM/dt)/1e\text{-}5M_{sun}yr^{-1}) (M_*/1M_{sun})^{1/4} (R_*/5R_{sun})^{-3/4}$

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

Temperatures and dimensions of envelope



Stahler & Palla 2004

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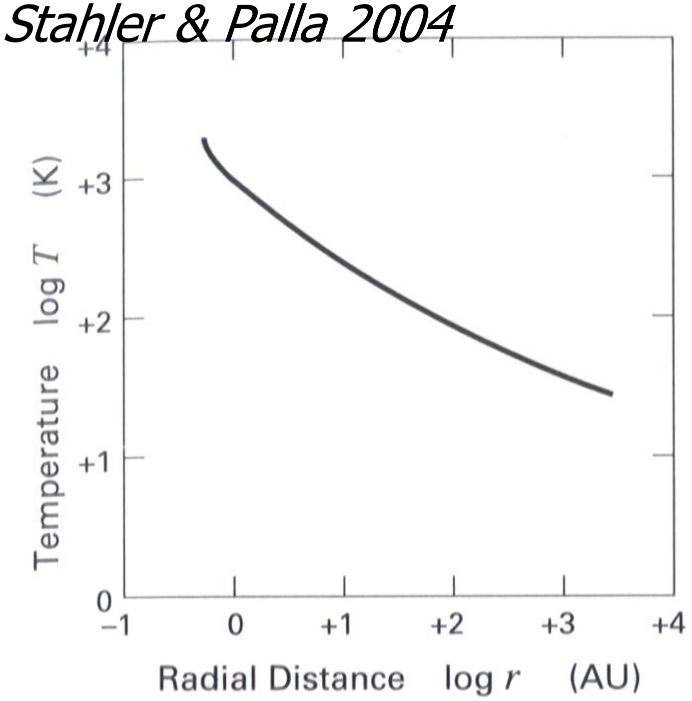
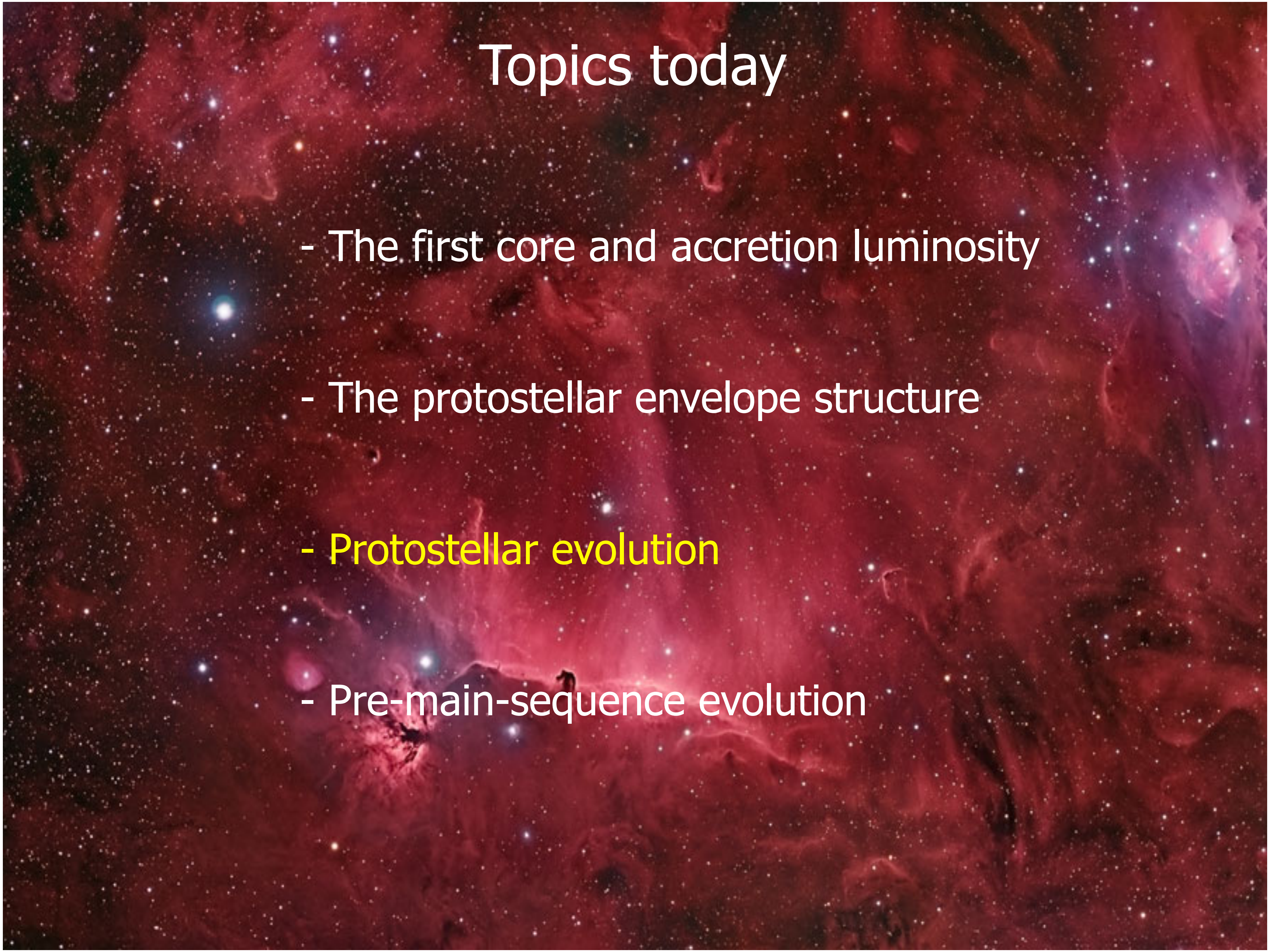


Stahler & Palla 2004

- 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:	$\sim 5 R_* \sim 0.02$ 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: $P = \rho a^2 = \rho/\mu \, \mathcal{R}T$ (4)

(μ mean molecular weight, $\mathcal{R}$ ideal gas constant, a sound speed)

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:

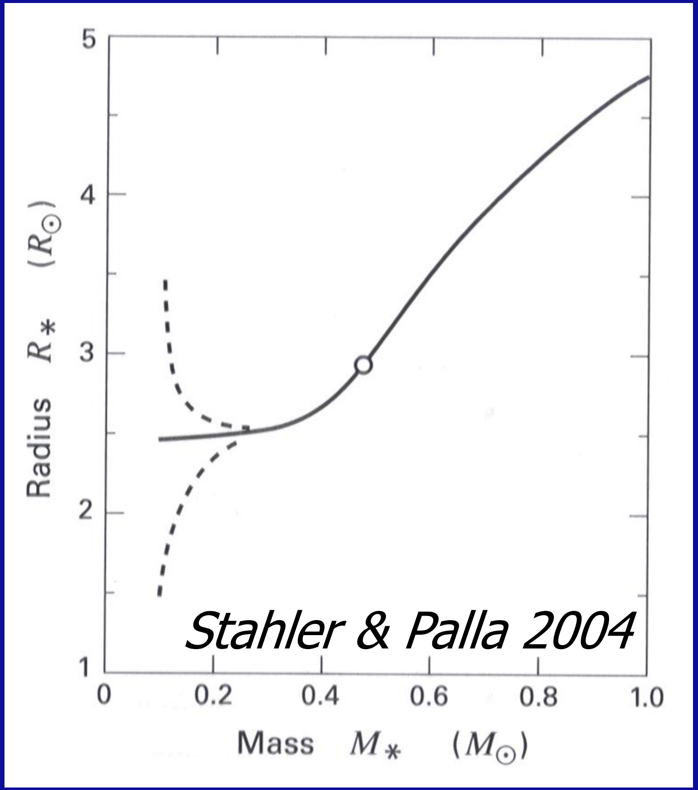
$$\partial L_{int}/\partial M_r = \varepsilon(\rho,T) - T\,\partial s/\partial t \qquad (6)$$

($\varepsilon(\rho,T)$ 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



Stahler & Palla 2004

- 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.

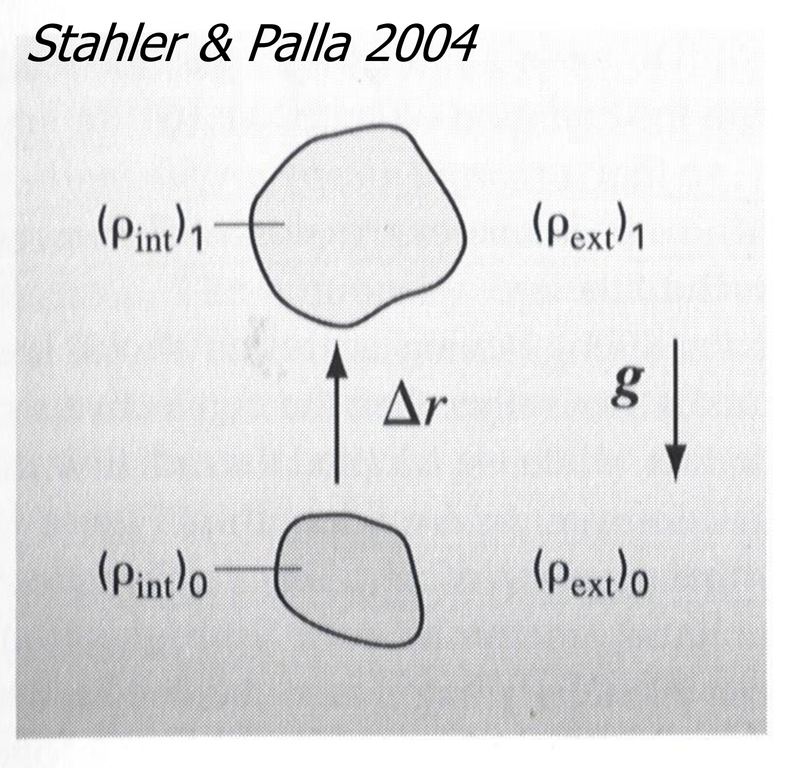
- Adding additional infalling mass shells → protostar can be described by entropy profile $s(M_r)$ (reflects conditions at accretion shock)

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

- In absence of nuclear burning → increasing $s(M_r)$

  (because rising M_* → rising infall velocity → larger accretion shock → L_{acc} increases → Protostellar radius increases with time)

Convection I

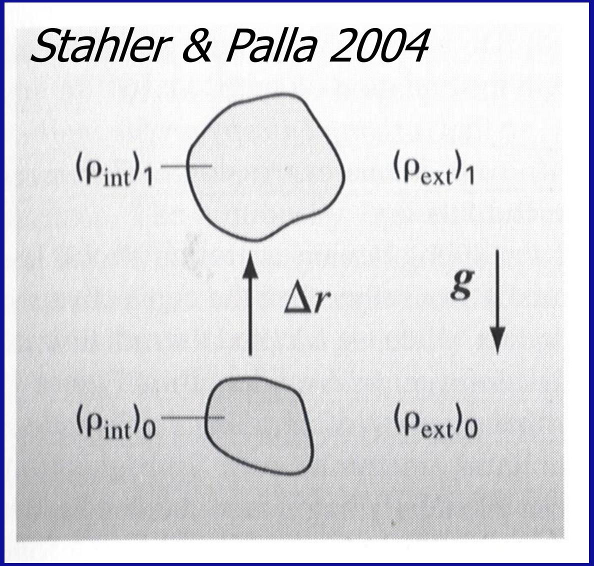


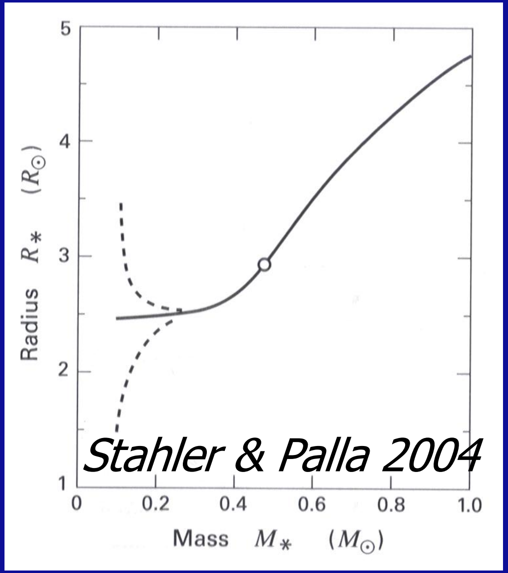
- Displace parcel outward. P_{ext} decreases.
  → parcel expands and $(\rho_{int})_1 < (\rho_{int})_0$

- **Question:**
  - 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

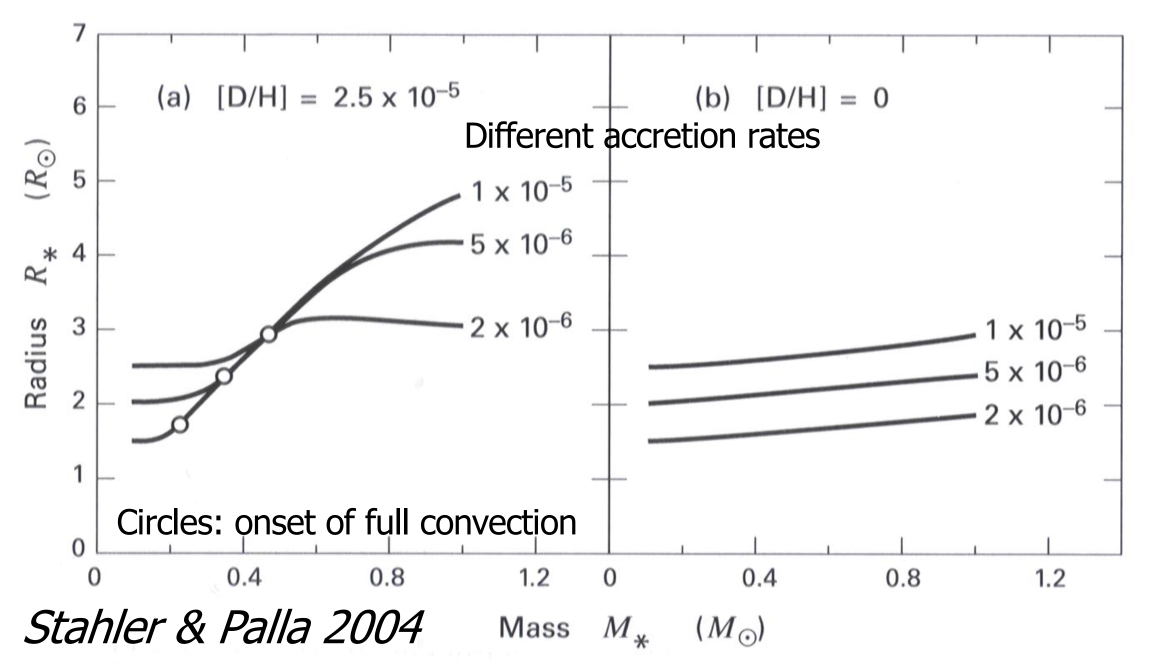




- M_*/R_* rises fast → interior T increase → Nuclear reactions start (at ~$0.3M_{sun}$ deuterium burning at ~10^6K).
  - → entropy profile turns $\partial s/\partial M_r < 0$
  - → too much energy for radiative transport in opaque interior
  - → convection starts

- $\partial s/\partial M_r < 0$ → 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



Different accretion rates

Circles: onset of full convection

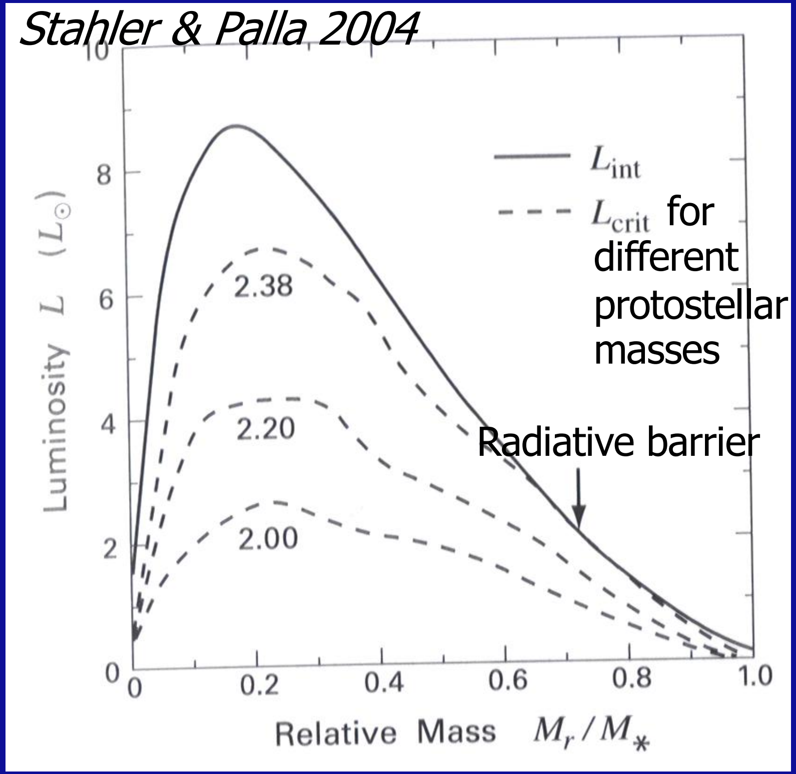
Stahler & Palla 2004

- $^2H + ^1H \rightarrow ^3He + \Delta E$ with ΔE ~ 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?


Stahler & Palla 2004

for different protostellar masses

Radiative barrier

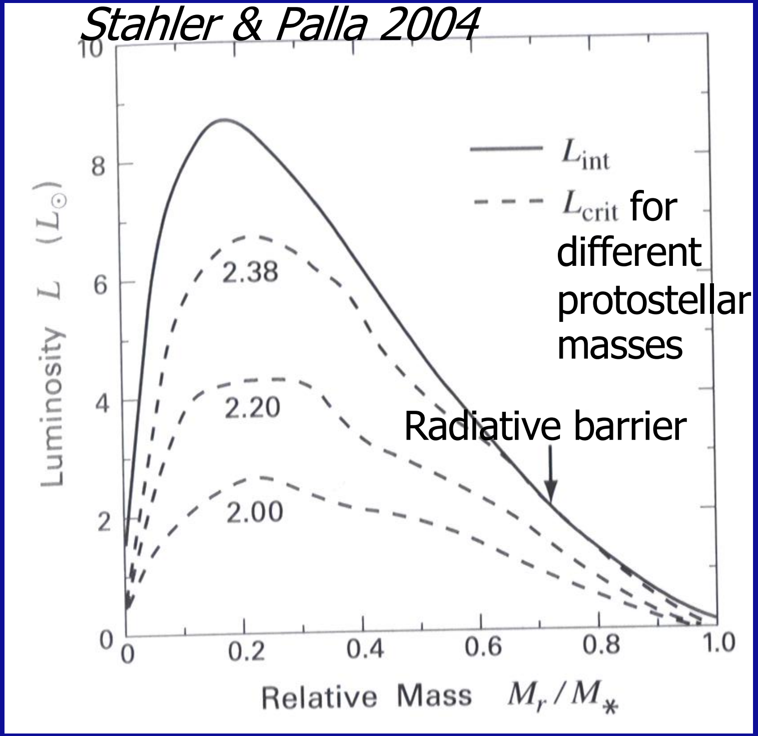
- Critical luminosity L_{crit} is maximum value carried by radiative diffusion. Depends on opacity of gas/plasma.
- Continuum opacity from free-free emission (Kramers-law opacity) scales

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

→ $L_{crit} \propto M_*^{11/2} R_*^{-1/2}$

For growing protostars → L_{crit} rises sharply surpassing interior luminosity.
→ Convection then disappears and protostar gets radiative barrier.

Deuterium shell burning I



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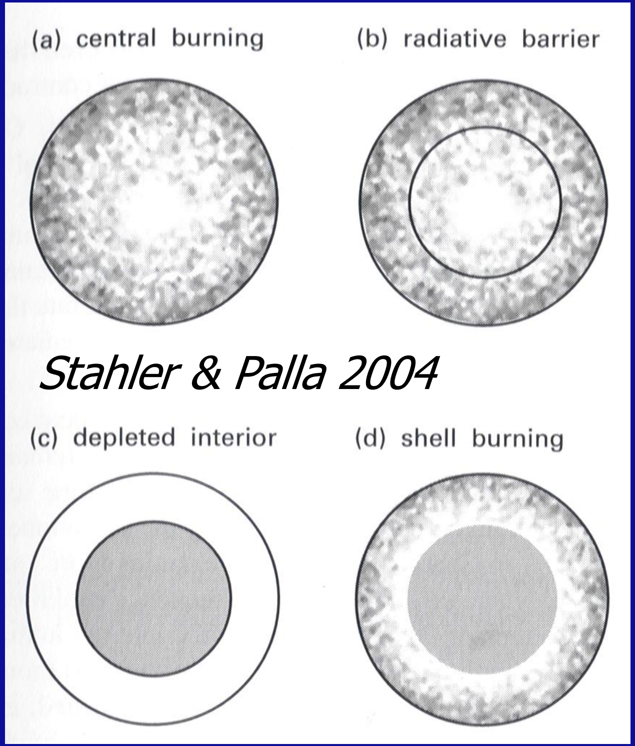
$L_{\rm crit}$ for different protostellar masses

Radiative barrier



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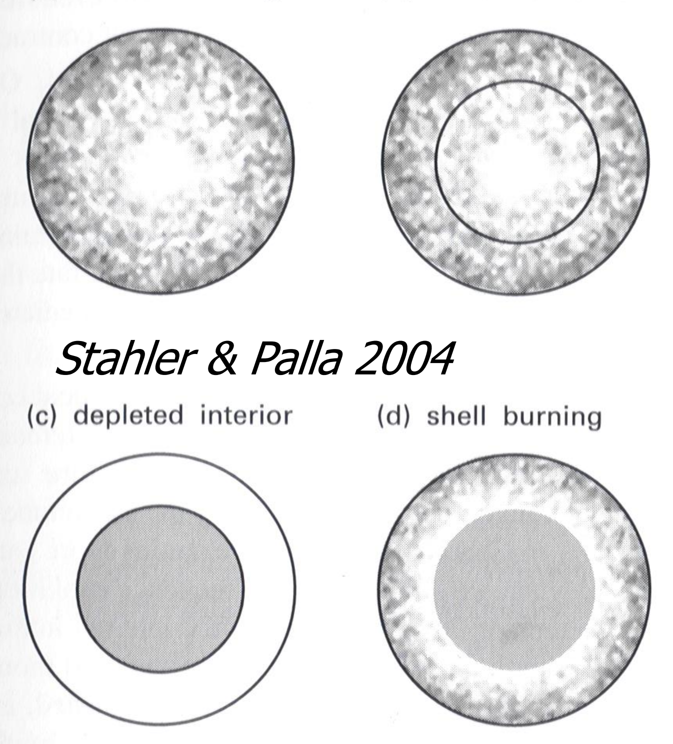
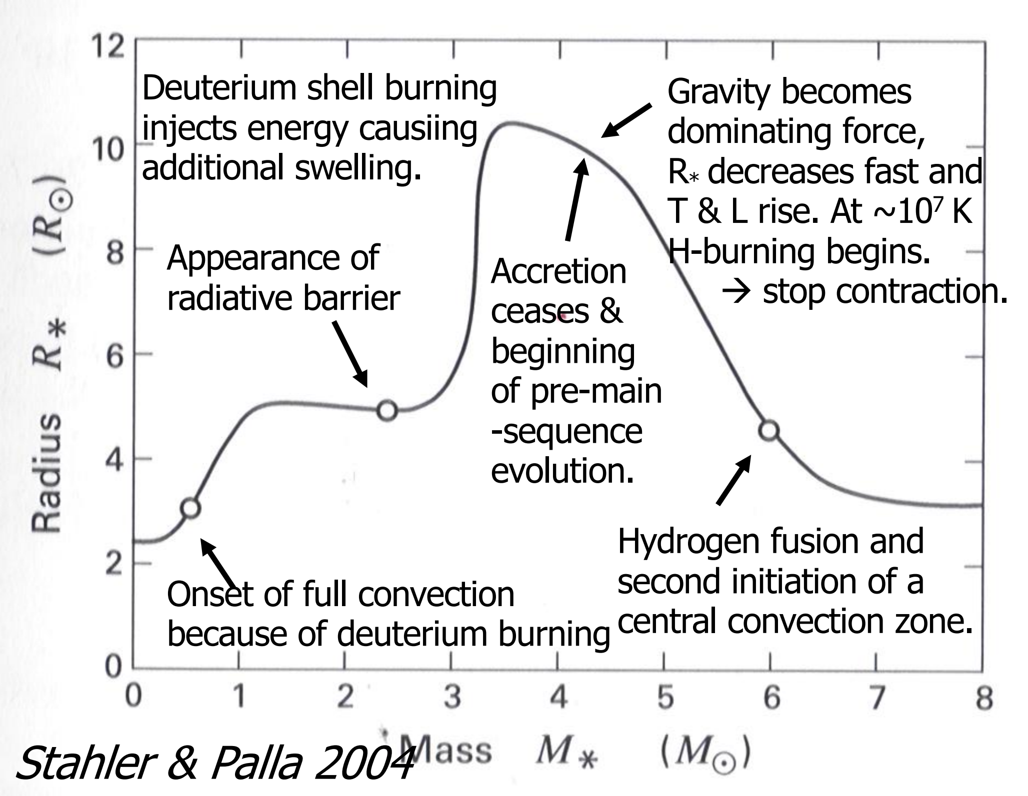
- Radiative barrier → no new deuterium to center & deut. consumed rapidly.
- Interior luminosity $L_{\rm int}$ declines below $L_{\rm crit}$
  → convection disappears in whole interior volume.

- 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



Stahler & Palla 2004



Deuterium shell burning injects energy causiing additional swelling.

Appearance of radiative barrier

Onset of full convection because of deuterium burning

Accretion ceases & beginning of pre-main -sequence evolution.

Gravity becomes dominating force, R_* decreases fast and T & L rise. At ~10^7 K H-burning begins.
→ stop contraction.

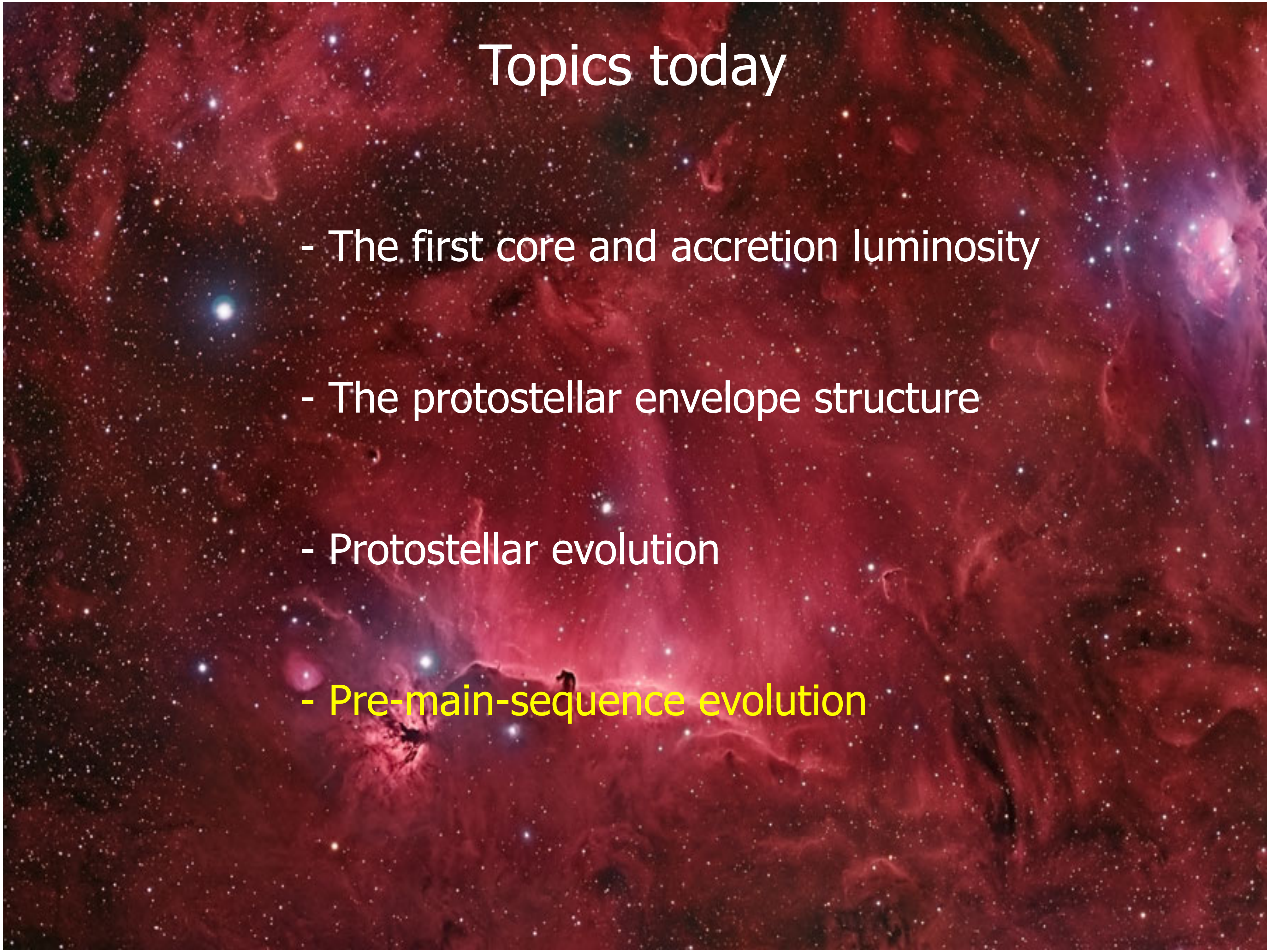
Hydrogen fusion and second initiation of a central convection zone.

Stahler & Palla 2004

- Deuterium shell burning accompanied by structural change of protostar.

- Shell burning injects heat → rises entropy s of the outer layers.
→ further swelling of the protostar

- Adding more mass → rise of L_{crit} → drives the radiative barrier & burning layer & convection zone outward.
→ Protostar (>~$2M_{sun}$) then almost fully radiatively stable.



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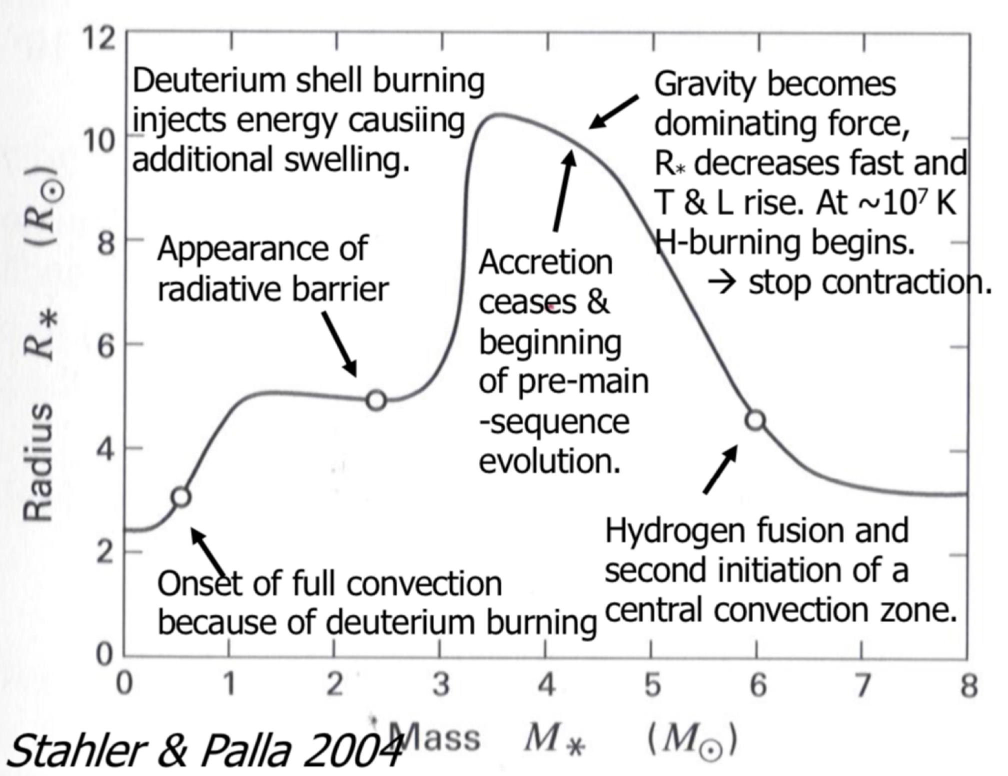
Protostellar vs. pre-main sequence evolution (mainly for low-mass protostars)

- Accretion ceases → protostar contracts → gain energy by gravity

→ Main luminosity not accretion but due to gravitational contraction.

→ Identify this point with end of protostellar and beginning of pre-main sequence phase (low-mass stellar evolution)



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Stahler & Palla 2004

Further contraction until H-burning I

- Different evolution for low- and high-mass pre-main sequence stars:

  - Low-mass:

    - still convective, still remaining deuterium burning

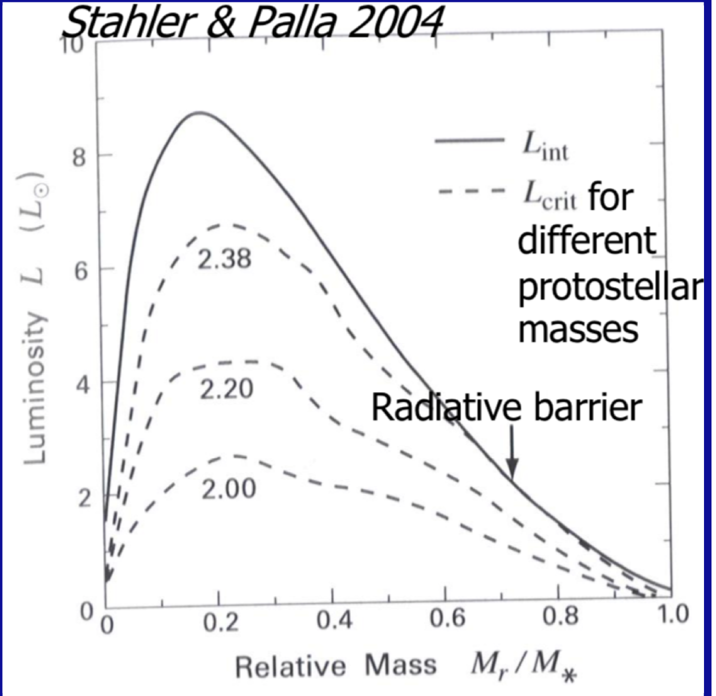
    - Hayashi tracks: Shrinking releases grav. energy & $T_{surface}$ approx. constant

    - $L = 4\pi R^2 \sigma_B T_{eff}^4 \propto R_*^2$ → L decreases → L falls below L_{crit}.
      → Radiative core forms again with a shrinking outer convective layer.

    - During further slow contraction internal energy, temperature & luminosity rise again until hydrogen burning starts → ZAMS.

    - Stars below ~$0.4 M_{sun}$ reach the ZAMS still fully convective.

Stahler & Palla 2004

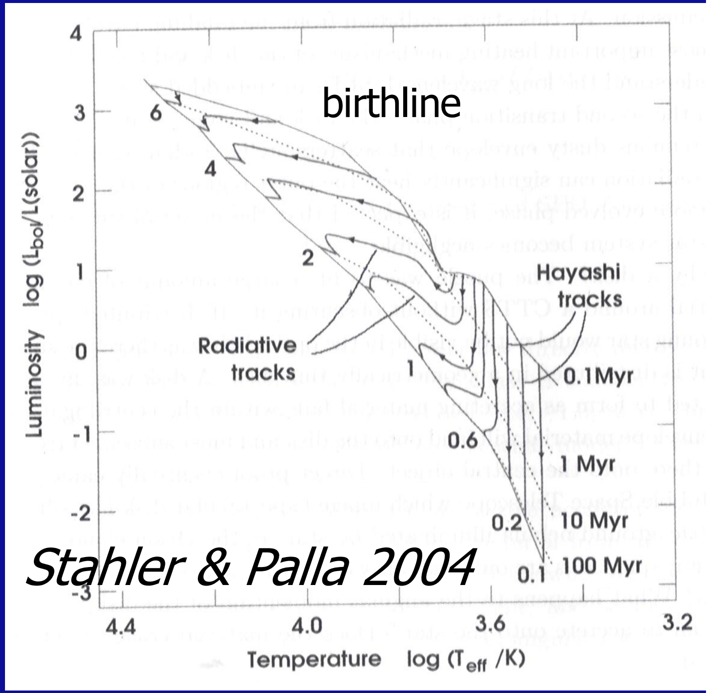


Further contraction until H-burning II

- Different evolution for low- and high-mass pre-main sequence stars:
  - <u>Intermediate- to high-mass:</u>
    - More massive not convective anymore but fully radiative
      → no phase of decreasing luminosity (although they also shrink).

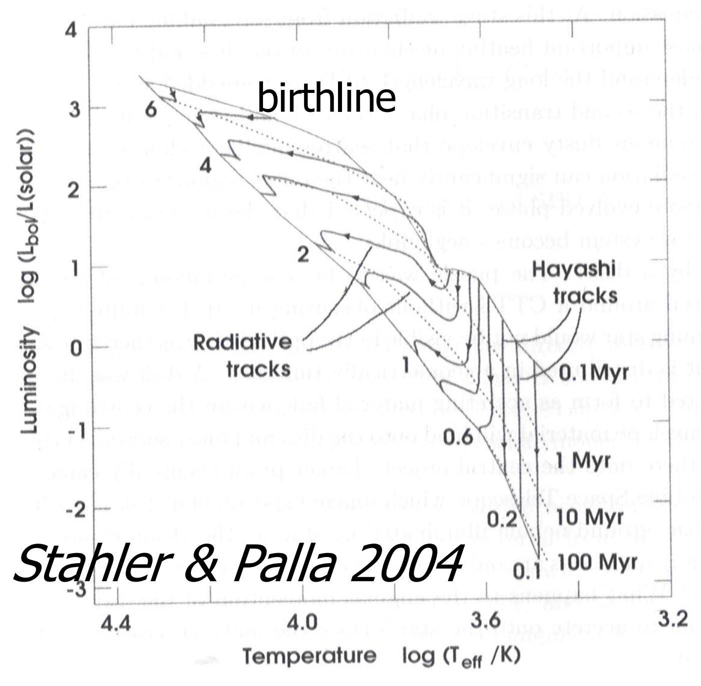
      → Always gain luminosity and temperature via gravitational energy (and decreasing deuterium shell burning)

      → Hydrogen ignites → ZAMS.



Stahler & Palla 2004

Hertzsprung Russel (HR) diagram I

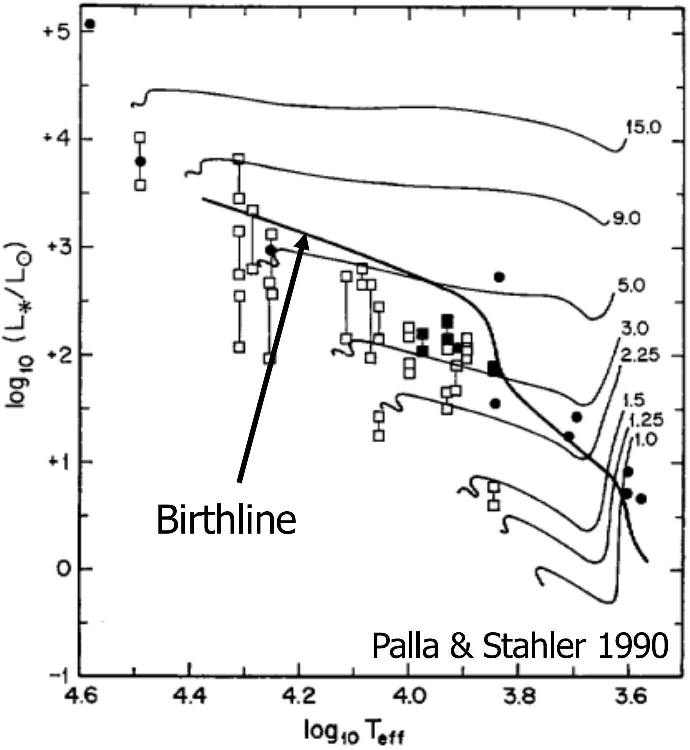


- Birthline first observationally → locus where stars first appear in the HR diagram emanating from their dusty natal envelope.

- Theoretically: birthline the time where the main accretion has stopped → pre-main sequence star gains the main luminosity from grav. contraction.

  → Approx. coincedes with quasi-static contraction in still convective phase

Hertzsprung Russel (HR) diagram II



Birthline

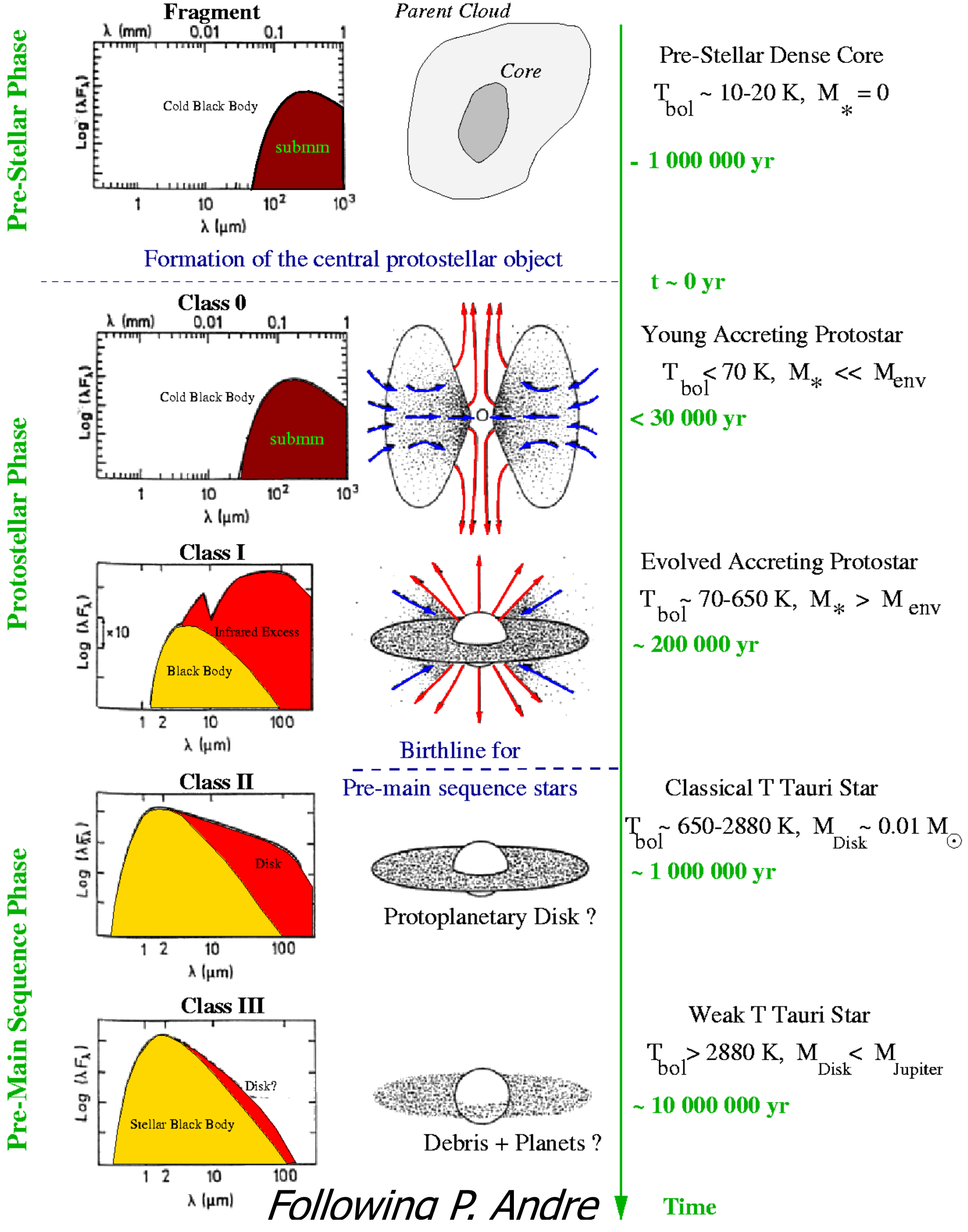
Palla & Stahler 1990

- Intermediate-mass protostars fully radiative when stopping accretion
  → no vertical Hayashi part but direct horizontal radiative tracks

- High-mass stars: short Kelvin-Helmholtz contraction time-scale
  → start nuclear H-burning - entering the ZAMS before accretion ends

- no (visible) pre-main sequence evolution since H-burning starts still deeply embedded in their natal cores

Observable spectral energy distributions (SEDs)



Formation of the central protostellar object

Birthline for
Pre-main sequence stars

Protoplanetary Disk ?

Debris + Planets ?

Pre-Stellar Dense Core

$T_{bol} \sim$ 10-20 K, $M_* = 0$

- 1 000 000 yr

t ~ 0 yr

Young Accreting Protostar

$T_{bol} < 70$ K, $M_* << M_{env}$

< 30 000 yr

Evolved Accreting Protostar

$T_{bol} \sim$ 70-650 K, $M_* > M_{env}$

~ 200 000 yr

Classical T Tauri Star

$T_{bol} \sim$ 650-2880 K, $M_{Disk} \sim 0.01\ M_\odot$

~ 1 000 000 yr

Weak T Tauri Star

$T_{bol} > 2880$ K, $M_{Disk} < M_{Jupiter}$

~ 10 000 000 yr

Time

Following P. Andre

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 as: “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.

- End of protostellar/beginning or pre-main sequence evolution → birthline.

- Pre-main sequence evolution in the Hertzsprung-Russel (HR) diagram.

Sternentstehung - Star Formation

Winter term 2022/2023

Henrik Beuther, Thomas Henning & Jonathan Henshaw

18.10 Today: Introduction & Overview (Beuther)
25.10 Physical processes I (Beuther)
08.11 Physcial processes II (Beuther)
15.11 Molecular clouds as birth places of stars (Henshaw)
22.11 Molecular clouds (cont.), Jeans Analysis (Henshaw)
29.11 Collapse models I (Beuther)
06.12 Collapse models II (Henning)
13.12 Protostellar evolution & pre-main sequence (Beuther)
20.12 Outflows/jets (Beuther)
10.01 Accretion disks I (Henning)
17.01 Accretion disks II (Henning)
24.01 High-mass star formation, clusters and the IMF (Henshaw)
31.01 Extragalactic star formation (Henning)
07.02 Planetarium@HdA, outlook, questions (Beuther)
13.02 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_ws2223.html

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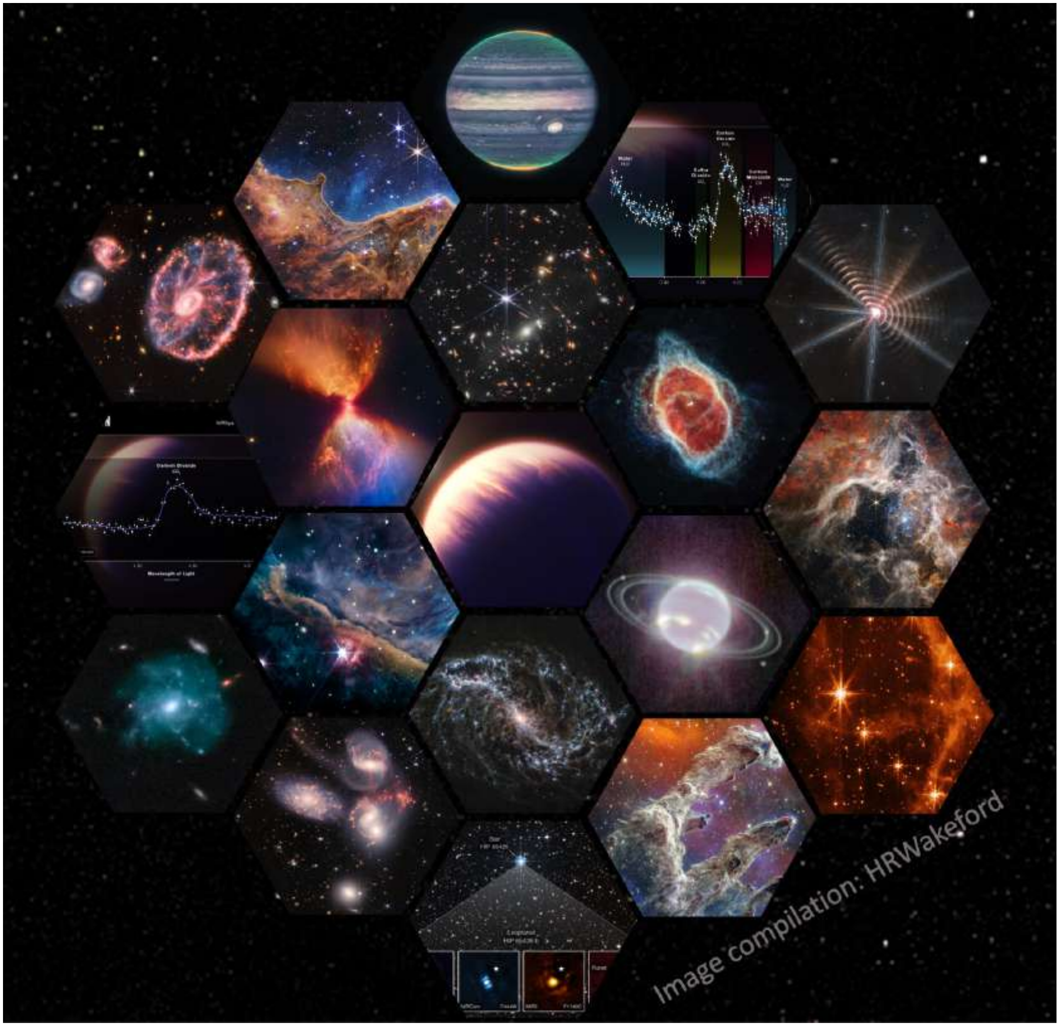
Heidelberg Joint Astronomical Colloquium

Winter Semester 2022 — Tuesday December 13th, 16:00

Main Lecture Theatre, Philosophenweg 12

Hannah Wakeford (University of Bristol):

Exploring the Diversity of Exoplanet Atmospheres



Caption: JWST has upgraded our view of the universe from the farthest galaxies to planetary atmospheres. Behind each image is a story that can be explored.

Those unable to attend the colloquium in person are invited to participate online through Zoom. More information, including the abstract and the Zoom link, is given on HePhySTO: https://www.physik.uni-heidelberg.de/hephysto/