Star formation

Switching-on fusion

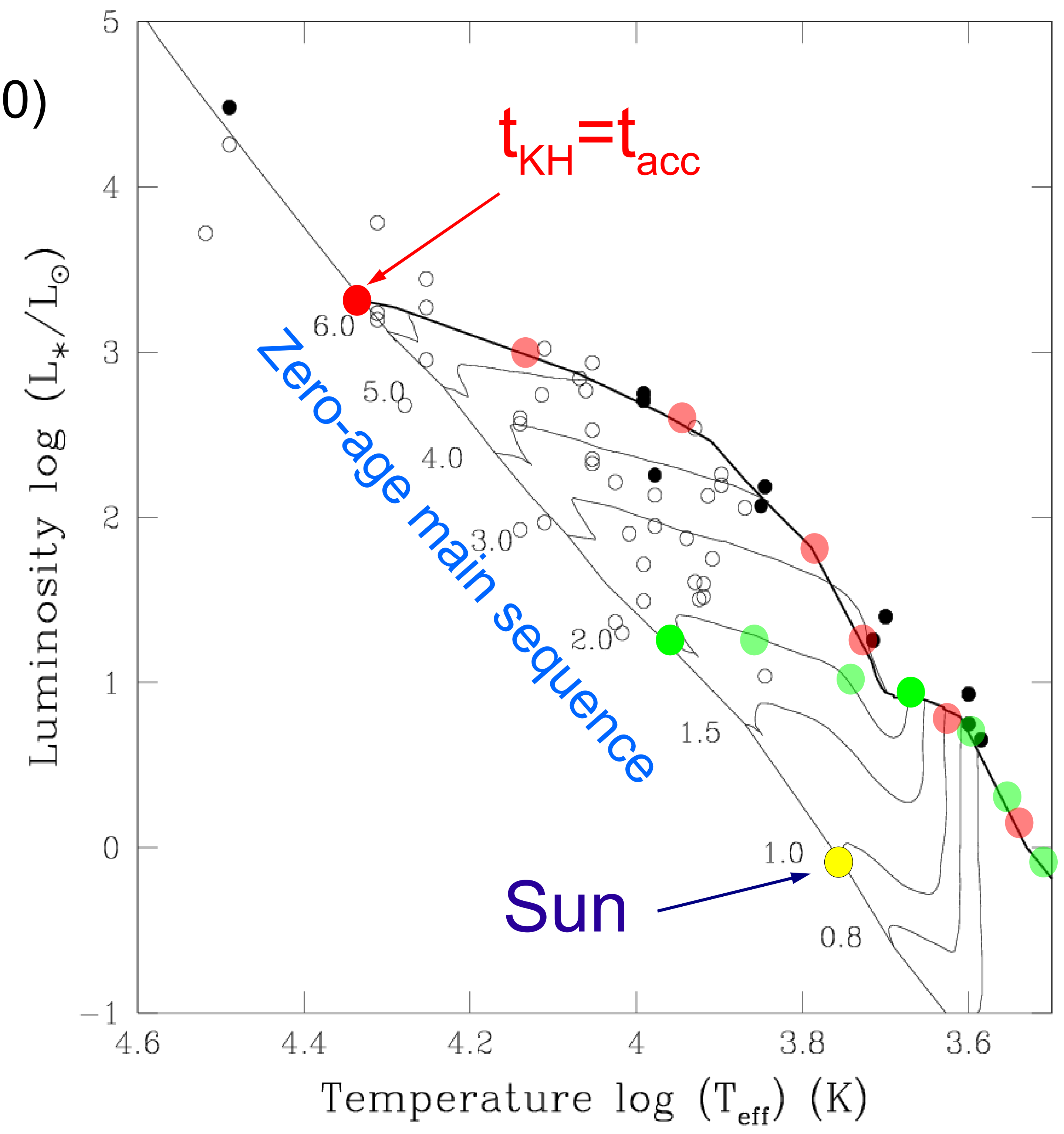
Global picture (for low-mass PMS)

- Start with isothermal collapse → Hayashi track
  - Luminosity dominated by accretion
- End of main accretion phase
  - Luminosity dominated by adiabatic contraction
- Fully convective core
  → continuation of Hayashi track
  - Temperature limited by Hayashi temperature (H^- opacity temperature)
- Increase of temperature to allow $L_{rad,max} > L$
  - Radiative transfer of luminosity
  - Reduced stellar contraction

→ Henyey track up to ignition

Palla & Stahler (1990)

dM/dt=10^{-5} M_o/yr



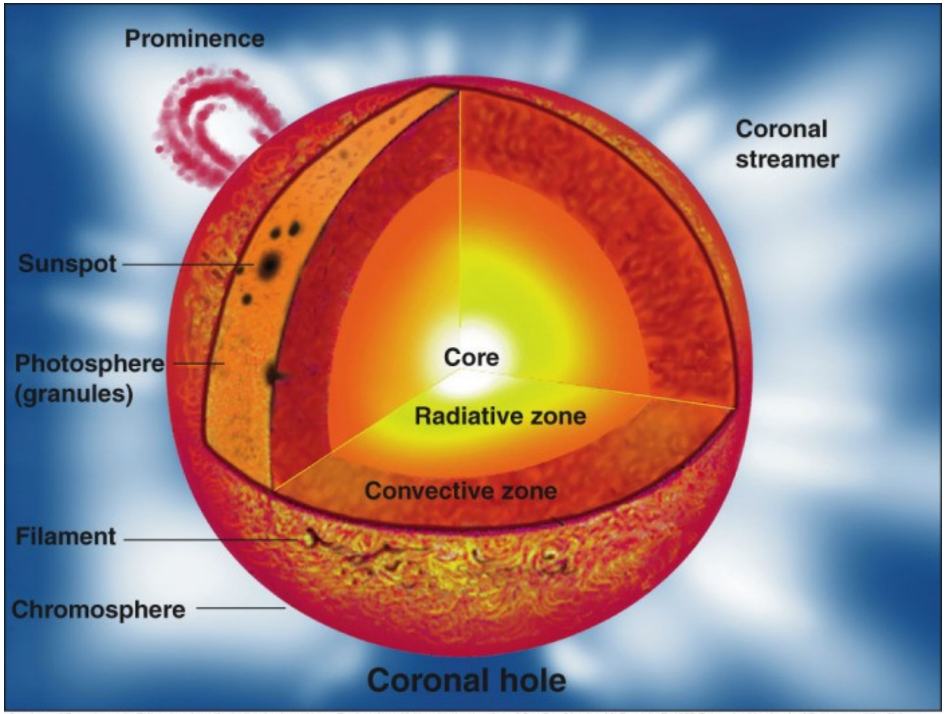
Massive stars are born on the Main Sequence!

Stellar structure

Spherical symmetry:

▪ $dP/dr = -\rho(r)\, G\, m(r) / r^2$	Hydrostatic equilibrium
▪ $dm/dr = 4\pi r^2 \rho$	Mass conservation
▪ $P \sim \rho^\gamma$	Equation of state

- Energy transport:
  - Radiative:
    centre of massive
    PMS
  - Convective:
    low mass,
    low T, high κ_R



Courtesy of Encyclopaedia Britannica, Inc.; illustration by Anne Hoyer Becker; from "A New Understanding of Our Sun," by Jay M. Pasachoff, 1989 Britannica Yearbook of Science and the Future

Stellar structure

Equation of state:

- $p \sim \rho^\gamma$
- Uniform equation of state through all radii for fully convective star
- ideal ionized gas: $\gamma=5/3$
  - $p = \Re/\mu \, \rho \, T$

→ Closed equation for mass-size relation:

- $M \propto R^{\frac{3\gamma-4}{\gamma-2}}$
- $M \sim R^{-3}$ for $\gamma=5/3$
  - Negative mass-size relation!
  - More massive stars are smaller!

Stellar structure

Temperature evolution from virialization:

$$L = -\frac{dE_{tot}}{dt} = -\frac{d(U+W)}{dt} \text{ with } 2U+W=0 \text{ (virial) and } W = -f\frac{GM^2}{R}$$

$$L = -\frac{1}{2}\frac{dW}{dt} = -\frac{1}{2}f\frac{GM^2}{R^2}\frac{dR}{dt}$$

f = 6/7 for polytropic gas with γ=5/3

$$L > 0 \quad \Rightarrow \quad \frac{dR}{dt} < 0 \quad \text{Radiative losses at the photosphere lead to gravitational contraction}$$

$$\frac{dU}{dt} = L > 0 \quad \text{Radiative losses lead to increase of temperature!}$$

- By radiating away energy, the star gets hotter!

→ negative specific heat !

- $T \sim R^{-1}$

Stellar structure

Special case: Fermi gas

- At high densities the Fermi pressure can exceed the thermal pressure
- Equation of state still $p \sim \rho^{\gamma}$, $\gamma=5/3$ but independent of temperature T
- If $p_{\text{Fermions}} > p_{\text{Ions}}$
  - Fermionic pressure stabilizes star
  - No further temperature increase in contraction
  - Determines fate of star → whether ignition temperature is reached

Ignition of the star

- D fusion: $p + d \rightarrow {}^{3}He + \gamma$
  - Critical temperature: 8×10^5 K
  - Energy production: $4.2\ 10^3\ J\ kg^{-1}\ s^{-1}\ X_D\ (T/10^6 K)^{11.8}$

- Li fusion: ${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$
  - Critical temperature: 2.5×10^6 K

- H fusion: $4p \rightarrow 4He + 4e^+ + 4v_e + 2\gamma$
  - Critical temperature: 10×10^6 K

H fusion

p-p process:

- $p + p \rightarrow d + e^{+} + v_{e}$
- $d + p \rightarrow {}^{3}He + \gamma$
  - ${}^{3}He + {}^{3}He \rightarrow {}^{4}He + p + p$ = PP-I

  - ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
    - ${}^{7}Be + e^{-} \rightarrow {}^{7}Li + v_{e} + \gamma$ = PP-II
      - ${}^{7}Li + p \rightarrow {}^{4}He + {}^{4}He$

  - ${}^{3}He + {}^{4}He \rightarrow {}^{7}Be + \gamma$
    - ${}^{7}Be + p \rightarrow {}^{8}B + \gamma$
      - ${}^{8}B \rightarrow {}^{8}Be + e^{+} + v_{e}$ = PP-III
        - ${}^{8}Be \rightarrow {}^{4}He + {}^{4}He$

H fusion

p-p process:

- PP-I, PP-II, PP-III are three independent ways to create ^{4}He from p.
- Same energy production, but different number of beta particles and neutrinos
- Temperature efficiency:
  - $T < 14\ 10^6$ K → PP-I dominating
  - $14\ 10^6\ K < T < 24\ 10^6$ K → PP-II dominating
  - $T > 24\ 10^6$ K → PP-III dominating

- Energy production:
  - Constrained by slowest reaction: $p+p \rightarrow d + e^+ + \nu_e$
  - $2.4\ 10^{16}\ J\ kg^{-1}\ s^{-1}\ X_H^2\ \exp(-3.4\ (T/10^9K)^{1/3})/(T/10^9K)^{2/3}$
    - Steep function of temperature ($\sim T^4$ at 10 Mio K)

H fusion

CNO cycle:

- At T > 20 10^6K

- $p + {}^{12}C \rightarrow {}^{13}N + \gamma$
  - ${}^{13}N \rightarrow {}^{13}C + e^+ + \nu_e$
    - ${}^{13}C + p \rightarrow {}^{14}N + \gamma$
      - ${}^{14}N + p \rightarrow {}^{15}O + \gamma$
        - ${}^{15}O \rightarrow {}^{15}N + e^+ + \nu_e$
          - ${}^{15}N + p \rightarrow {}^{12}C + {}^4He$ = CNO-I

          - ${}^{15}N + p \rightarrow {}^{16}O + \gamma$
            - ${}^{16}O + p \rightarrow {}^{17}F + \gamma$ = CNO-II
              - ${}^{17}F \rightarrow {}^{17}O + e^+ + \nu_e$
                - ${}^{17}O + p \rightarrow {}^{14}N + {}^4He$

H fusion

CNO cycle:

  - ^{12}C acts as catalyst
- Energy production:
  - Complex interplay of the multiple reactions
  - Still only approximately known
  - $4.4\ 10^{21}\ \mathrm{J\ kg^{-1}\ s^{-1}}\ X_H Z \exp(-15.2\ (T/10^9\mathrm{K})^{1/3})/(T/10^9\mathrm{K})^{2/3}$
  - Extremely steep function of temperature
  - $\sim T^{18}$ around 20 Mio K
  - Completely dominating at high temperatures

He fusion:

  - At $T > 100$ Mio K
  - Only relevant at end of stellar life, not in star-formation.

Brown dwarfs

$M < 0.08\ M_\odot$:

- $p_{\mathrm{Fermions}} > p_{\mathrm{ions}}$ at $T < 10^6$K
- Critical temperature for H fusion is never reached.

→ Brown dwarf

$M > 0.08\ M_\odot$:

- $p_{\mathrm{Fermions}} < p_{\mathrm{ions}}$
- Temparture grows by contraction above 10^6K
- H fusion starts

→ Star

Brown dwarfs

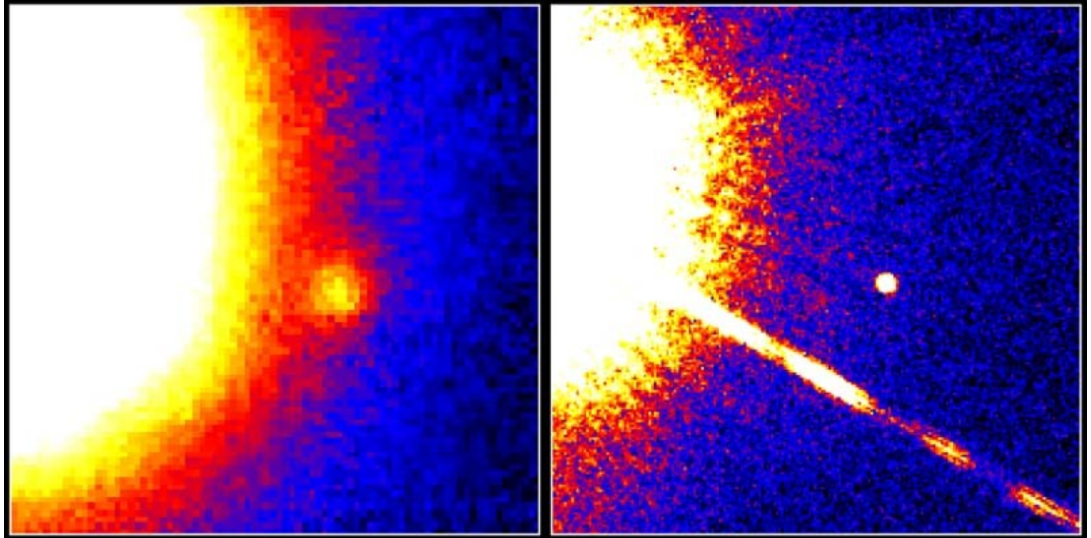
Stellar structure

- Determined by equation of state for Fermi gas
  - $M = M_{BD} R^{-3}$
  - $M_{\mathrm{BD}} = \frac{92\hbar^6}{G^3 m_e^3 m_p^5} \left(\frac{Z}{A}\right)^5$
    - Z – average atomic number
    - A – average atomic weight
  - For a pure Fermi gas, the final stable state is well-defined.

Brown dwarfs

- Brown dwarfs can only radiate their contraction energy
- The follow the Hayashi tracks until the end of their life
  - For $M > 13M_J$ D fusion is still possible ($M_J \sim 10^{-3}\ M_\odot$)
    - Gives only small luminosity enhancement
  - They are still bright when they are young
    - Contraction luminosity allows us to find only young brown dwarfs

Brown Dwarf Gliese 229B

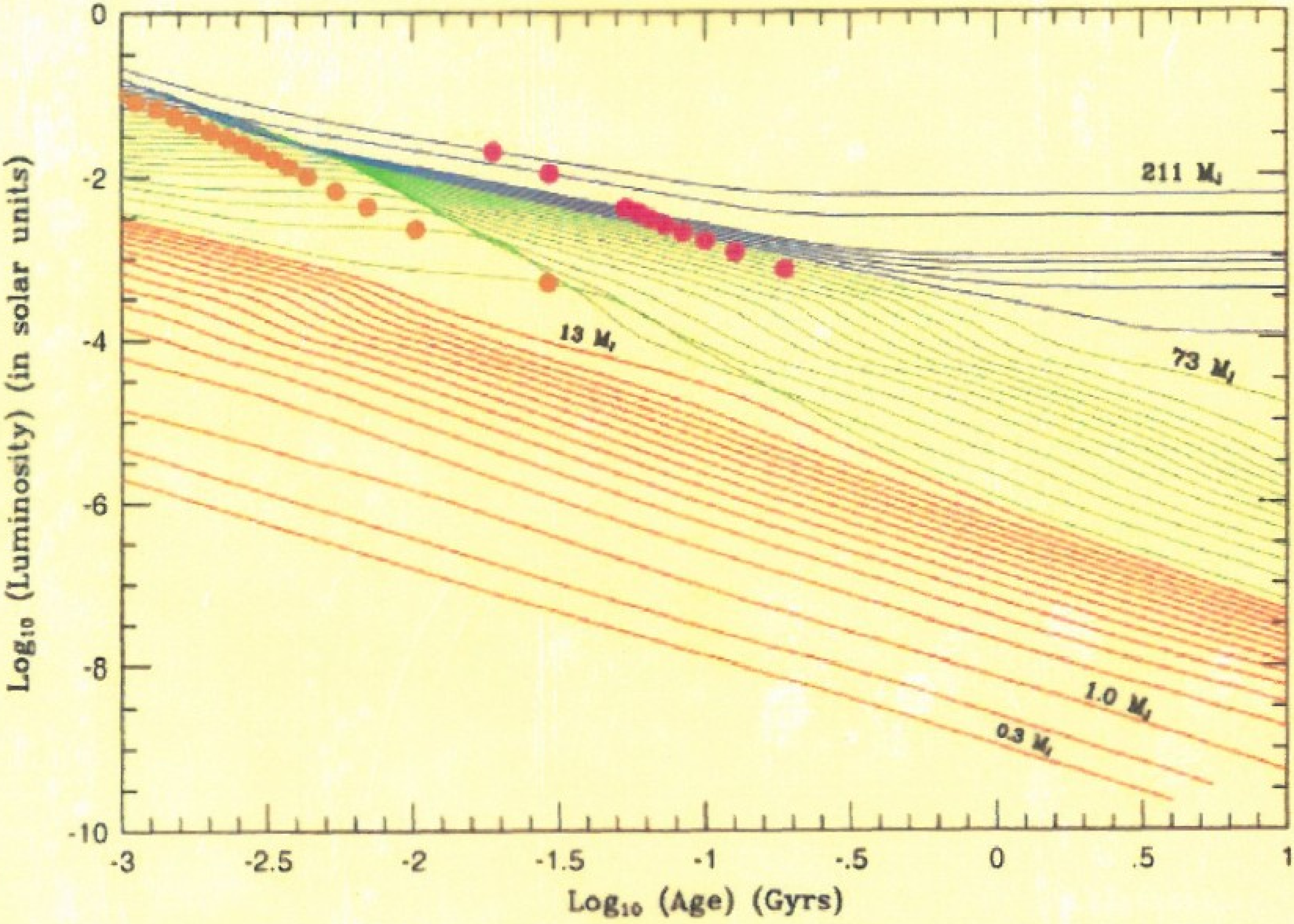


Palomar Observatory
Discovery Image
October 27, 1994

Hubble Space Telescope
Wide Field Planetary Camera 2
November 17, 1995

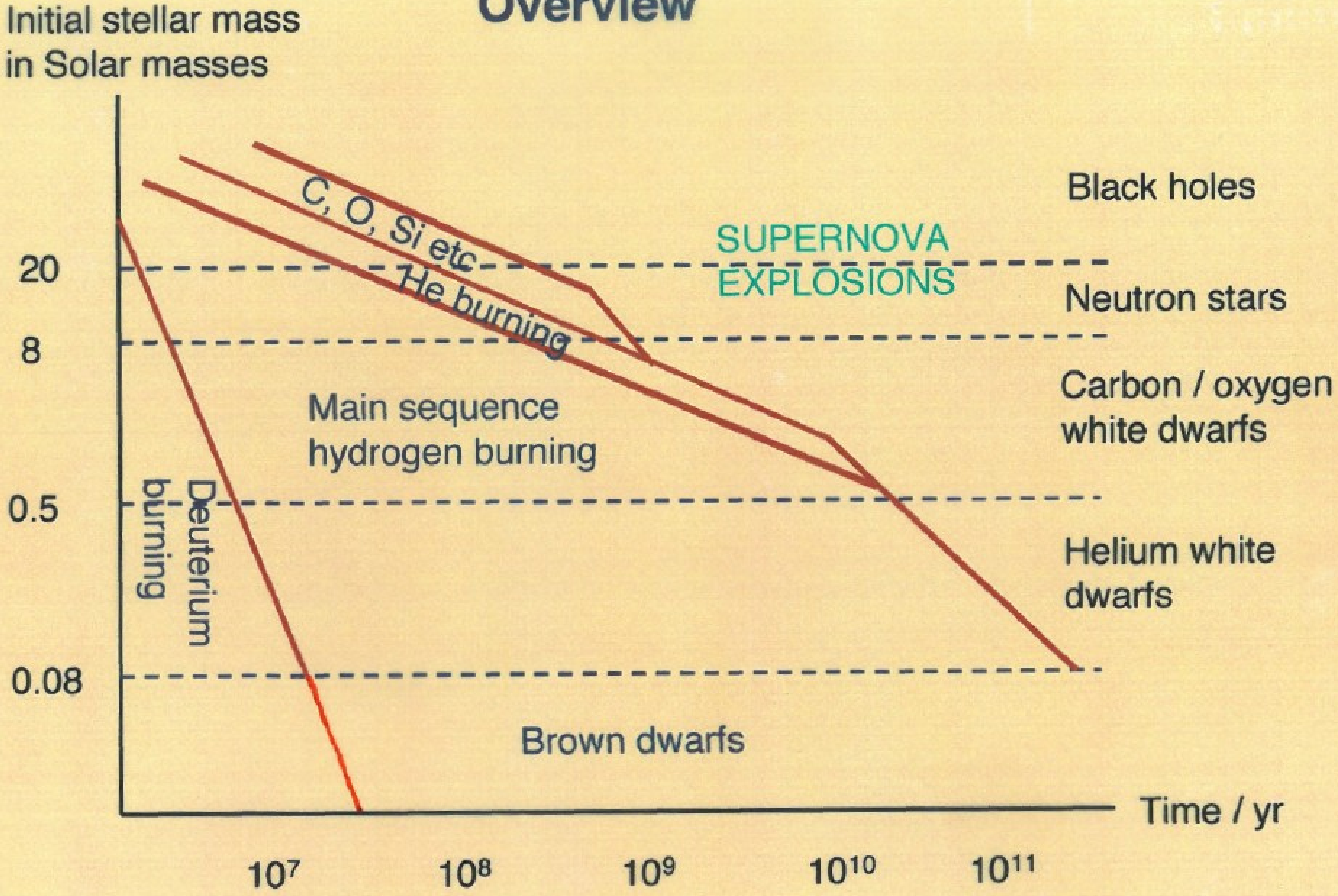
PRC95-48 · ST ScI OPO · November 29, 1995
T. Nakajima and S. Kulkarni (CalTech), S. Durrance and D. Golimowski (JHU), NASA

Luminosity evolution of stars, brown dwarfs, and planets



Burrows et al. 2001

Overview


Initial stellar mass in Solar masses
20
8
0.5
0.08
C, O, Si etc
He burning
SUPERNOVA EXPLOSIONS
Main sequence hydrogen burning
Deuterium burning
Brown dwarfs
Black holes
Neutron stars
Carbon / oxygen white dwarfs
Helium white dwarfs
Time / yr
10^7
10^8
10^9
10^{10}
10^{11}

Li depletion

- Li fusion happens at $T \geq 2.5\ 10^6$ K
  → it is quickly removed
- Li (671nm) absorption is only seen in the atmospheres of very young stars
- Li absorption can be used to measure stellar ages

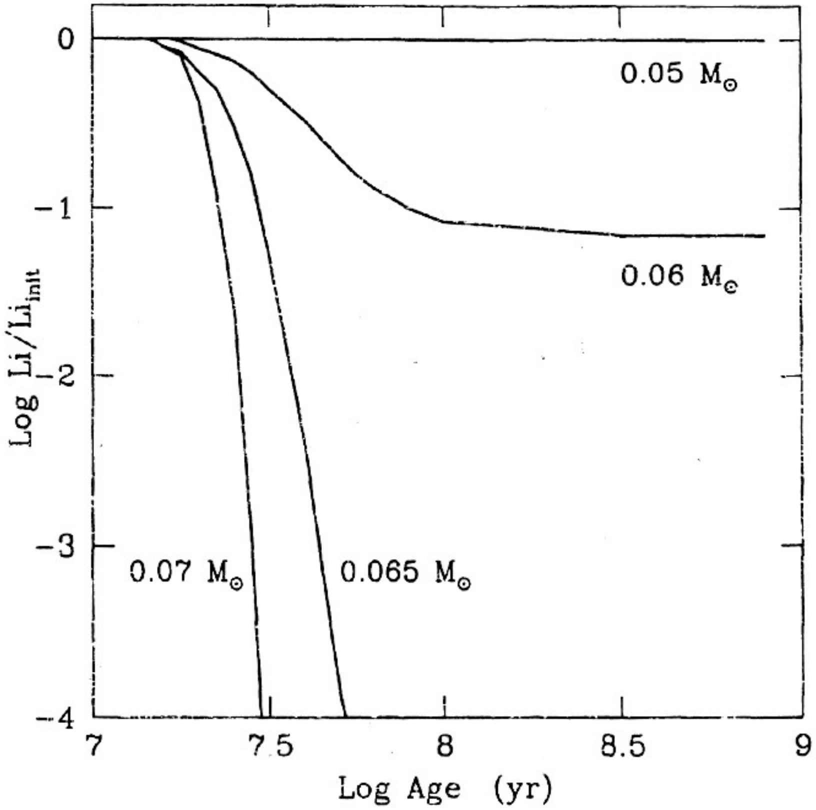


Fig. 31. ^{7}Li-depletion as function of time for stars in the mass range 0.07 to $M_\odot$. (From Rebolo et al. [63])

Li depletion

- Li absorption can be used to measure stellar ages

Unsolved problem: “post-T-Tau gap”

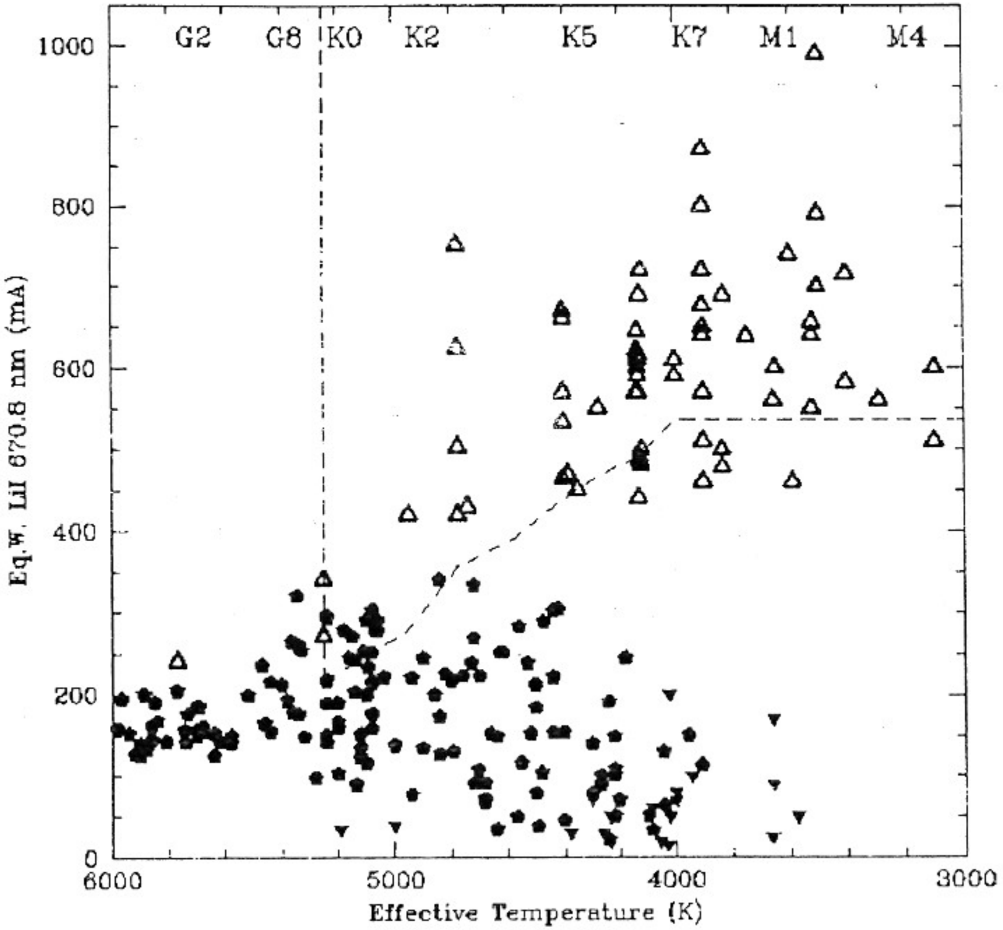


Fig. 30. The equivalent widths of the LiI 6708 Åabsorption line of low-mass stars as a function of T_{eff}. T Tauri stars are shown by the empty triangles and low-mass mass members of various young open clusters by filled symbols. The dashed line represents the locus of minimum equivalent width values for log N(Li)=2.8, and the cutoff for the maximum T_{eff} =5250 K of T Tauri stars. (From Martín [47])

Li depletion

Detailed models:

- Depth of the convection zone determines atmospheric Li depletion
  - $M < 0.5M_\odot$:
    fully convective,
    Li immediately depleted
  - $M < 1.7M_\odot$:
    Convection down to 2.5Mio K, depletion by factor ~100
  - $M > 1.7M_\odot$:
    depletion only on time scales of 10^9a
- Critical test for stellar evolution models

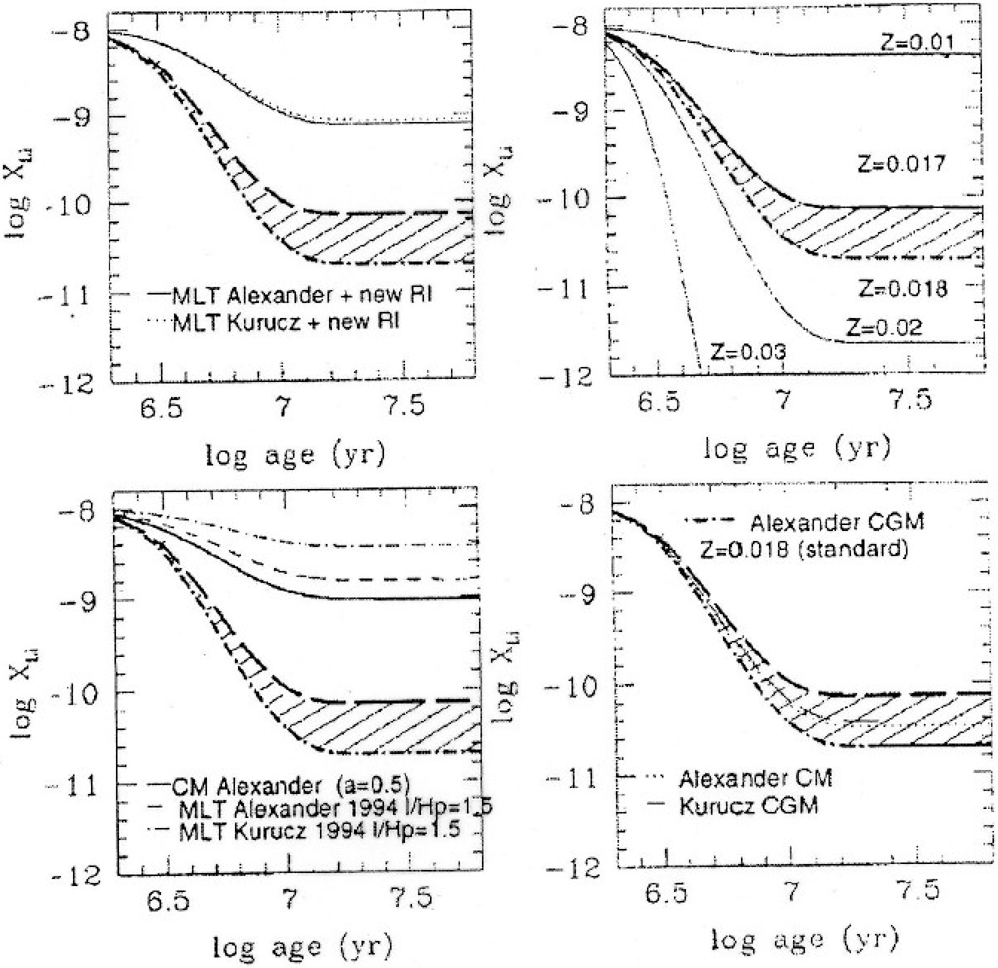


Fig. 29. The dependence of ^{7}Li-depletion as function of time for a 1 $M_\odot$ PMS star. The four panels illustrate the sensitivity on opacity (upper left), metallicity (upper right), prescription for convection (lower left), and a combination of opacity and turbulence. The shaded area in all models represents the standard solar model with Y=0.28, Z=0.017-0.018, and the turbulent spectrum of Canuto et al. (1996). (From D'Antona & Mazzitelli [32])

Deuterium burning

- Critical temperature: 8×10^5 K
- Energy production: $4.2\ 10^3$ J kg^{-1} s^{-1} X_D $(T/10^6\mathrm{K})^{11.8}$
  - Extreme temperature sensitivity
  - Reaction is always self-sustaining
  - As soon as critical temperature is reached all D is burned
- Deuterium burning is limited by supply!
  - Accretion of fresh material provides luminosity

$$L_D = \dot{M} X_D Q_D / m_H$$

  - $X_D \sim 2\ 10^{-5}$, $Q_D = 5.5$ MeV

$$L_D = 12 L_\odot \frac{\dot{M}}{10^{-5} M_\odot \mathrm{a}^{-}1}$$

Deuterium burning

- Energy production: $4.2\ 10^3\ \mathrm{J\ kg^{-1}\ s^{-1}}\ X_D\ (T/10^6\mathrm{K})^{11.8}$
  - Temperature in interior rises
  - Heating leads to increase of radius

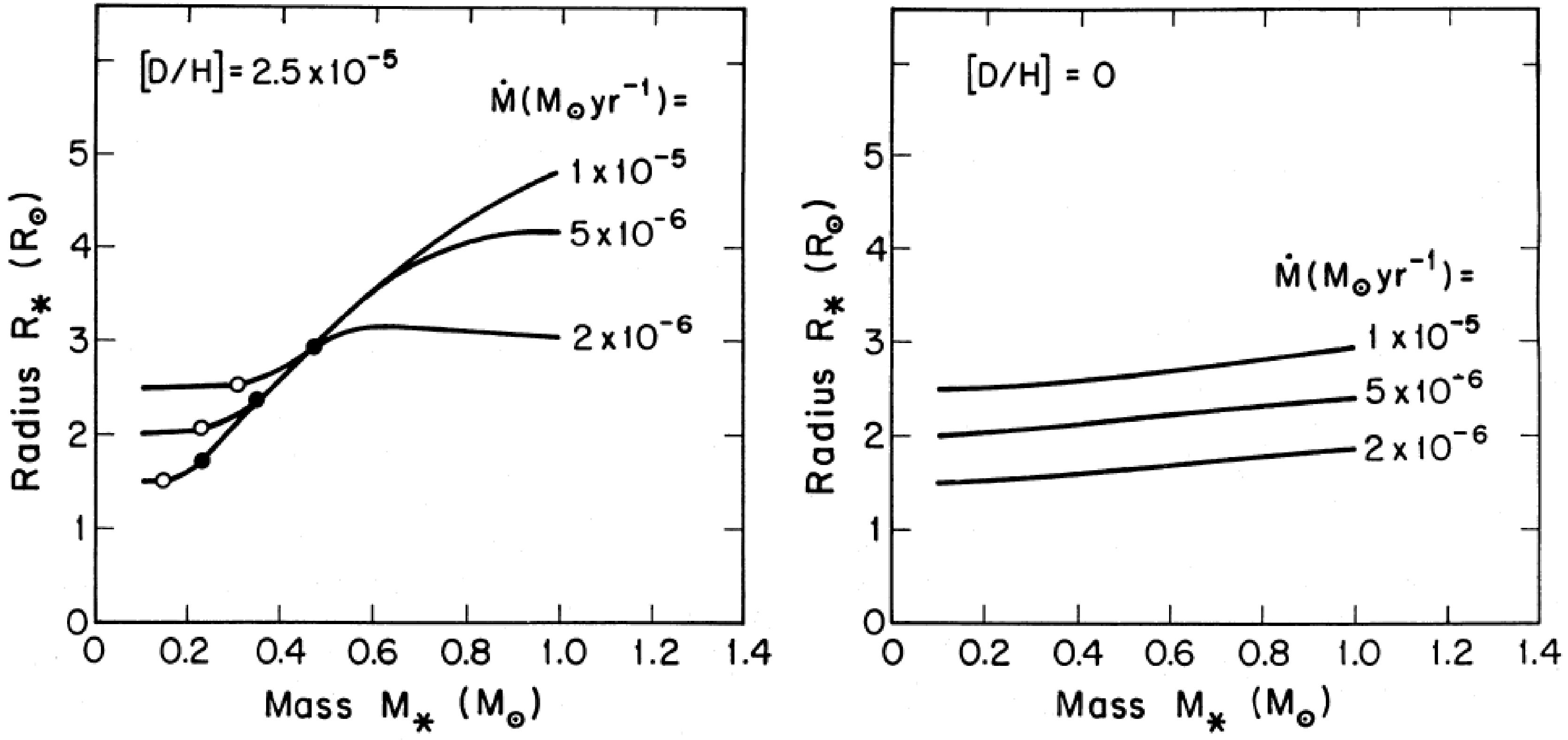


FIG. 7.—Effect of the accretion rate on the mass-radius relation (*a*) For a fixed [D/H] of 2.5×10^{-5}, the core radius is shown as a function of mass for the indicated values of $\dot{M}$. The open and filled circles again mark the onset of deuterium burning and of full convection, respectively. (*b*) For a [D/H] of 0, the radius is plotted against mass for the same values of $\dot{M}$. In this case, the cores are radiatively stable.

Geometry of deuterium burning

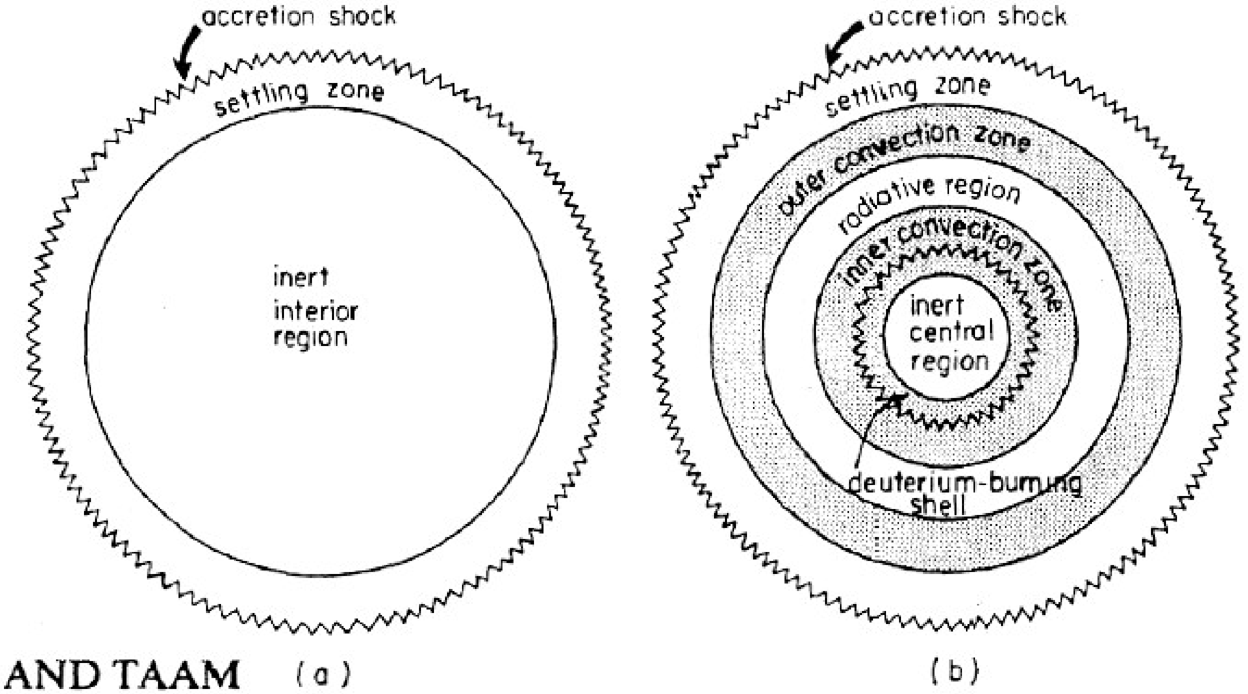
- $M < 3M_\odot$: (T Tauri stars)
  - Critical temperature for D burning only in center
  - Core fusion zone

  - $M < 0.6\ M_\odot$:
    - Star remains fully convective
  - $M > 0.6\ M_\odot$:
    - Temperature increase triggers radiative stability
    - Switch over to Henyey track

  - Continued hydrostatic evolution to the H fusion

Geometry of deuterium burning

- $M > 3M_\odot$: (Herbig Ae/Be stars)
  - Quick switch over to radiative core
    - Strong increase of radius: factor 2
  - Temperature for D burning already in outer layers → D burning shell

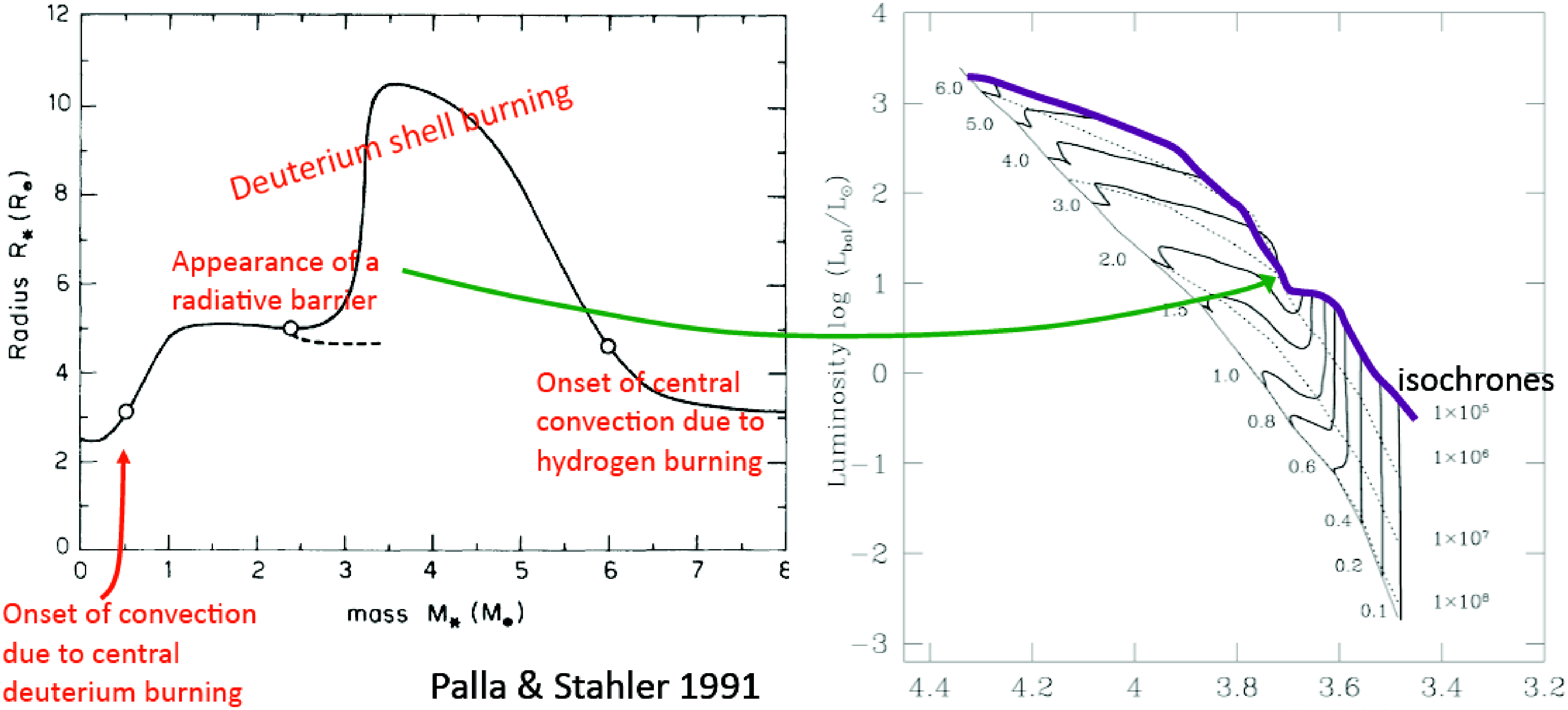


STAHLER, SHU, AND TAAM

FIG. 1.—The structure of the hydrostatic core during the main accretion phase: (*a*) prior to deuterium burning, and (*b*) following the off-center ignition of deuterium. The relative size of the settling zone has been exaggerated for clarity.

Evolution to the main sequence

Radius of protostars and deuterium shell burning



Deuterium shell burning

Appearance of a radiative barrier

Onset of central convection due to hydrogen burning

Onset of convection due to central deuterium burning

Palla & Stahler 1991

During protostar evolution

Palla 2000, Aussois school

Zero-ago main sequence differs from main sequence due to residual accretion and embedding in disk and parental cloud