AY 20 Fall 2010

MAIN-SEQUENCE and POST MAIN-SEQUENCE STELLAR EVOLUTION

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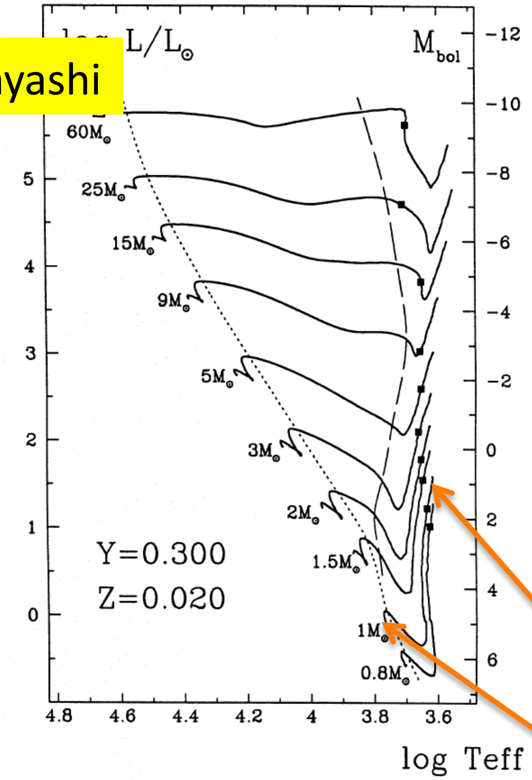
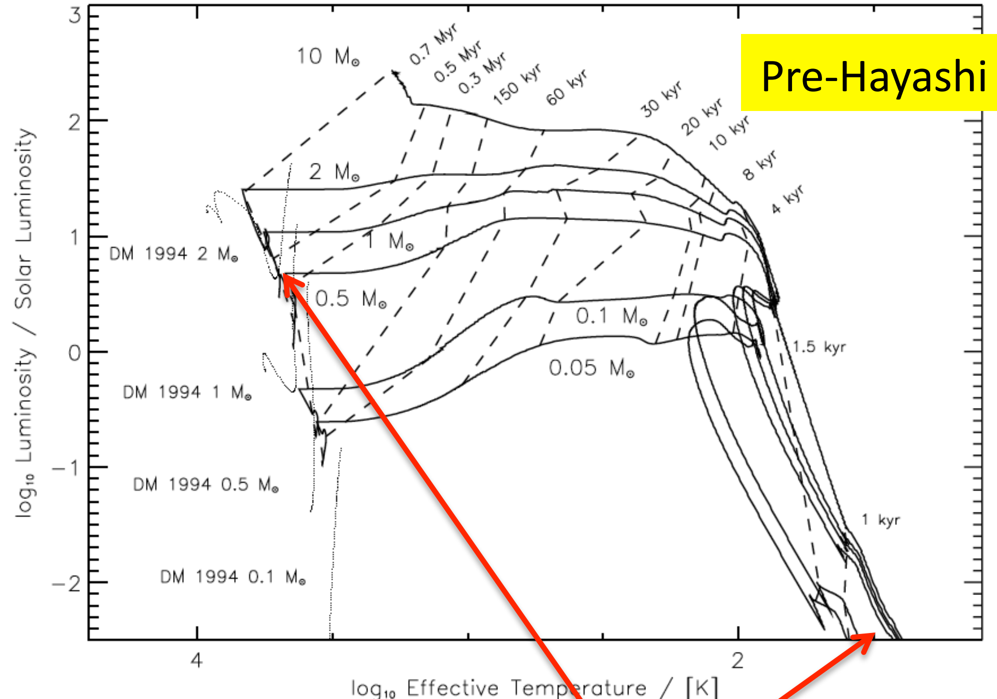
Reading: Carroll & Ostile, Chaper 13.1 and 13.2 (and something from 15)

From the last class: **pre-main sequence evolution**

Post-Hayashi



Pre-Hayashi



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

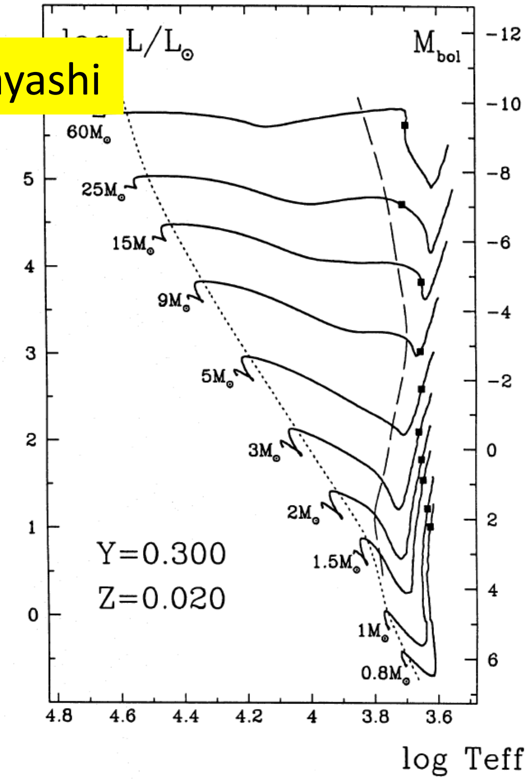
Kelvin-Helmholtz
From Hayashi to main sequence

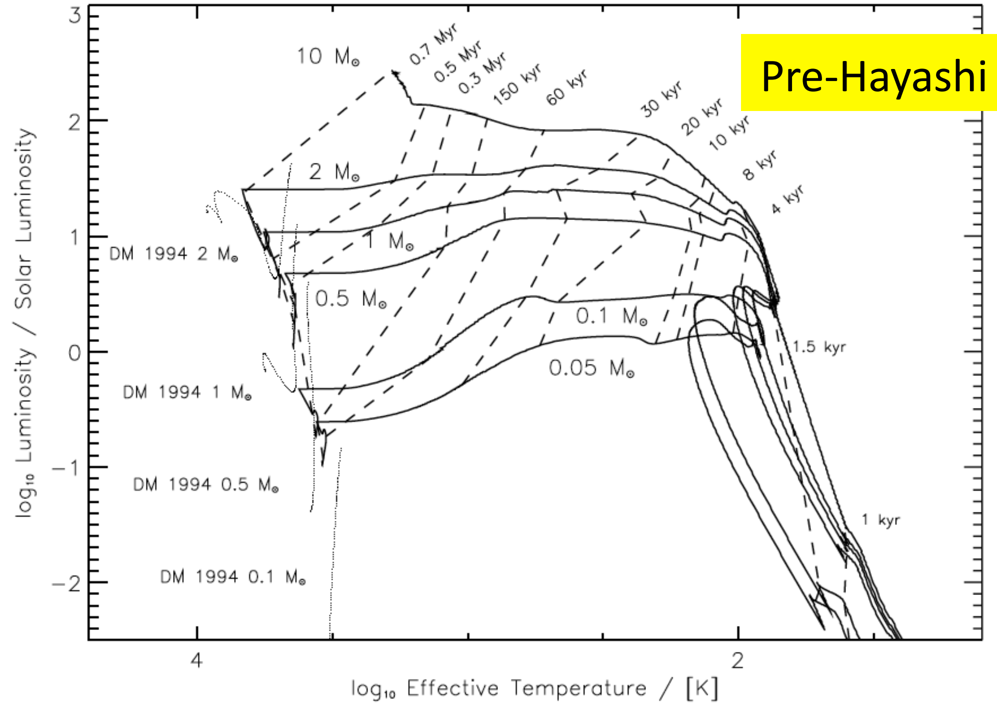
$$t_{KH} = \frac{3}{10}\frac{GM_*^2}{R_*}\frac{1}{L_*} \approx 10^7\, yr$$

Free-fall
To reach the Hayashi track

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

From the last class: **pre-main sequence evolution**

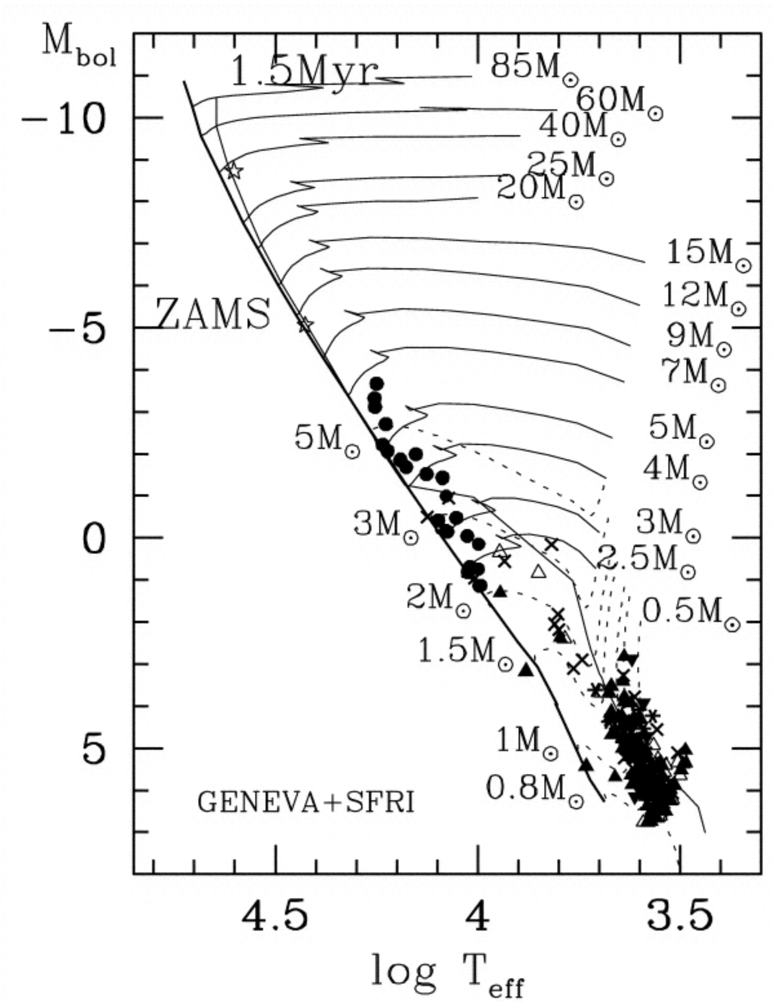




$t_n >> t_{KH} >> t_{ff}$ → Most stars are observed on the main sequence

The arrival position on the Hayashi track and on the main sequence depends on the stellar mass. The evolutionary time scale are shorter for larger masses

H-R diagram for stars in NGC 2264



NGC 2264

Stellar evolution on the main-sequence

- All energy comes from the H burning:

$$t_{nuclear} = \frac{E_{nuclear}}{L_{sun}}; \quad E_{nuclear} = \Delta m \times c^2; \quad \Delta m = 4 \times m(H) - m(He) = 0.007 \times m(H);$$

If 10% of the mass of the sun is converted in He, we get $\Delta m = 1.4 \times 10^{30}$ g -> $E_n = 1.25 \times 10^{51}$ erg -> $L_{sun} = 2 \times 10^{33}$ erg ->

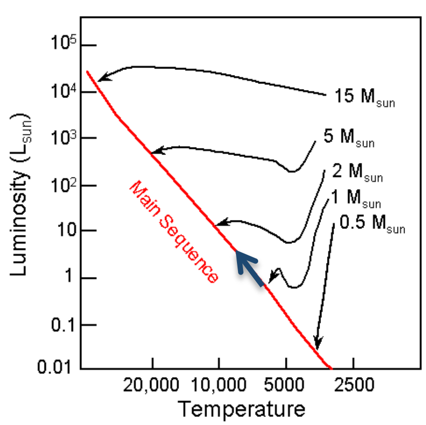
$t_n = 6.3 \times 10^{17}$ s = 2×10^{10} yr

- During the main sequence H is converted in He, and the mean molecular weight increases

Recall the mean molecular weight of a fully ionized gas: $\frac{1}{\mu_i} \approx 2X + \frac{3}{4}Y + \left\langle \frac{1+z}{A} \right\rangle_i Z; \quad \left\langle \frac{1+z}{A} \right\rangle_i \approx \frac{1}{2}$ X=0.70, Y=0.28, Z=0.02 -> A=15.5

To have a stable star $\left(P = nkT = \frac{\rho kT}{\mu m_H} \right)$ ρ or T must increase with μ_i to balance the gravity, i.e the **core must shrink**

- The compression of the core leads to a higher density, and higher temperature (and larger radius) since half of the released gravitational energy is absorbed by the gas (virial theorem)



Recall the energy released during PP I chain (Ch. 10.3): $\varepsilon_{pp} \approx const \times \rho \times X^2 \times T_6^4$ increases with time. $L_\star$ therefore increases

- The star moves toward slightly larger temperature and luminosities along the main sequence

Main sequence evolution: low mass Vs high mass stars

$\varepsilon_{pp} \sim \varepsilon_{CNO}$ @ 2×10^7 K

$0.26\ M_{sun} < M < 1.5\ M_{sun}$

H burning follows the PP I chain. Applies over a large region

$$\varepsilon_{pp} \approx const \times \rho \times X^2 \times T_6^4$$

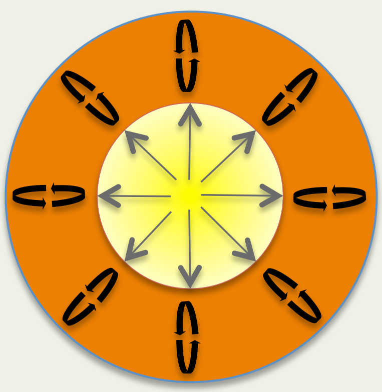
In the core

$\left|\frac{dT}{dr}\right| < \left|\frac{dT}{dr}\right|_{ad}$ → Radiative transport

No mixing, H abundance increases outward

In the surface layer

$\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad}$ → Convection (low T, high opacity)



M > 1.5 Msun

H burning follows the CNO chain. Applies in a smaller core

$$\varepsilon_{CNO} \approx const \times \rho \times X \times X_{CNO} \times T_6^{19.9}$$

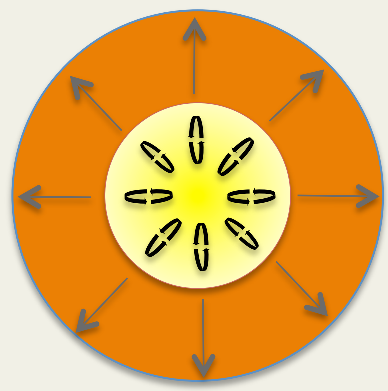
In the core

$\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad}$ → Convection

The core is mixed, X decreases uniformly

In the surface layer

$\left|\frac{dT}{dr}\right| < \left|\frac{dT}{dr}\right|_{ad}$ → Radiative transport



Main sequence evolution: low mass Vs high mass stars

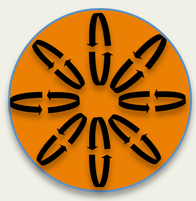
$0.08\ M_{sun} < M < 0.26\ M_{sun}$

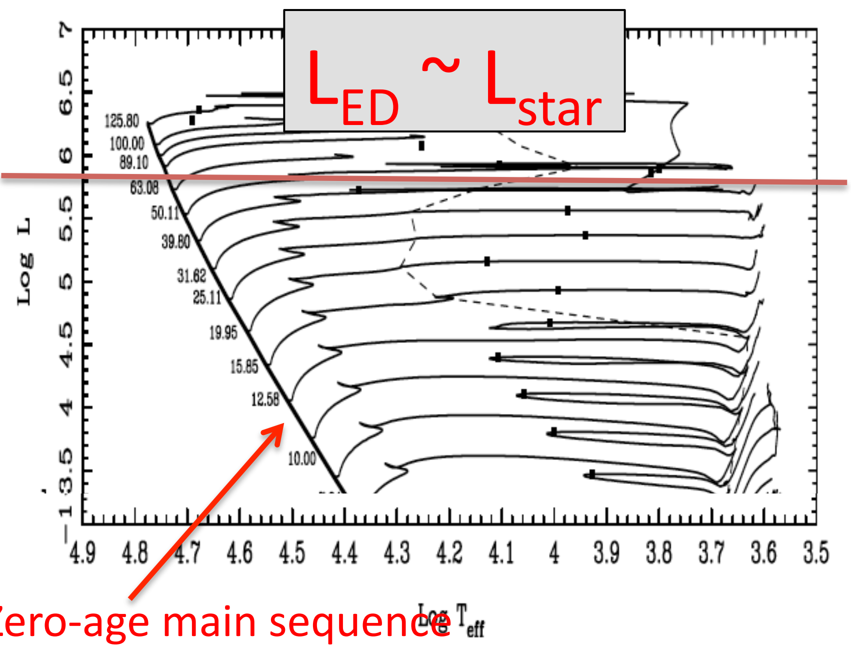
Little H burning (PP I chain) in the core

$$\varepsilon_{pp} \approx const \times \rho \times X^2 \times T_6^4$$

$$\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad} \rightarrow \text{Convection}$$

The star is fully convective





M > 60 Msun

H burning follows the CNO chain. Applies in a smaller core

$$\varepsilon_{CNO} \approx const \times \rho \times X \times X_{CNO} \times T_6^{19.9}$$

The core is convective, the surface is radiative

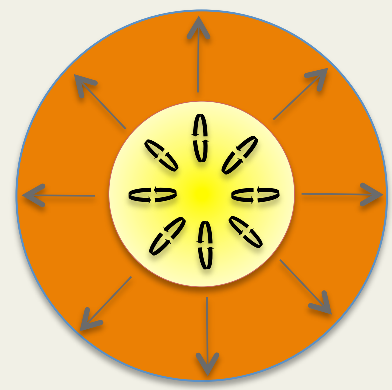
Recall the Eddington limit: maximum radiative luminosity that a star can have and remain in hydrostatic equilibrium

$$\frac{dP_{rad}}{dr} = -\frac{\bar{k}\rho}{c} \times \frac{L_*}{4\pi R_*^2} = -G\frac{M_*\rho}{R_*^2} = \frac{dP}{dr}$$

$$L_{ED} = \frac{4\pi Gc}{\bar{k}} M_* \rightarrow \frac{L_{ED}}{L_{sun}} \approx 3.8 \times 10^4\, M_* / M_{sun}$$

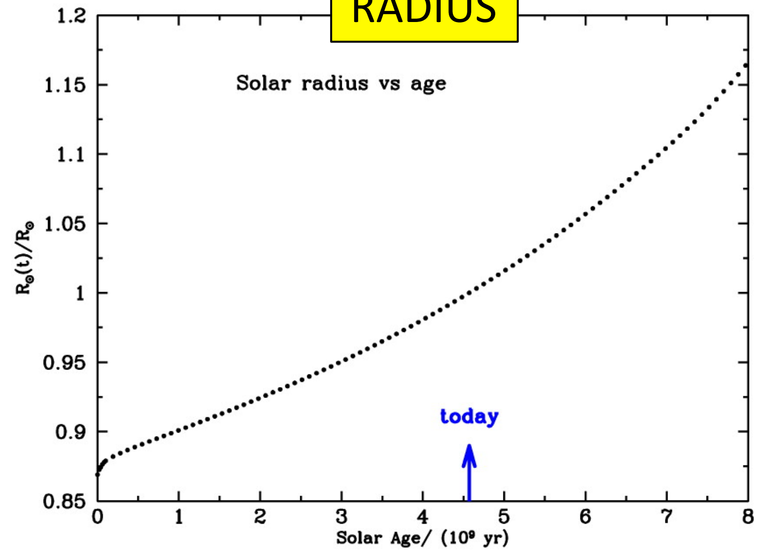
$$L_{ED}(60 M_{sun}) \approx 2.3 \times 10^6 L_{sun}$$

The envelope is loosely bound – mass loss

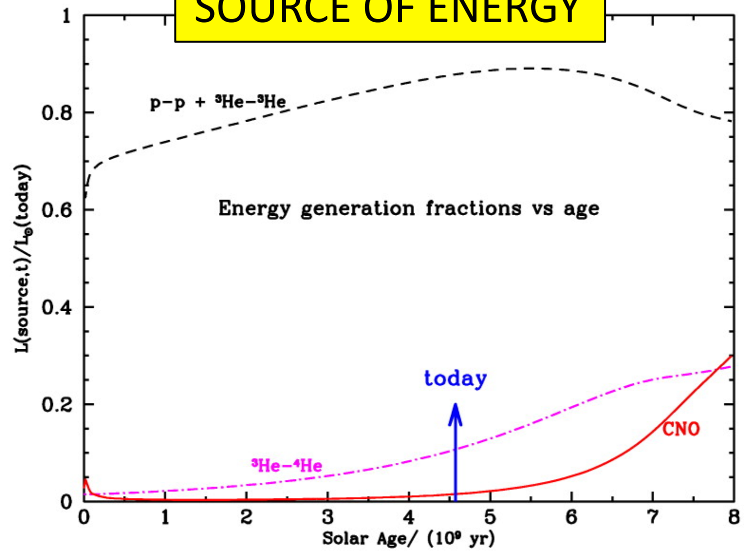


Main sequence evolution for a solar type star

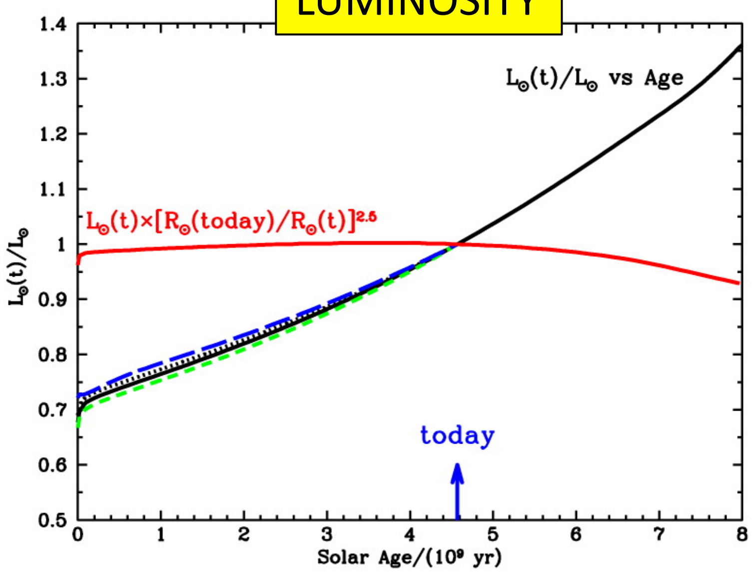
RADIUS



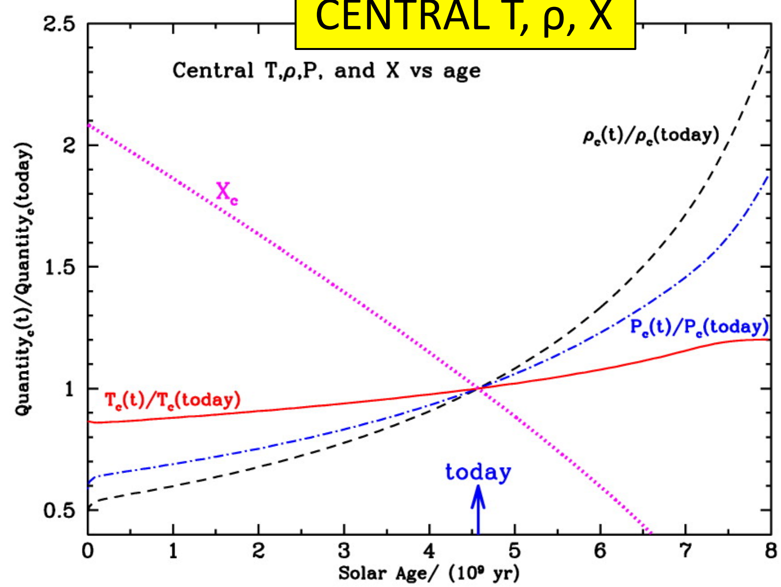
SOURCE OF ENERGY



LUMINOSITY

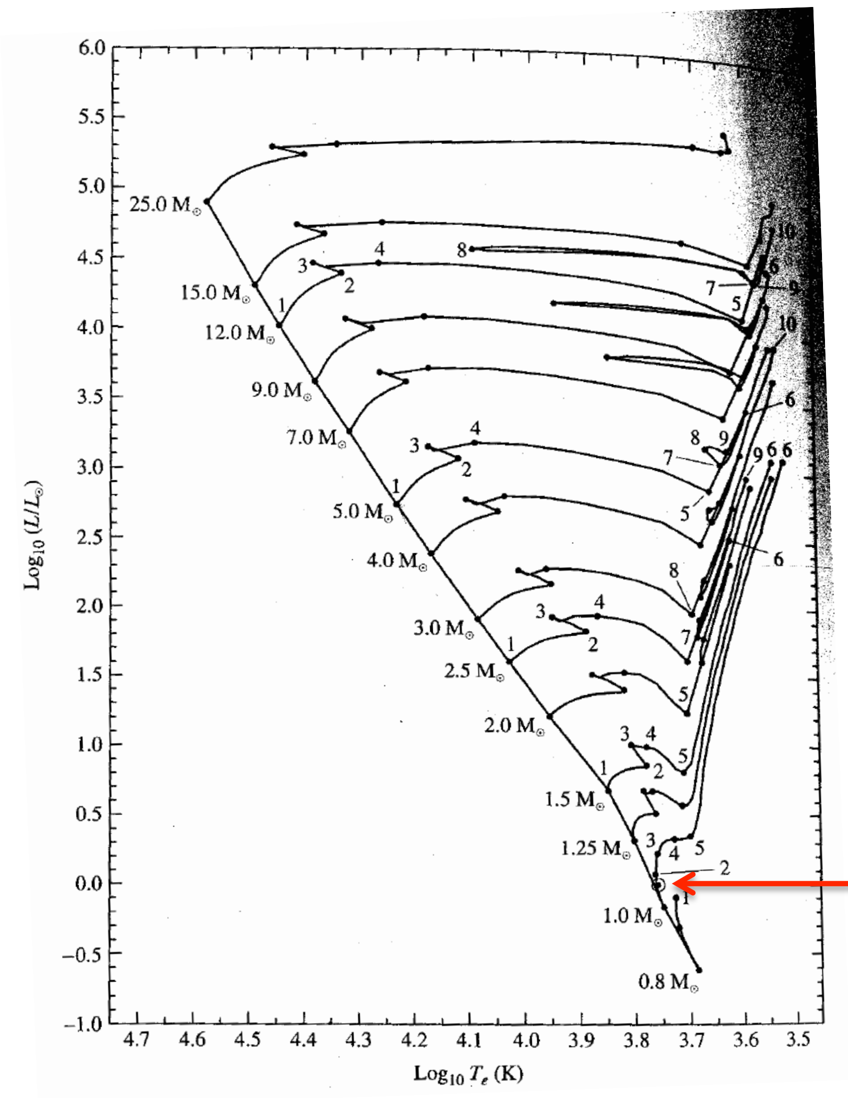


CENTRAL T, ρ, X



Suggested reading: Bahcall et al. 2001, ApJ, 555, 990

Theoretical Evolutionary tracks for M = 1 M_{sun}



Interior structure of the present-day Sun

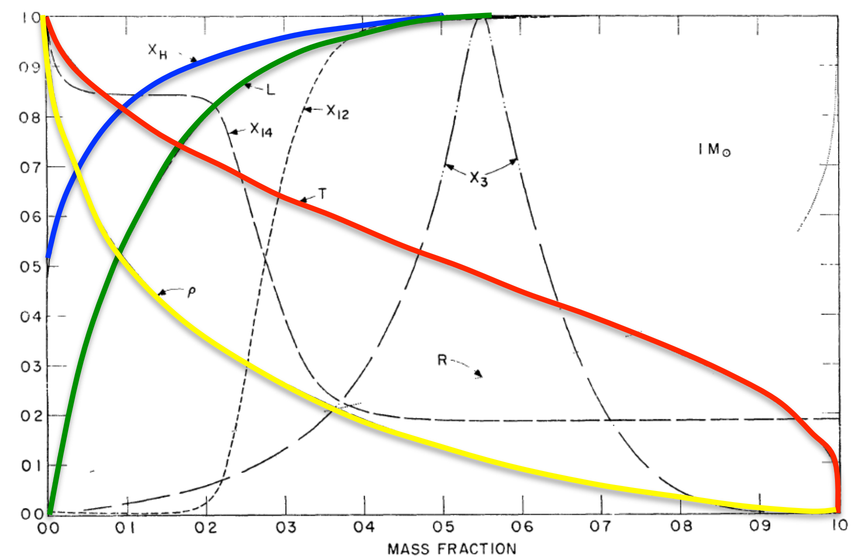
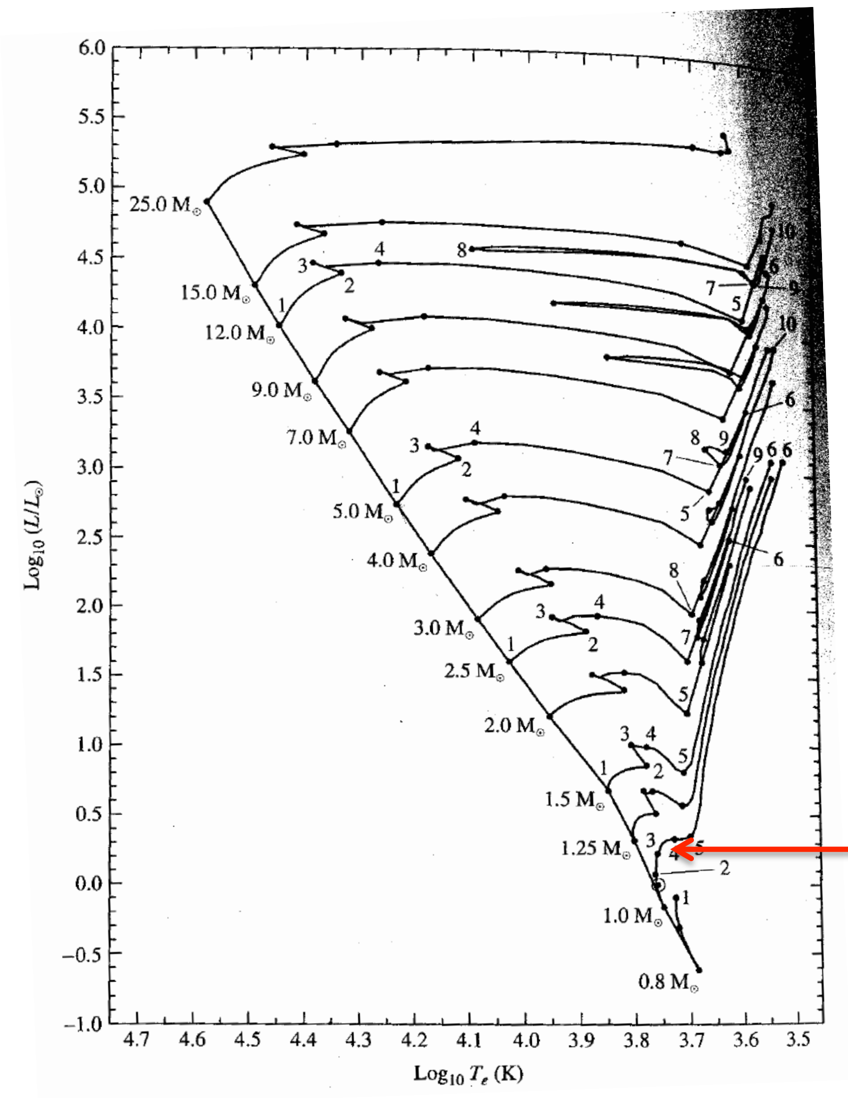


Fig 8.—The variation with mass fraction, for a 1 $M_\odot$ star, of state and composition variables when $t = 4.26990 \times 10^9$ yr. Variables have the significance: ρ = density (gm/cm^3), T = temperature (10^6 °K), L = luminosity ($3\ 86 \times 10^{33}$ ergs/sec), R = radius ($6\ 96 \times 10^{10}$ cm), and X_i = central abundance by mass of $H^1(X_H)$, $He^3(X_3)$, $C^{12}(X_{12})$, and $N^{14}(X_{14})$ Scale limits correspond to $0\ 0 \leq \rho \leq 159\ 93$, $0.0 \leq T \leq 15.910$, $0.0 \leq L \leq 1.0575$, $0.0 \leq R \leq 0.96830$, $0.0 \leq X_H \leq 0\ 708$, $0\ 0 \leq X_3 \leq 4\ 20 \times 10^{-3}$, $0.0 \leq X_{12} \leq 3.61 \times 10^{-3}$, and $0\ 0 \leq X_{14} \leq 6\ 40 \times 10^{-3}$ The mass fraction in the static envelope is $9\ 9622 \times 10^{-5}$, as it is also in Figs 9–11, and stellar radius is $R_s = 0\ 96830\ R_\odot$. Central pressure (not shown) is $2\ 5186 \times 10^{17}$ dyne/cm^2.

Theoretical Evolutionary tracks for M = 1 M_{sun}



Interior structure of the Sun at t= 9.2×10^9 yr

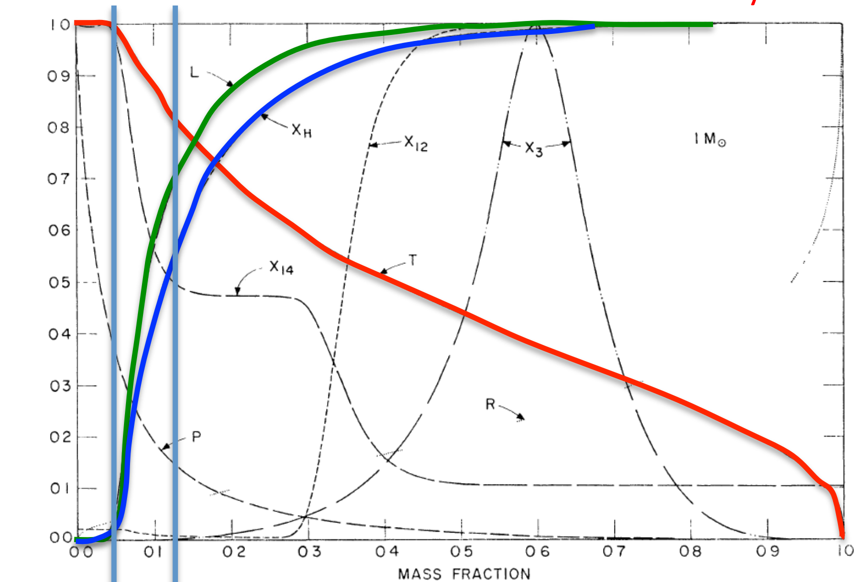


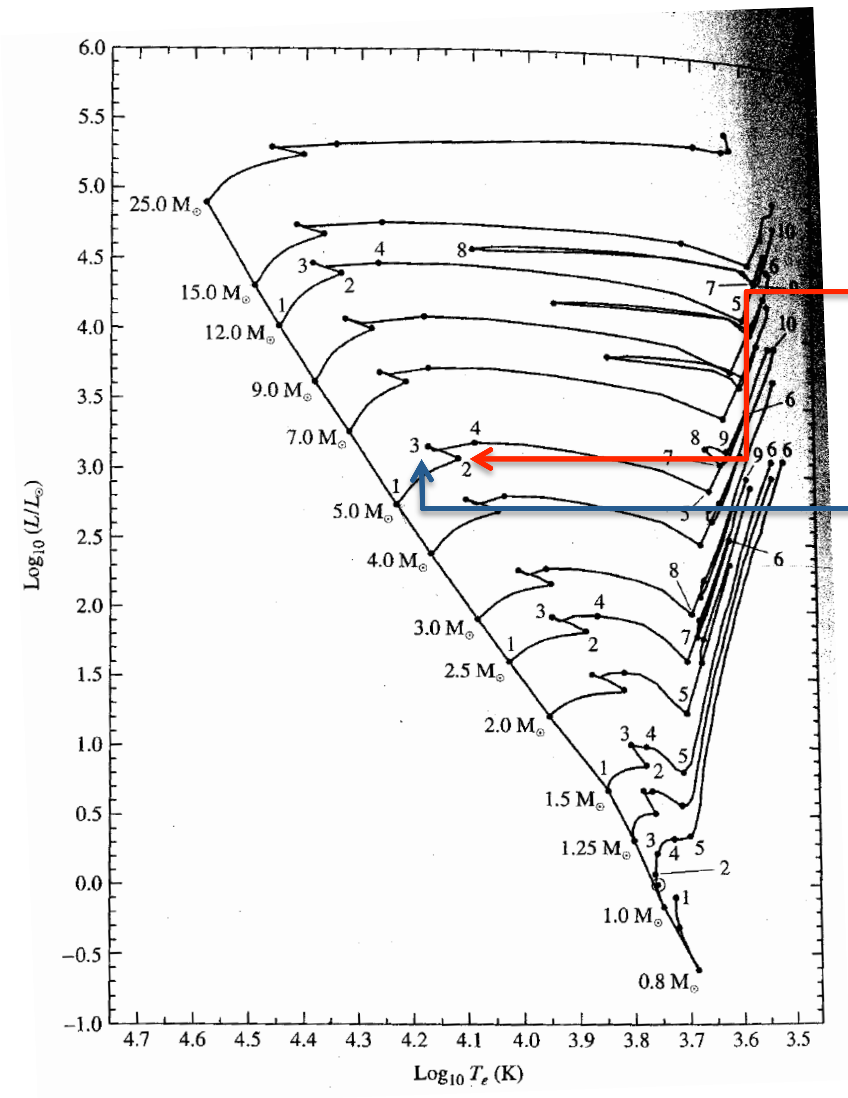
FIG 9.—The va iation with mass fraction, for a 1 $M\odot$ star, of state and composition variables when $t = 9.20150 \times 10^9$ yr. Variables have the same significance and units as in Fig. 8. In addition, pressure P is given in units of 10^{17} dyne/cm². Scale limits correspond to $0.0 \leq P \leq 13.146$, $0.0 \leq T \leq 19.097$, $0.0 \leq L \leq 1.1283$, $0.0 \leq R \leq 1.2681$, $0.0 \leq X_H \leq 0.708$, $0.0 \leq X_3 \leq 5.15 \times 10^{-3}$, $0.0 \leq X_{12} \leq 3.61 \times 10^{-3}$ and $0.0 \leq X_{14} \leq 1.15 \times 10^{-2}$. Stellar radius is $R_s = 1.3526\ R\odot$, and central density (not shown) is 1026.0 gm/cm³.

H burning continues in a shell around the core

Formation of an isothermal He core

THIS IS THE END OF THE MAIN SEQUENZE PHASE

Theoretical Evolutionary tracks for M > 1.5 M_{sun}



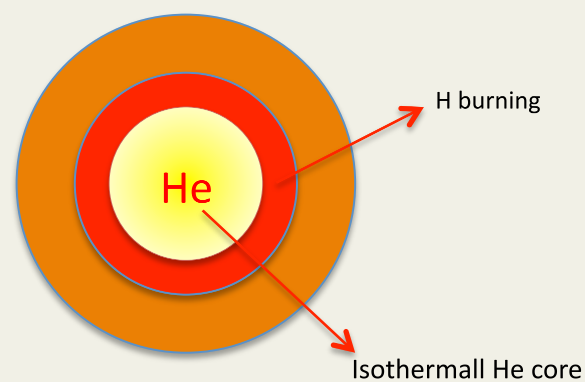
M > 1.5 Msun

In the core

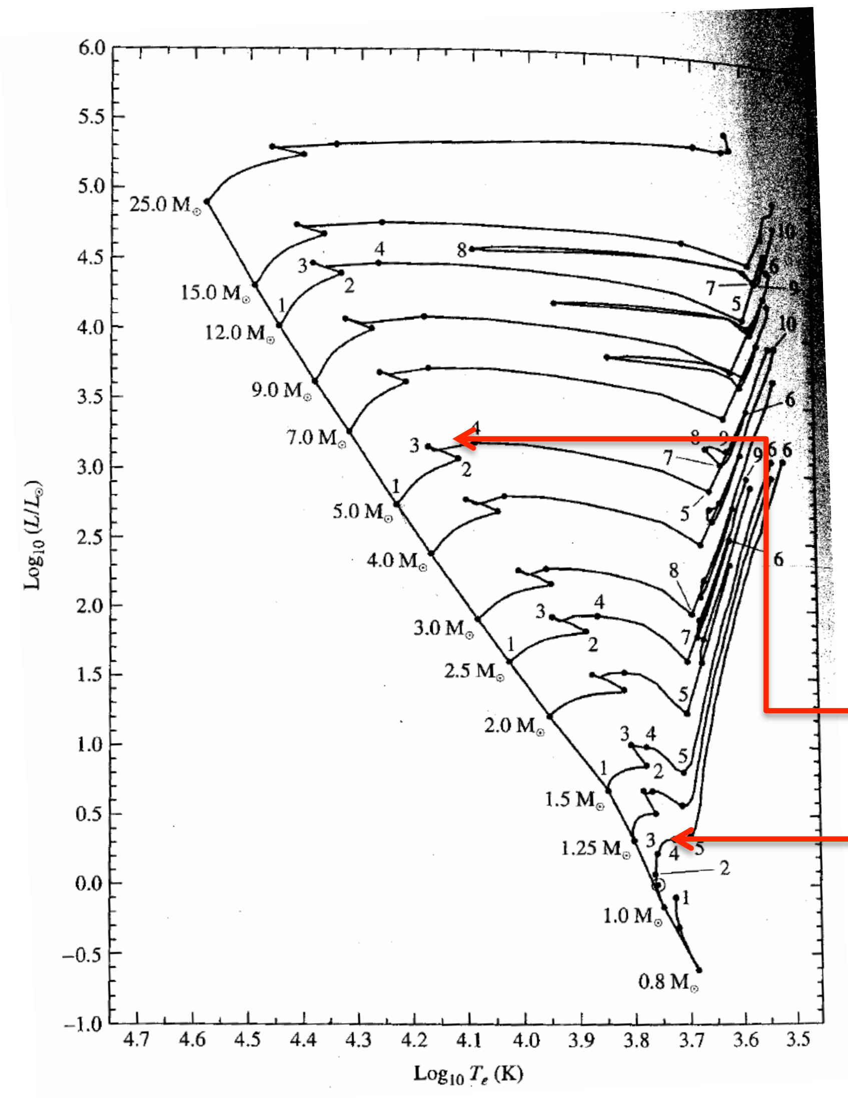
$$\left|\frac{dT}{dr}\right| > \left|\frac{dT}{dr}\right|_{ad} \rightarrow \text{Convection}$$

The core is mixed, X decreases uniformly and the H burning stops suddenly when X < few % (#2).
This is the end of the main sequence phase

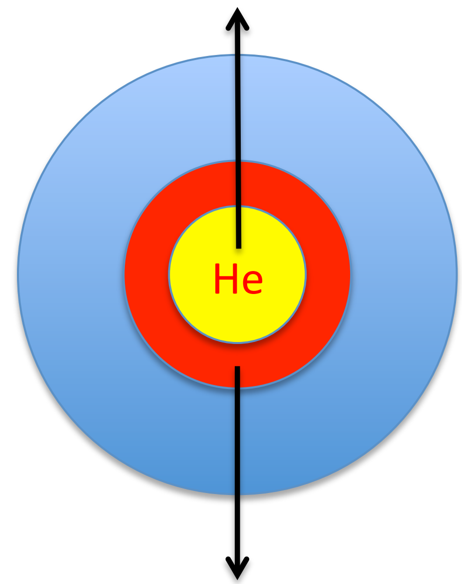
When this happens the gravity takes over (no H burning in the shell) and the stars contracts on a K-H time scale. The contraction leads to higher T_{eff}. Part of the gravitational energy is released and the luminosity increases. H stars to burn in a shell (#3).



Theoretical Evolutionary tracks: post-main sequence evolution



Formation of an isothermal He core in both low and high mass stars. The core mass increases with time until the fails to support the outer layers



H burning continues in a shell around the core. The luminosity slightly increases. Part of the energy is used to expand the envelope. T_{eff} decreases.

The Schönberg-Chandrasekhar limit

$$\left(\frac{M_{ic}}{M}\right)_{SC} \approx 0.37 \times \left(\frac{\mu_{env}}{\mu_{ic}}\right)^2$$

- Assume normal abundance in the envelope

X=0.70, Y=0.28, Z=0.02 -> A=15.5

- Core is depleted by H

X=0.0, Y=0.98, Z=0.02 -> A=15.5

- Gas is fully ionized

$$\frac{1}{\mu_i} \approx 2X + \frac{3}{4}Y + \left\langle\frac{1+z}{A}\right\rangle_i Z; \quad \left\langle\frac{1+z}{A}\right\rangle_i \approx \frac{1}{2}$$

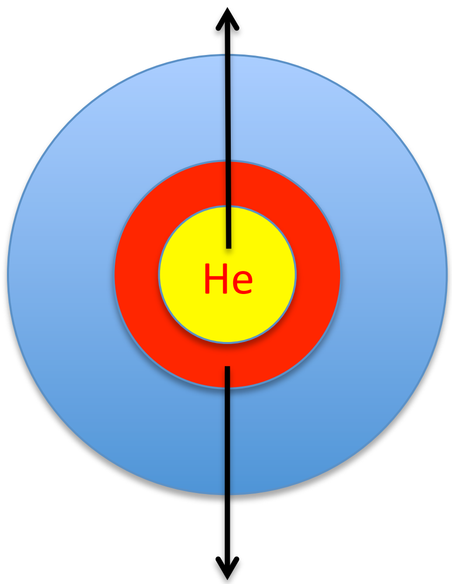
↓

$$\frac{1}{\mu_{env}} = 1.4 + 0.21 + 0.01 \rightarrow \mu_{env} = 0.62$$

$$\frac{1}{\mu_{ic}} = 0 + 0.73 + 0.01 \rightarrow \mu_{ic} = 1.35$$

$$\left(\frac{M_{ic}}{M}\right)_{SC} \approx 0.37 \times \left(\frac{\mu_{env}}{\mu_{ic}}\right)^2 \approx 0.08$$

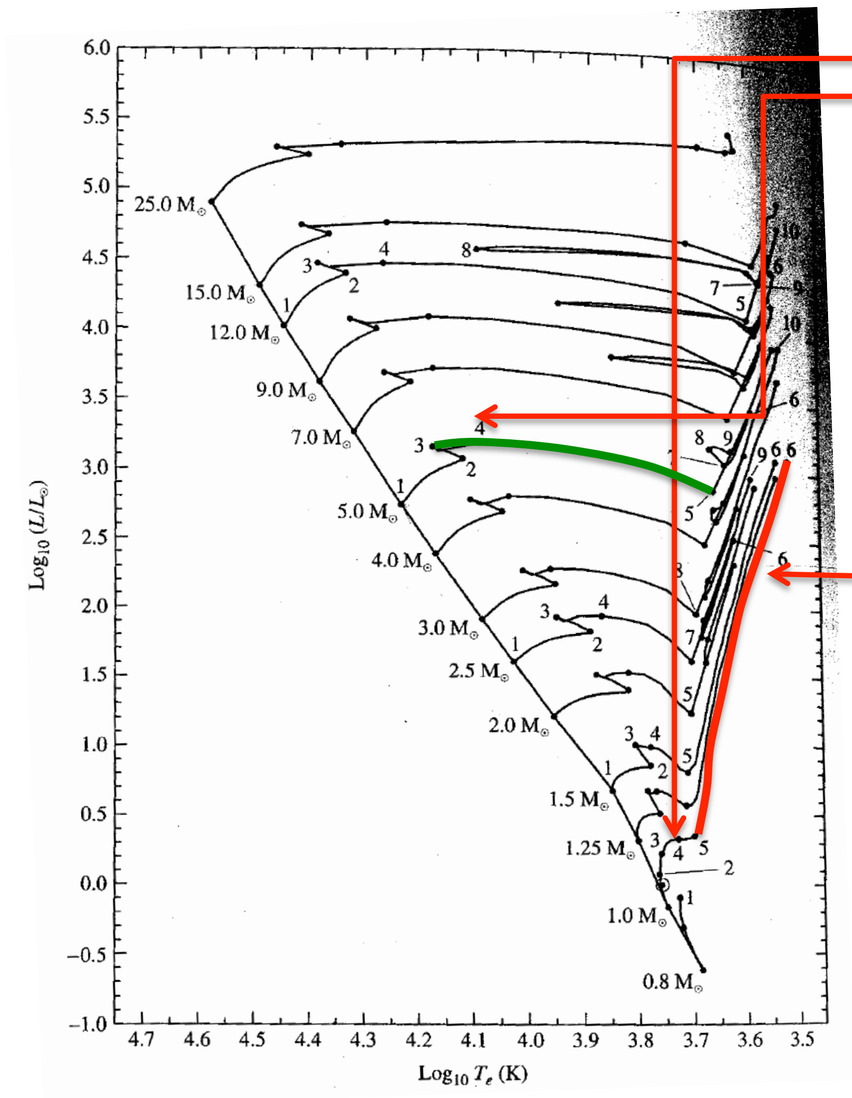
Formation of an isothermal He core in both low and high mass stars. The core mass increases with time until the fails to support the outer layers



H burning continues in a shell around the core. The luminosity slightly increases. Part of the energy is used to expand the envelope. T_{eff} decreases.

But: the density in the stellar core is so high that the gas is (partially) degenerate. This provides an additional source of pressure. The SC limits can increase to 0.13

Theoretical Evolutionary tracks: the (SUB) GIANT BRANCH

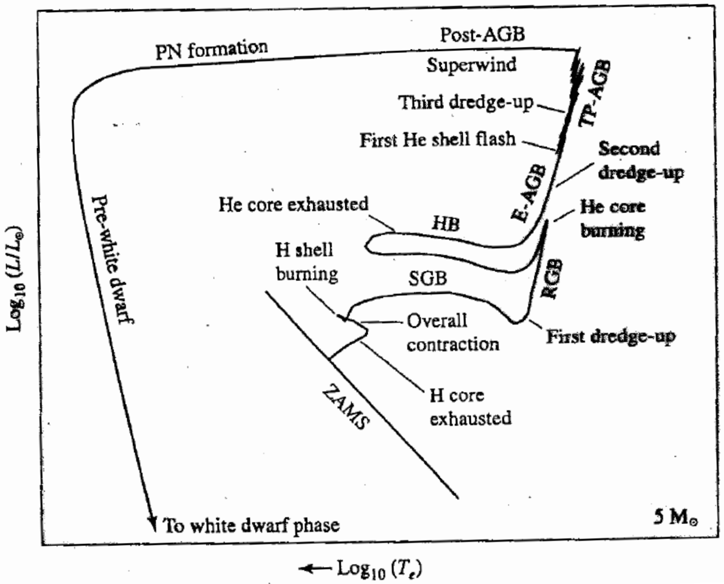


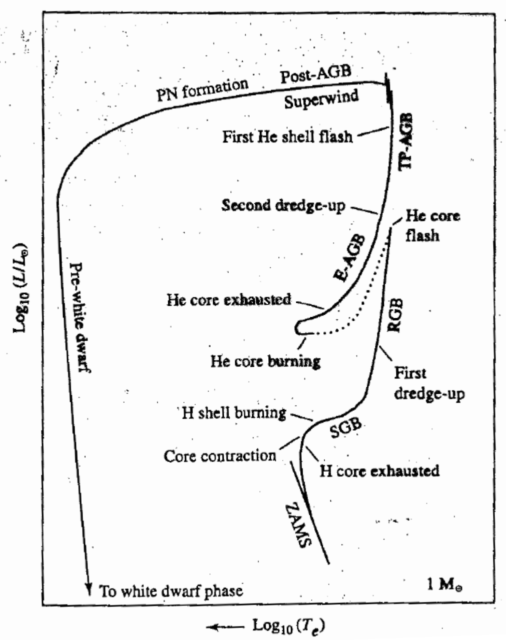
When the core mass reaches the SC limits, the core starts to contract on the K-H time scale (#4). Part of the gravitational energy is absorbed by the envelope, which expands. The star becomes colder (i.e. red) and very large **(SUBGIANT BRANCH)**. Part of the emitted energy is used to expand the envelope. The luminosity may decrease (#5).

Stellar envelope expands, T_{eff} decreases, opacity increases due to H^-. A convective zone develops in the stellar surface in both low and intermediate mass stars. Convection transports more energy than radiation, and the luminosity increases rapidly (RED GIANT BRANCH)

Along RGB the convection reaches the “core”, where the composition was changed due to fusion (PP I and CNO). The composition of the surface changes (more ^{3}He, less Li, more ^{14}N, less ^{12}C). This mixing is called FIRST DREDGE-UP

Post-main sequence evolution: the red giant tip and He burning





At the tip of the red giant branch:

5 Msun, L ~ 3200 Lsun (x6 L_{MS}), T_{eff} ~ 4000K, R ~ 100 R_{sun} ~ 0.6 AU

T_{core}= 10^8 K, ρ = 10^7 kg m^{-3}

• tunneling effect possible -> triple α process (ρ^3)

$$ {}^4_2He + {}^4_2He \leftrightarrow {}^8_4Be + {}^4_2He \rightarrow {}^{12}_6 C + \gamma $$

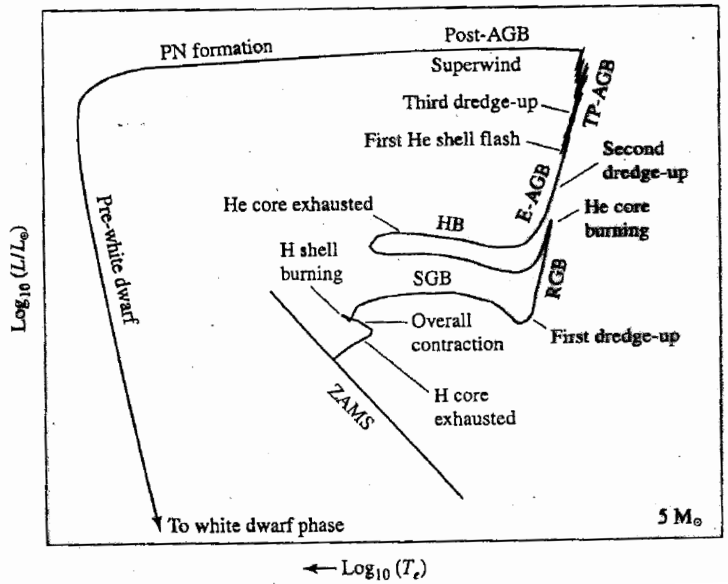
• the fusion energy expands the core, which pushes the H-burning shells to larger radii. H-burning slows down and the luminosity decreases

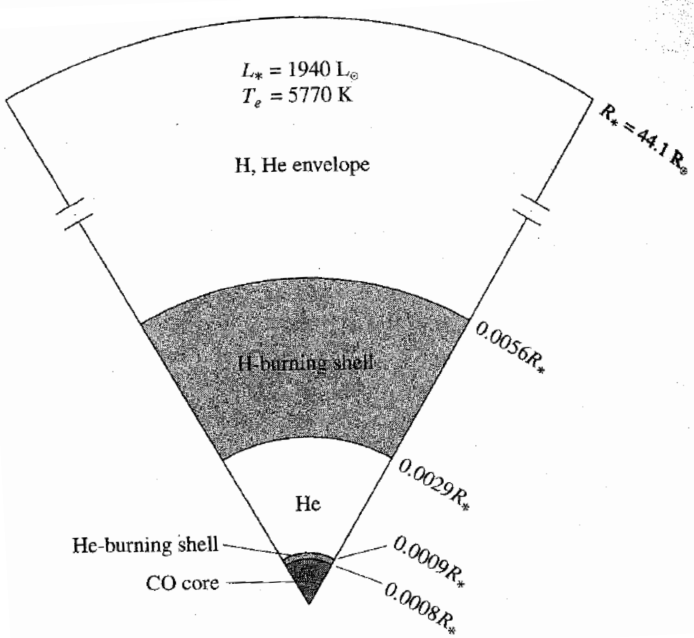
1 Msun, L ~ 1200 Lsun, T_{eff} ~ 3500K, R ~ 100 R_{sun} ~ 0.4 AU

M < 1.8 Msun, core is strongly degenerate, and loses energy due to the high neutrino flux. The core cools down and collapses. Eventually T reaches 10^8K and ρ=10^7 kg m^{-3}. He fusions is almost explosive (Helium flash). Most of the energy is used to remove the gas degeneracy, (Teff and L decreases).

When the degeneracy is removed the He can fuse “normally” and the core expands (turn around on the H-R diagram)

Post-main sequence evolution: Horizontal Branch and Asymptotic Giant Branch





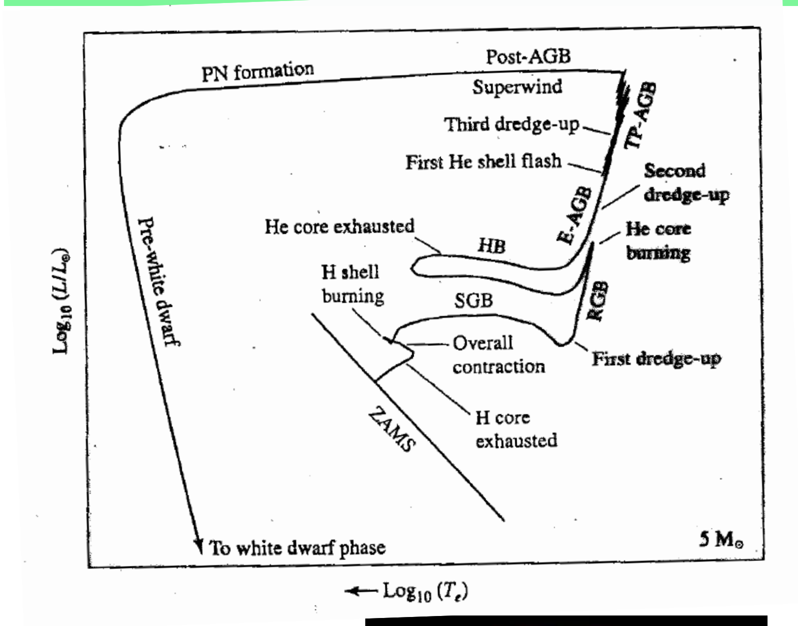
• The He burning proceed in the core (convective since $\varepsilon_{3\alpha} \propto T_8^{41.0}$), recall the convective core in MS due to CNO steep temperature dependence). H burning in a convective shell. M_{ic} increases, core contract (again similar to the end of MS). This is the blueward part of the Horizontal Branch

• He burn-out, core is made by C and O, temperature decreases (similar to the SGB). Redward part of the HB. Pulsation are possible (observed as periodic variation in the luminosity). He burns in shell. The core becomes degenerate

• When the HB intercept the Hayashi track, He starts to burn in a shell (H is also burning in the convective layer). He burning causes the envelope to expand causing the **second dredge-up** (analog to the RGB). For a 5 Msun, core T=10^8 K, $\rho = 10^9$ kg m^{-3}. The luminosity increases (Asymptotic Giant Branch). At the end of the AGB the star experience thermal pulses, He shell flash due to degeneracy (analog to the He core flash at the tip of the RGB) and third dredge-up (bring C in the surface, C stars).

• AGB stars lose mass in the form of stellar wind, enriching the ISM.

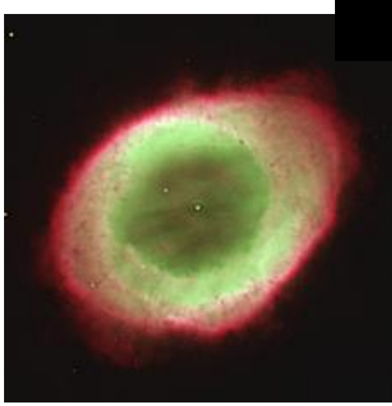
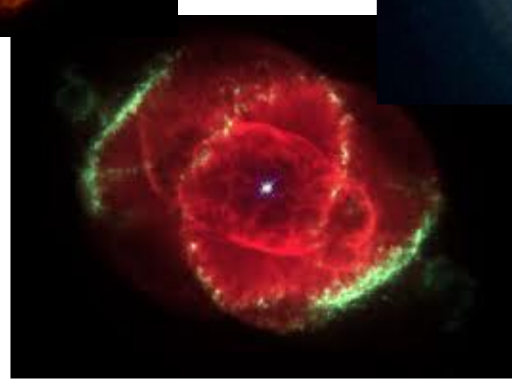
Post-main sequence evolution: Post AGB, White Dwarf, and Planetary Nebulae



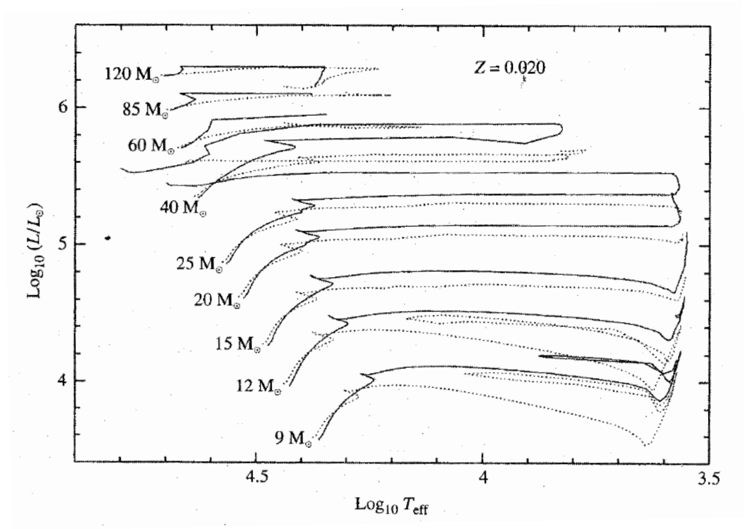
- The post AGB evolution depends on the initial stellar mass. For $M < 8\ M_{sun}$:

–He shell burning creates more C and O
–The core becomes more and more degenerate.
–$M_c < 1.4\ M_{sun}$ (Chandrasekhar limit). C and O burning, to form O, Ne and Mg.
–Superwinds develop with mass loss of $10^{-4}\ M_{sun}\ yr^{-1}$.
–The outermost shell becomes molecular.
–T_{eff} increases rapidly as the internal regions are "exposed"
– H and He-shell burning stops, and the luminosity drops.
– The core will cool down becoming a **white dwarf,** surrounded by an expanding shell called **planetary nebula** (nothing to do with planets!)



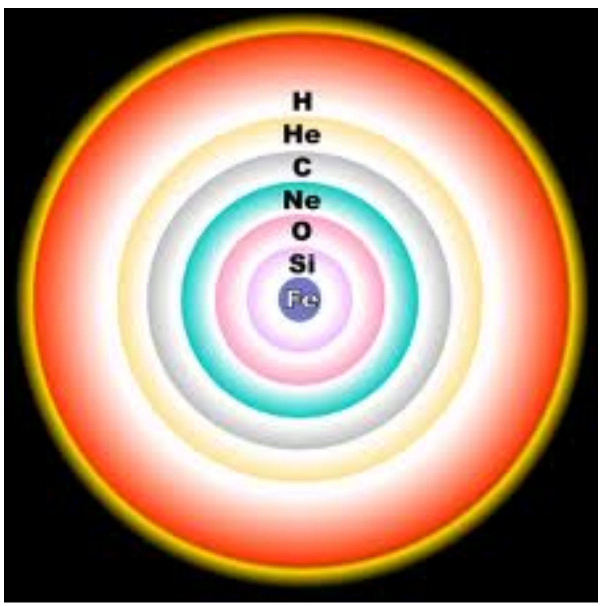

Post-main sequence evolution: massive stars, $M > 8 M_{sun}$



- The C burns producing O, Ne, Na, and Mg. This leads to an "onion-like" structure.
- The O burns producing Si.
- At T~3x10^9 K, Si burns producing S, S-> Ar -> ... -> Fe
- Fe has the maximum binding energy per nucleon -> after Fe, the nuclear reaction becomes endothermic.

The time scale for nuclear reactions becomes VERY short (e.g. 20 Msun):

H burning – 10^7 yr
He burning – 10^6 yr
C burning – 300 yr
O burning – 200 days
Si burning – 2 days



- photodisintegration occurs (endothermic process!):

$$^{56}_{26}Fe + \gamma \rightarrow 13\,^{4}_{2}He + 4n$$

$$^{4}_{2}He + \gamma \rightarrow 2p^{+} + 2n$$

- electron capture (neutrino carry most of the energy):

$$p^{+} + e^{-} \rightarrow n + \nu_e$$

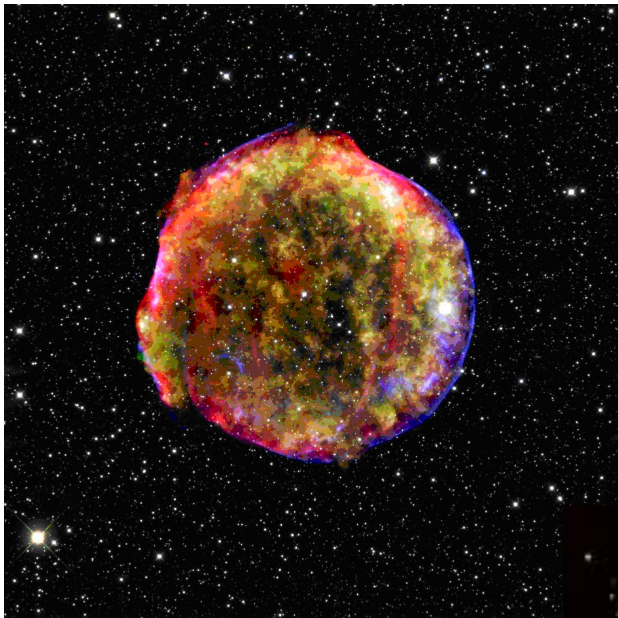
- the electron degeneracy pressure vanishes, gas pressure decreases due to Fe photodisintegration -> core collapses (ρ reaches 8x10^{17} kg m^{-3})!

- CORE COLLAPSE SUPERNOVA

if $M_{zams} < 25\ M_{sun}$: neutron star
if $M_{zams} > 25\ M_{sun}$: black hole

Post-main sequence evolution: supernova remnants

Tycho's Supernova Remnant
(11 November 1572)



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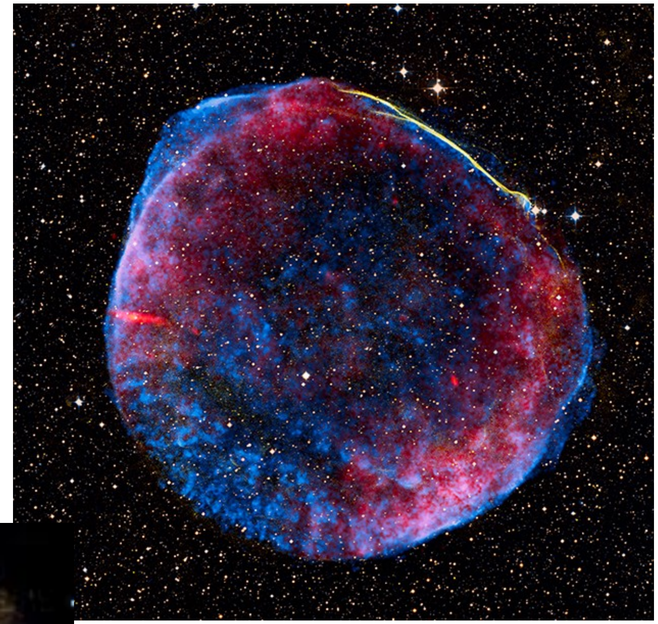

Crab nebula
(Chinese and Arab 1054)

Measuring the stellar age using the stellar evolution: globular cluster