

*The Later Evolution of
Low Mass Stars
(< 8 solar masses)*

<http://apod.nasa.gov/apod/astropix.html>

The sun - past and future

Time (10^9 years)	Luminosity (L_{\odot})	Radius (R_{\odot})	T_{central} (10^6 °K)
Past			
0	0.7688	0.872	13.35
0.143	0.7248	0.885	13.46
0.856	0.7621	0.902	13.68
1.863	0.8156	0.924	14.08
2.193	0.8352	0.932	14.22
3.020	0.8855	0.953	14.60
3.977	0.9522	0.981	15.12
Now			
4.587	1.000	1.000	15.51
Future			
5.506	1.079	1.035	16.18
6.074	1.133	1.059	16.65
6.577	1.186	1.082	17.13
7.027	1.238	1.105	17.62
7.728	1.318	1.143	18.42
8.258	1.399	1.180	18.74
8.7566	1.494	1.224	18.81
9.805	1.760	1.361	19.25

central density
also rises though
average density
decreases

During 10 billion years
the sun's luminosity
changes only by about
a factor of two.

After that though,
changes become
rapid

$$P_c = \frac{\rho_c N_A k T_c}{\mu_c} \quad \mu(\text{pure H}) = 0.5$$

$$\mu(\text{pure He}) = 1.3333$$

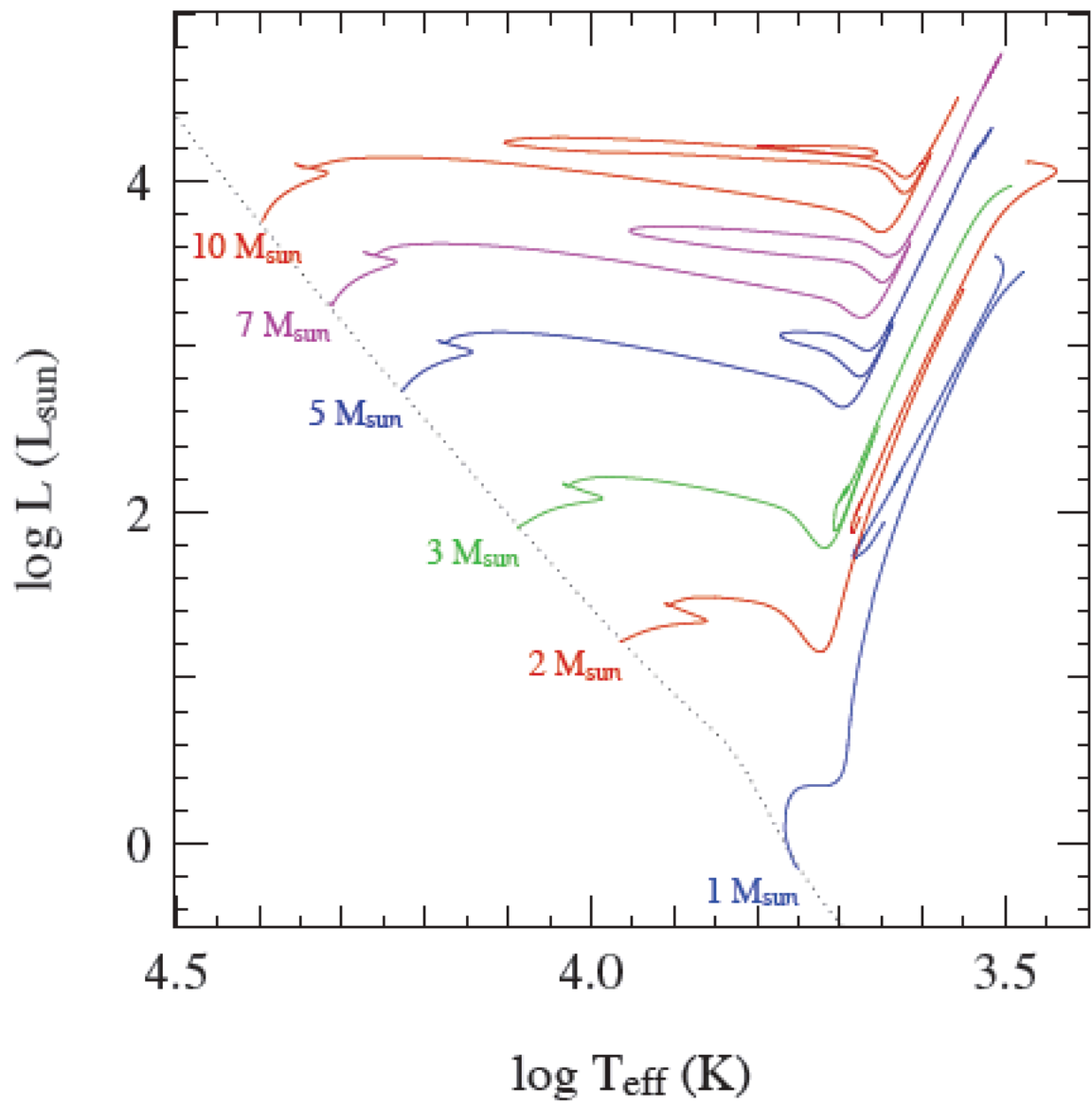
* Adapted from Turck-Chièze et al. (1988).

Composition $X = 0.7046$, $Y = 0.2757$, $Z = 0.0197$.

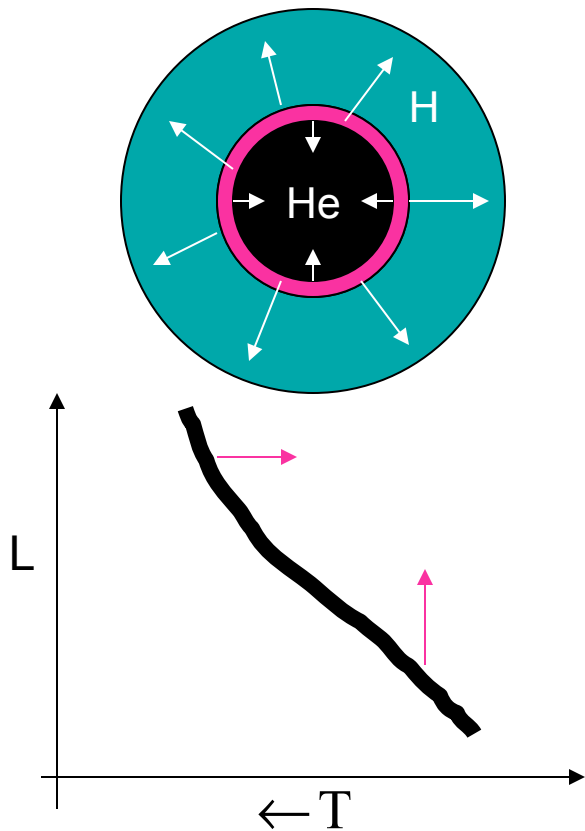
Present values are R_{\odot} and L_{\odot} .

** For time t before the present age $t_{\odot} = 4.6 \times 10^9$ years,
 $L/L_{\odot} \approx 1/[1+0.4(1-t/t_{\odot})]$

Red Giant



What happens when the sun runs out of hydrogen in its center?



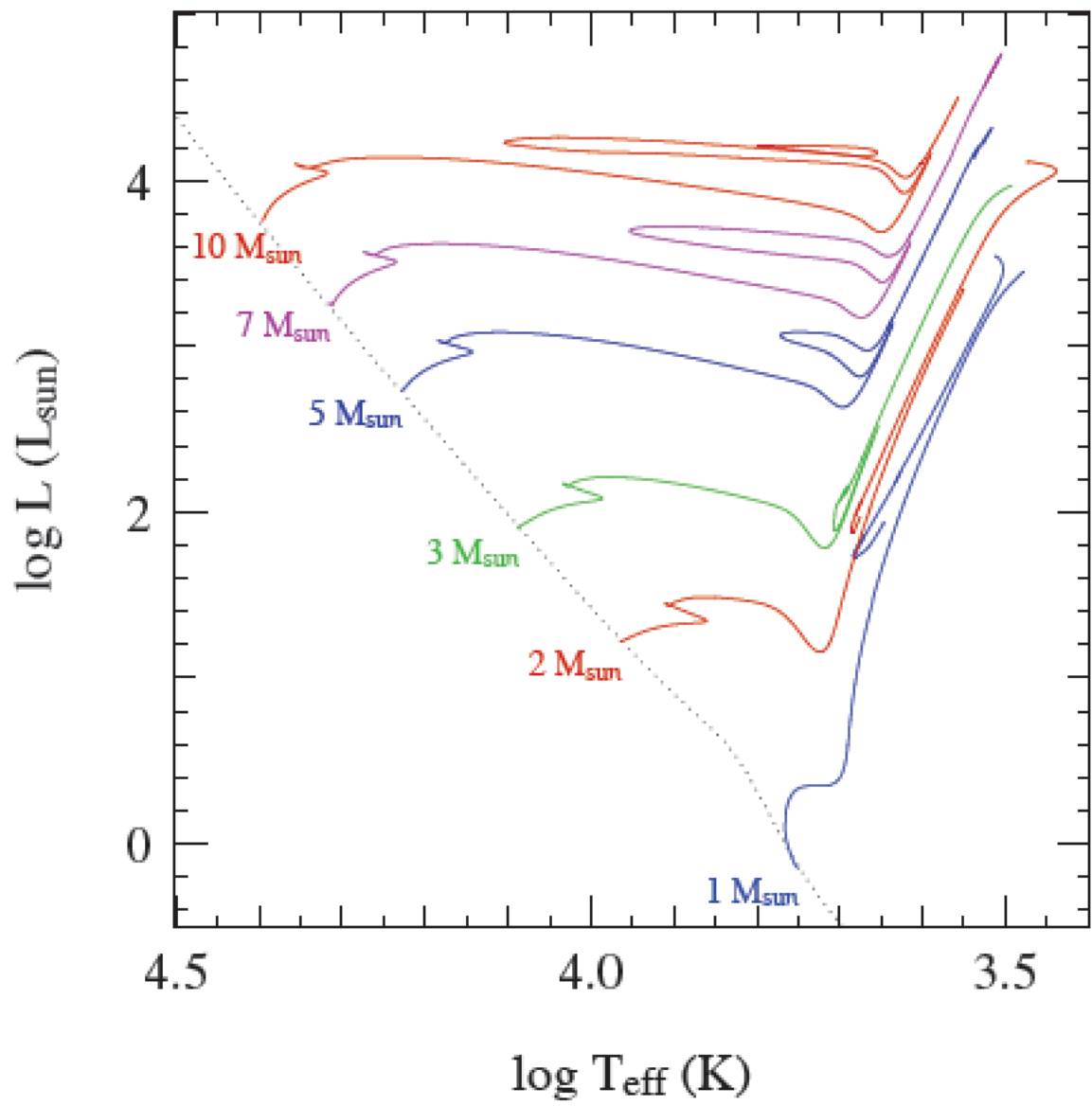
EVOLUTION TO THE RED GIANT STAGE

- Once hydrogen is exhausted in the center, the star is no longer a main sequence star. Hydrogen continues to burn however in a thick shell.
- (Helium) core contraction leads to heating of both the helium and the overlying hydrogen shell.
- This increases the rate of hydrogen burning in the shell ($\epsilon \propto T^{20}$). The luminosity of this shell goes above what the star had on the main sequence.

The outer envelopes of

- Stars that were completely convective on the main sequence stay that way. Their luminosity goes up ($M \lesssim 0.5 M_{\odot}$).
- Other stars do *not* immediately get brighter. Instead the extra energy goes into expanding the overlying material. The radius of the star increases at nearly constant luminosity.
- All stars converge on ~ 4000 K, but at varying luminosities. Once there, the extra luminosity of the H-shell translates into an increasing luminosity for the star itself.

All outer layers become convective



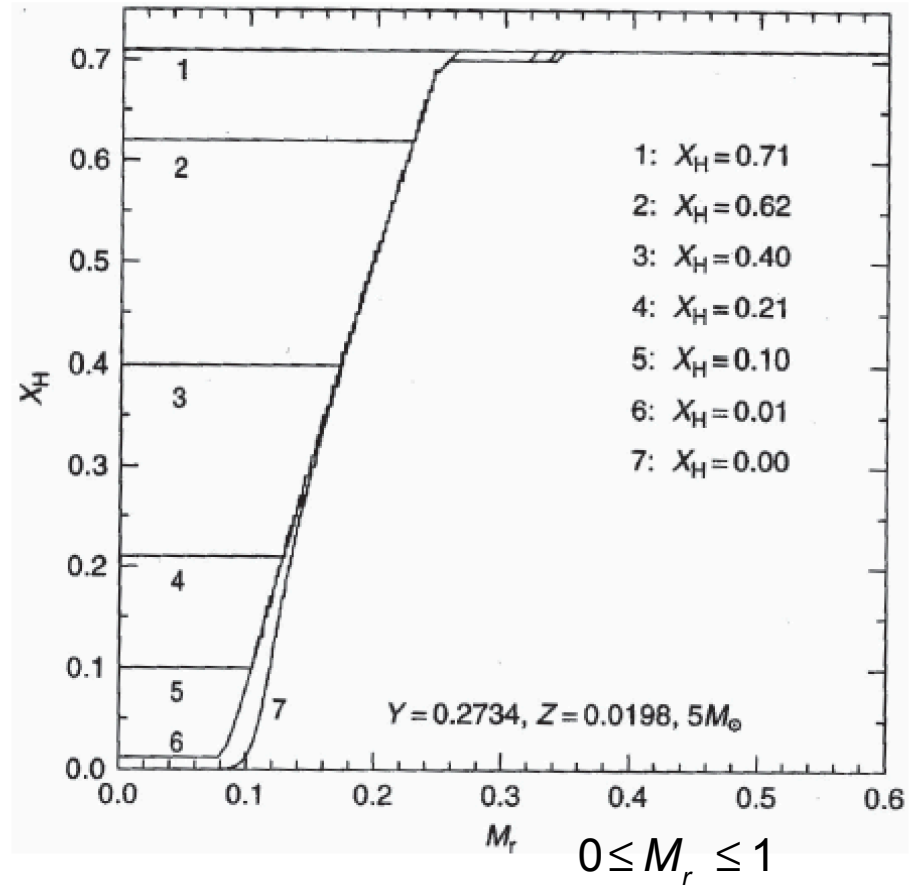
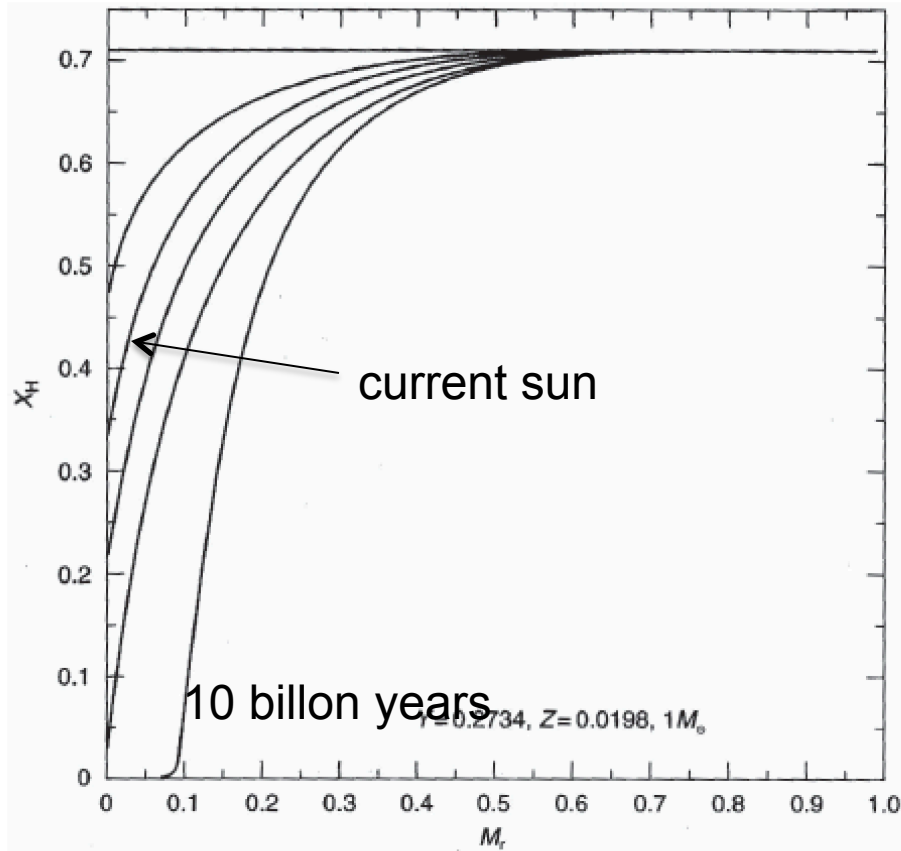
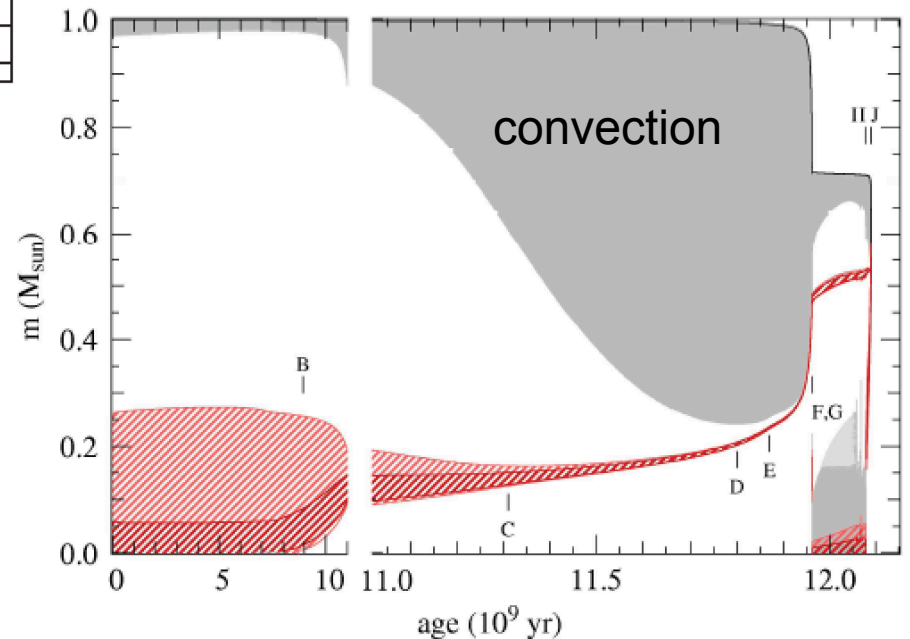
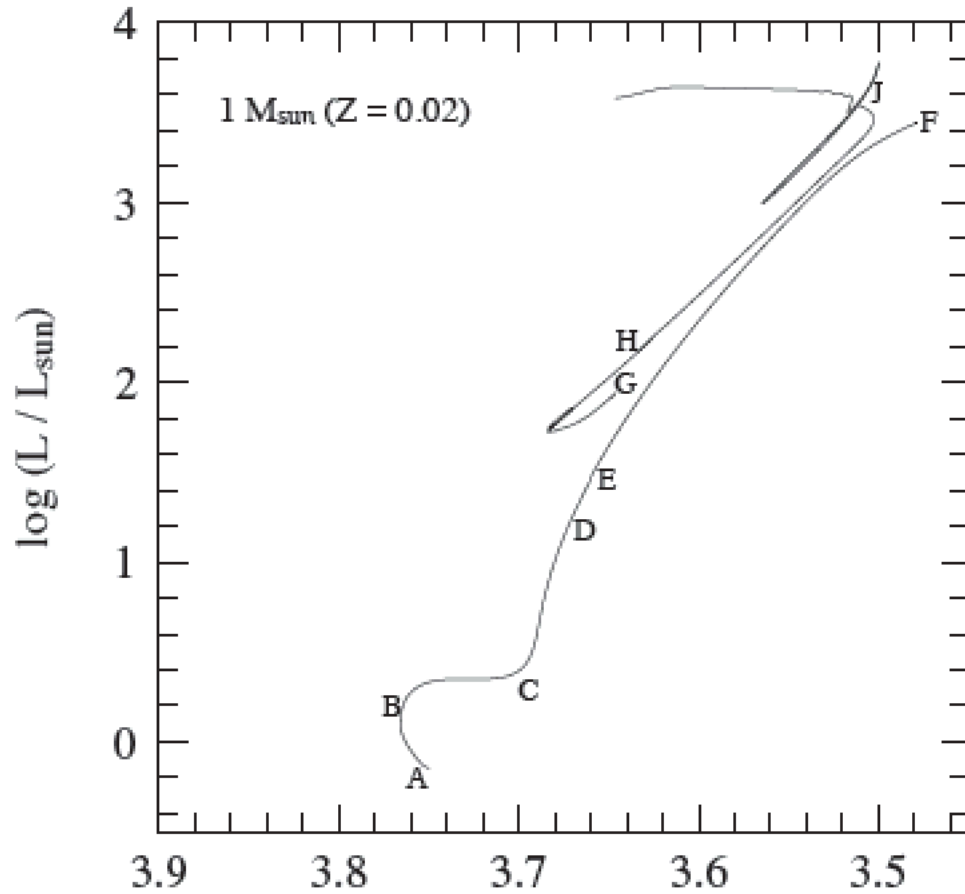


Figure 9.10. Hydrogen abundance profiles at different stages of evolution for a $1 M_{\odot}$ star (left panel) and a $5 M_{\odot}$ star (right panel) at quasi-solar composition. Figures reproduced from SALARIS & CASSISI.

Once the hydrogen depleted core exceeds about 10% of the star's mass, that depleted core can no longer support its own weight and begins to contract rapidly. This causes vigorous hydrogen shell burning that expands the star to red giant proportions

One Solar Mass

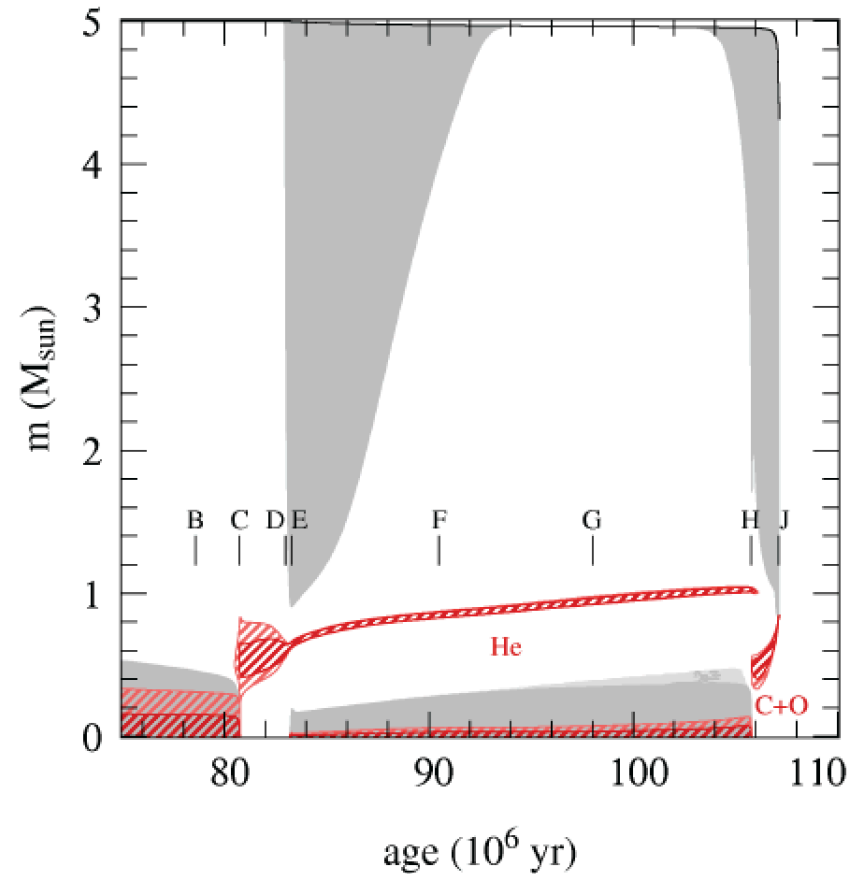
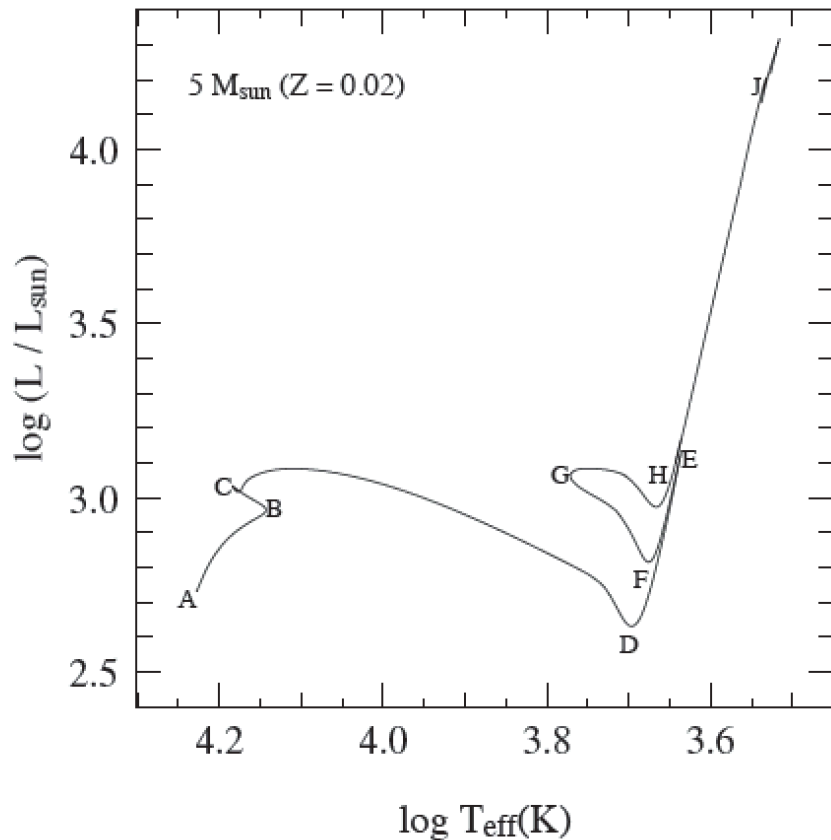
- A H ignition
- B H depletion at center
- C narrowing of H shell, RG formation. He core has becomes degenerate
- D H burning in a thin shell
- F He flash

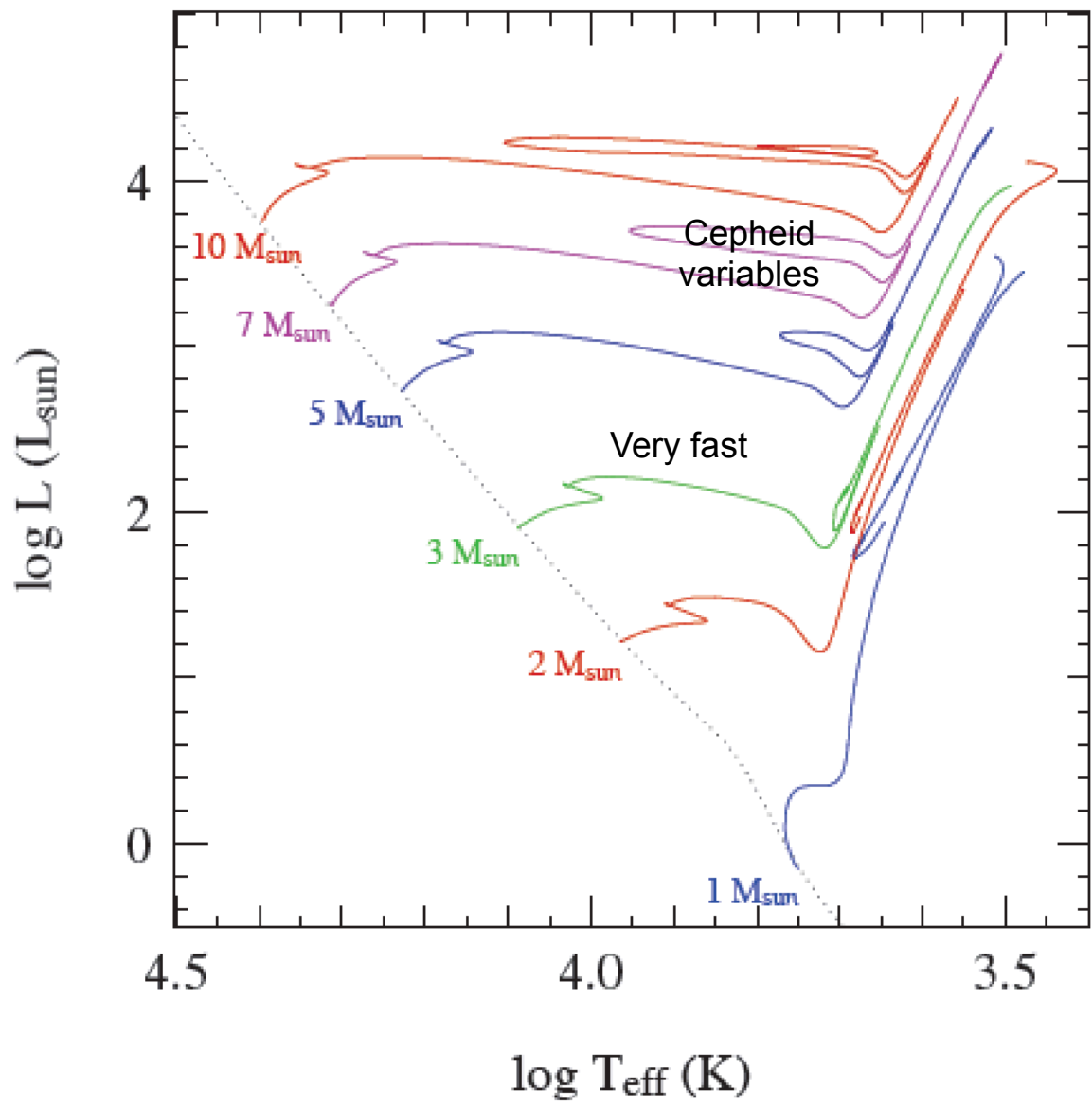


5 Solar Masses

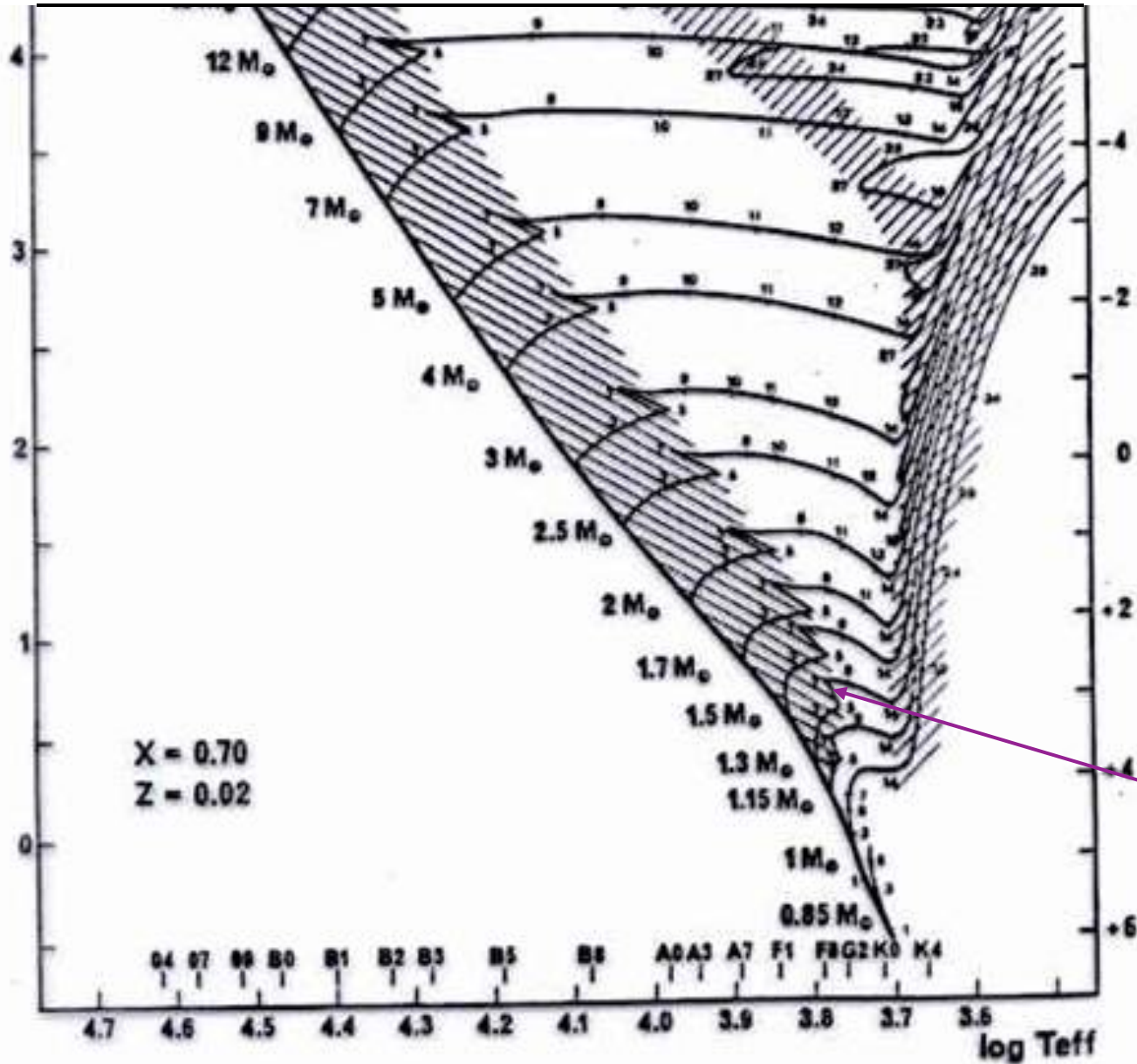
- A H ignition
- B $H = 0.03$ – rapid contraction
- C H depletion in center

- C → D Very fast towards end HR gap.
- D He core now bigger; H shell narrows
- E Red giant formation, He ignition





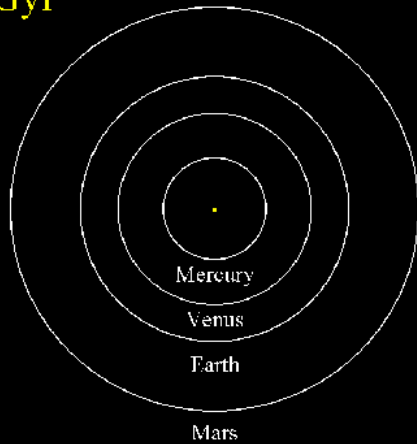
Evolution to Red Giant Stage



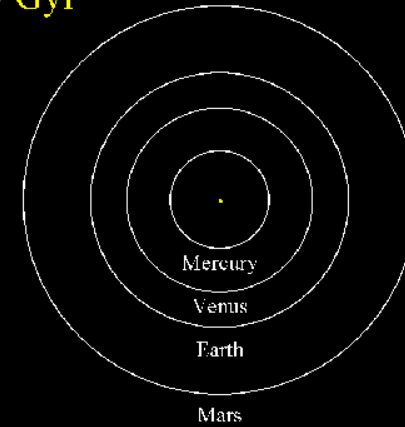
cross hatching indicates where in the HR-diagram a star spends a long time.

H-shell ignition

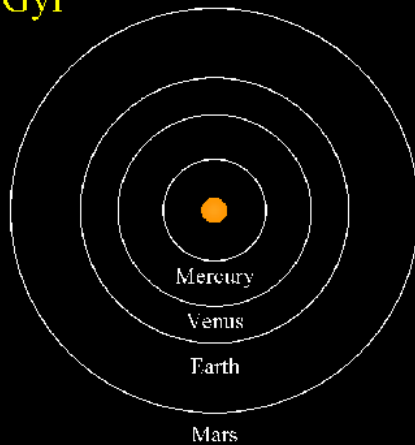
The View From Above Today
T=4.55Gyr



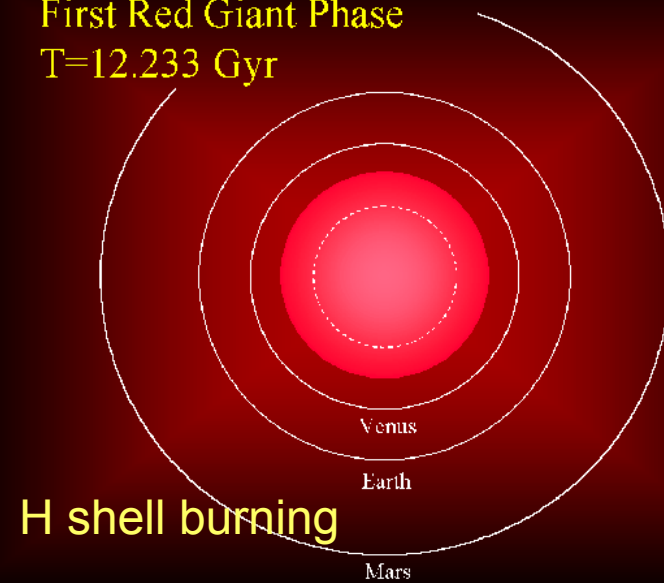
Hydrogen Core Exhaustion
T=10.9 Gyr



Subgiant Phase
T=11.6 Gyr



First Red Giant Phase
T=12.233 Gyr



The Seven Ages of the Sun

- Main sequence 10.9 Gy

- First red giant 1.3 Gy



- Helium burning 120 My

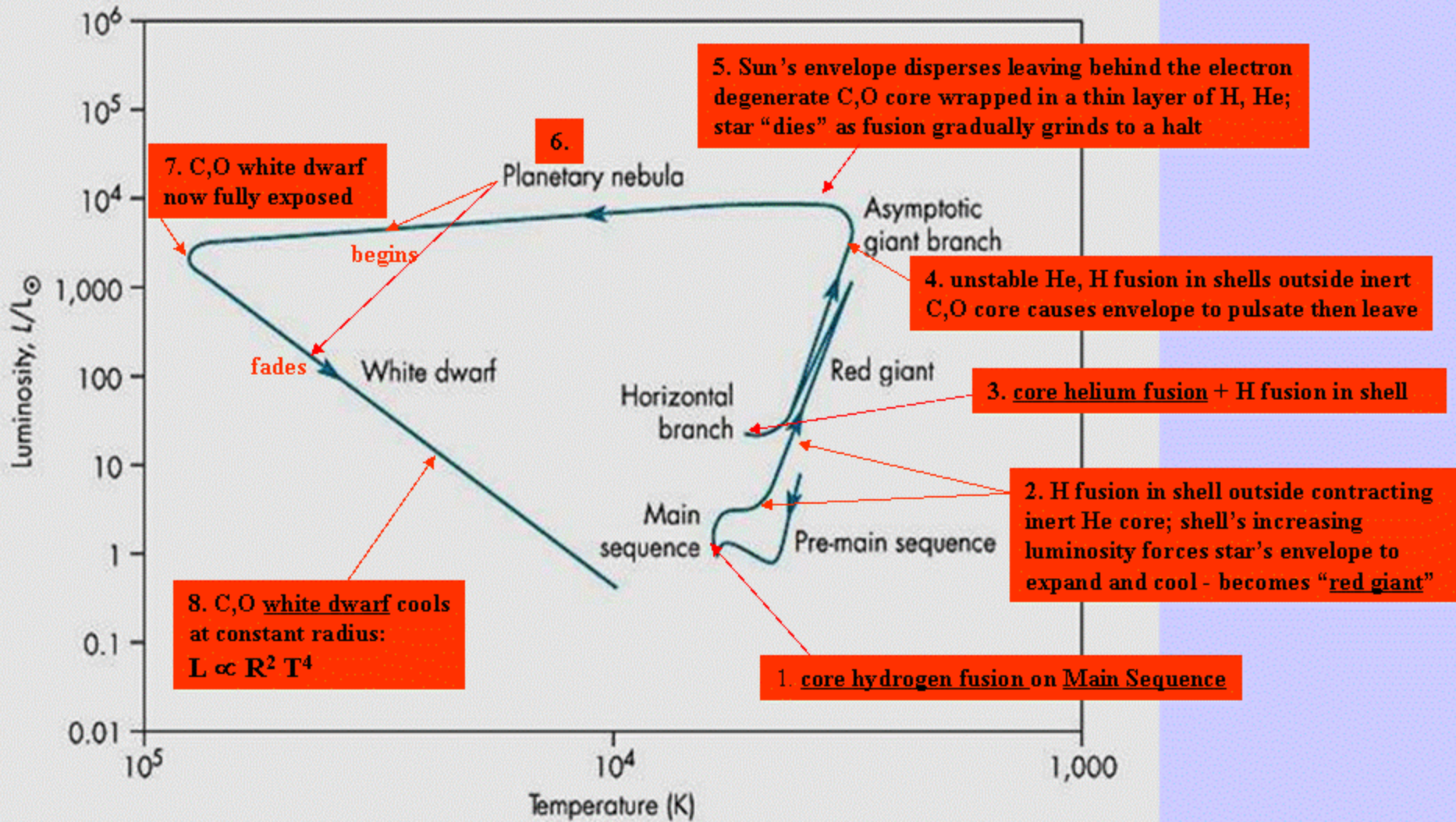
- Second red giant 20 My

- Unstable pulsation 400 Ky

- Planetary nebula 10 Ky

- White dwarf forever

Evolution in HR Diagram The Sun



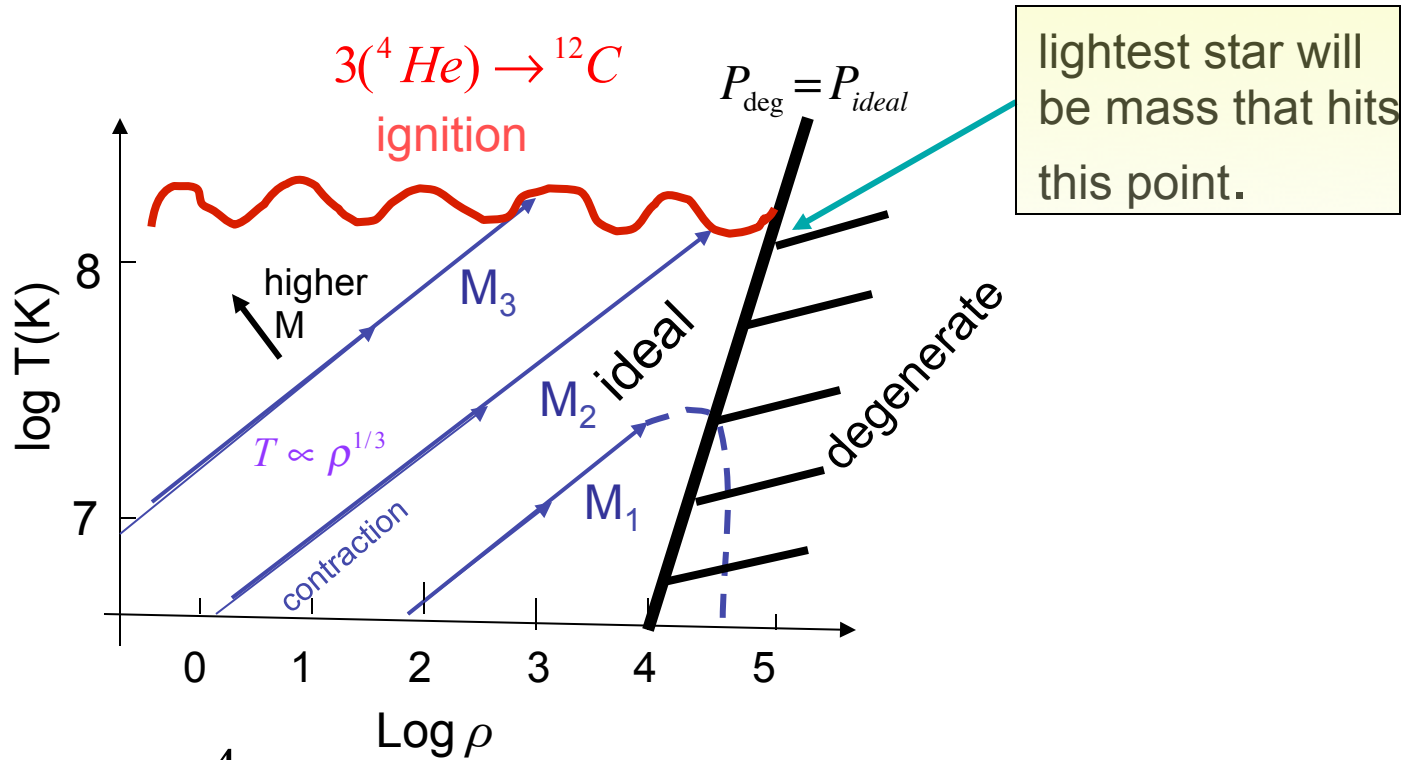
*Helium Burning
and Beyond*

HELIUM IGNITION

- Core contraction continues until a) a temperature of about 150 million K is reached or b) the core becomes degenerate

● Stars lighter than $0.5 M_{\odot}$ end their lives here. They never get hot enough to ignite helium burning. Such stars (will some day) end up as *helium white dwarfs*

- Heavier stars ignite helium burning at about 150 million K (hotter in bigger stars). Between 0.5 and about $2 M_{\odot}$, helium ignites in a *helium flash* - a degenerate thermonuclear runaway.



$$T \propto \frac{M}{R}$$

$$M \sim \frac{4\pi}{3} R^3 \rho$$

$$\Rightarrow R \propto \left(\frac{M}{\rho} \right)^{1/3}$$

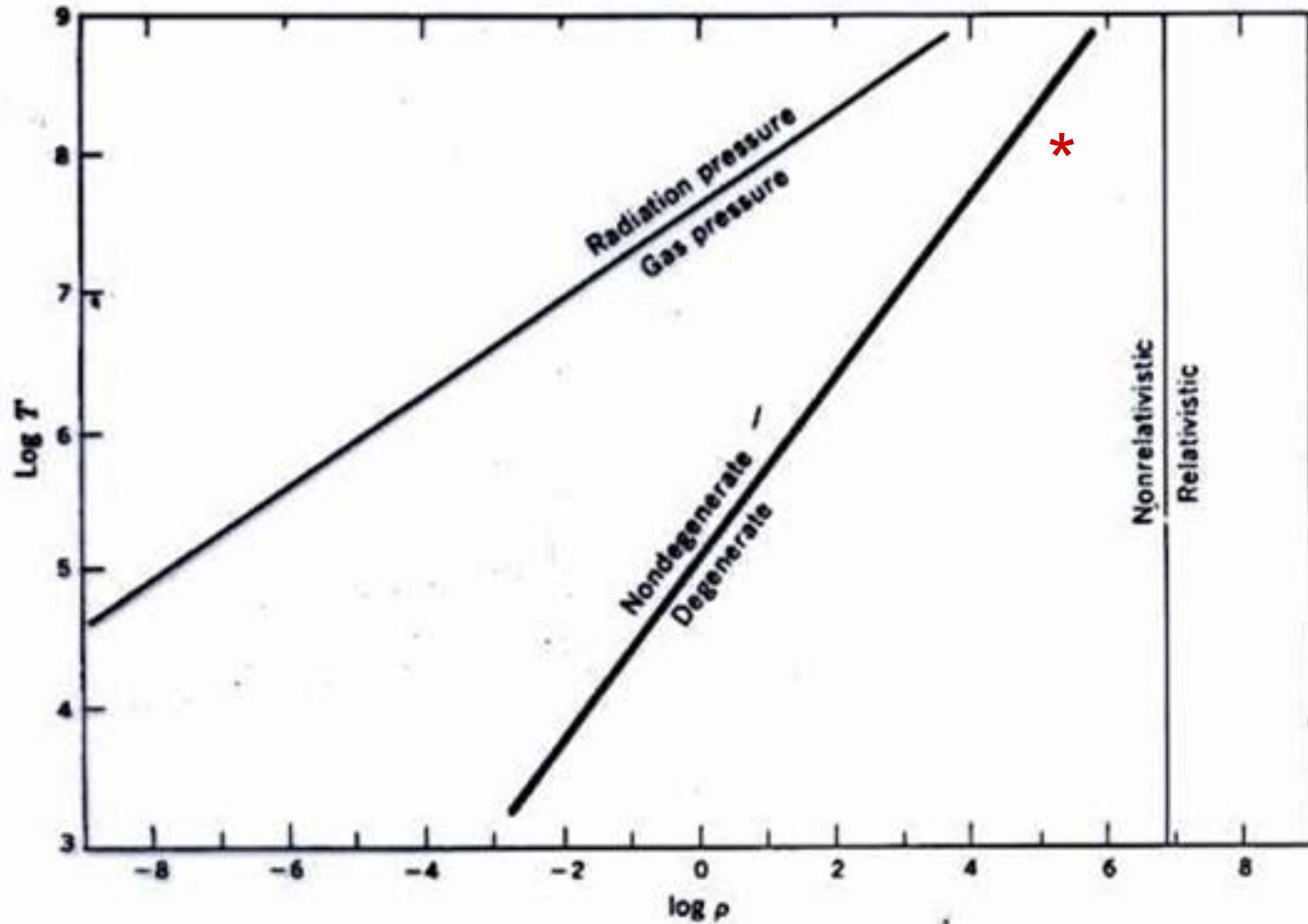
$$T \propto \frac{M \rho^{1/3}}{M^{1/3}}$$

$$T \propto M^{2/3} \rho^{1/3}$$

$T \propto \rho^{1/3}$ for a given M and
 T at a given ρ is higher
 for bigger M

The critical He mass for He ignition is 0.5 solar masses

He Flash ignition conditions are degenerate



Degenerate Thermonuclear Runaway

Energy generation \uparrow

Temperature \uparrow

But pressure at least initially does not go up,
there is no expansion and no cooling so

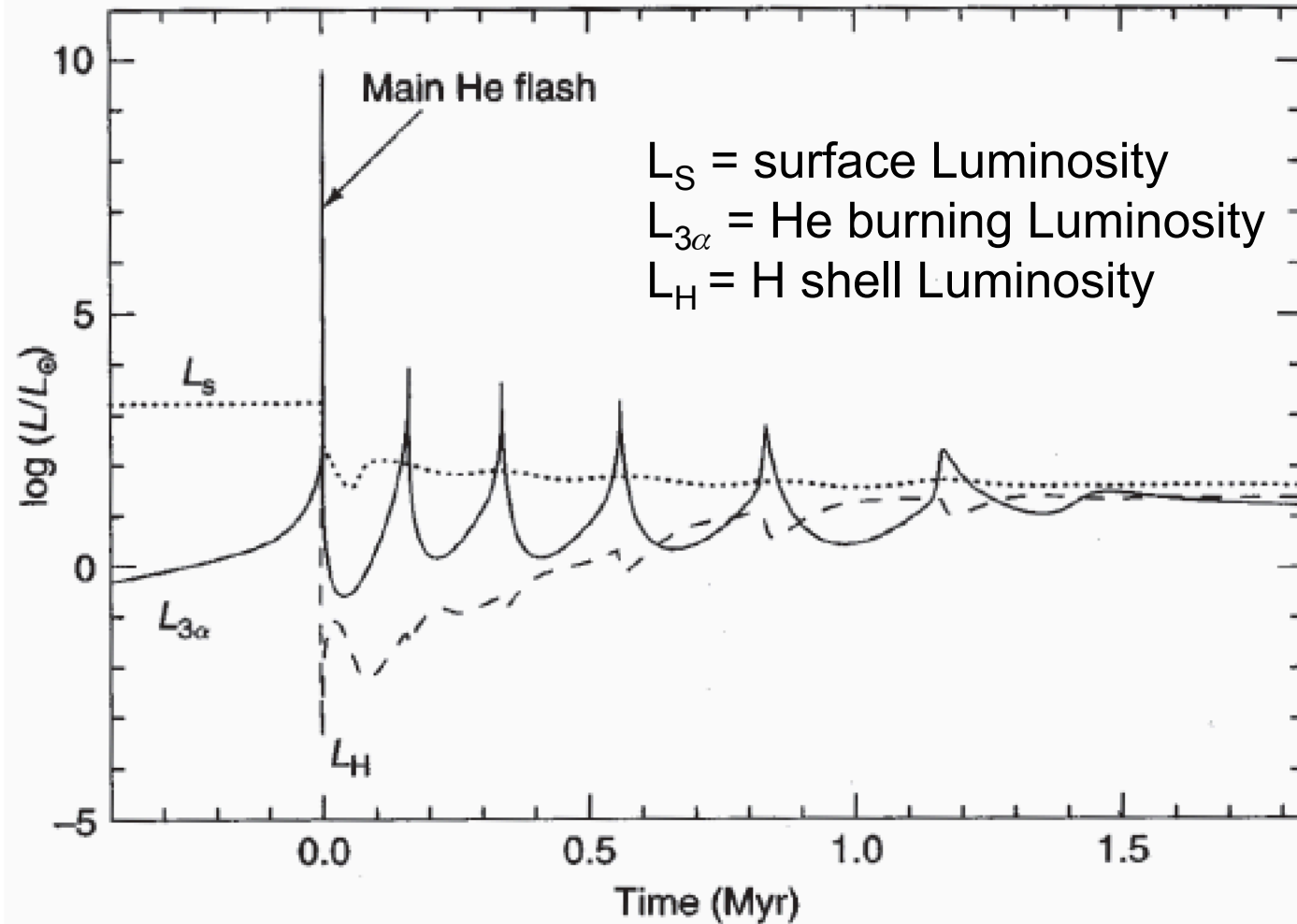
Energy generation \uparrow some more

Temperature \uparrow some more

Until finally the burning is going on explosively
then finally T rises so much that the gas becomes
non-degenerate and expands violently

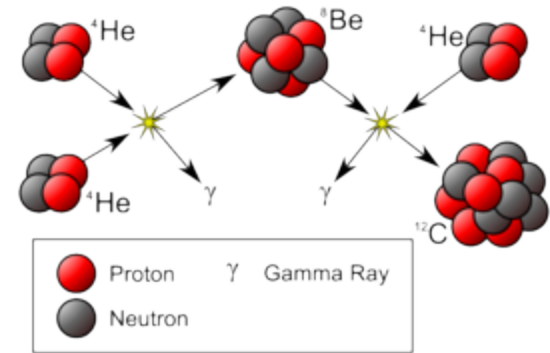
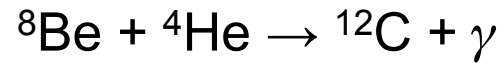
- For example the sun first ignites helium burning at about 10^5 g cm^{-3} . Here pressure is mainly due to degenerate electrons. An explosion ensues, lasting only a few minutes. Up to 100 billion solar luminosities in center.
- The explosion is brief and only burns a small fraction of the helium. The core expands, the hydrogen burning shell goes out, and eventually the star actually becomes *fainter*. Adjustment time scale $\sim 10^6 \text{ yr}$
- After a Kelvin-Helmholtz time (for the helium core), it again ignites helium but at lower density (non-degenerate). Helium burning then proceeds peacefully.
- Stars heavier than $2 M_{\odot}$ ignite helium gently the first time.

http://en.wikipedia.org/wiki/Helium_flash



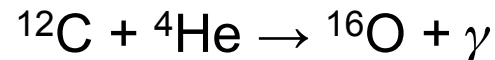
About 3% of the helium burns during the He flash in a solar model

Helium Burning

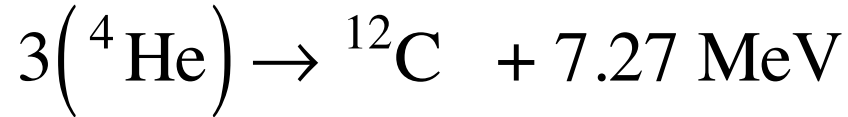


Helium burning, often called the triple-alpha process occurs above temperatures of 100,000,000 K. ${}^8\text{Be}$ is unstable and decays back into He in 2.6×10^{-16} secs, but in the stellar interior a small equilibrium of ${}^8\text{Be}$ exists. The ${}^8\text{Be}$ ground state has almost exactly the energy of two alpha particles. In the second step, ${}^8\text{Be} + {}^4\text{He}$ has almost exactly the energy of an excited state of ${}^{12}\text{C}$. This resonance greatly increases the chances of Helium fusing and was predicted by Fred Hoyle.

As a side effect some Carbon fuses with Helium to form Oxygen:



The net result is:



or $5.8 \times 10^{17} \text{ erg g}^{-1}$

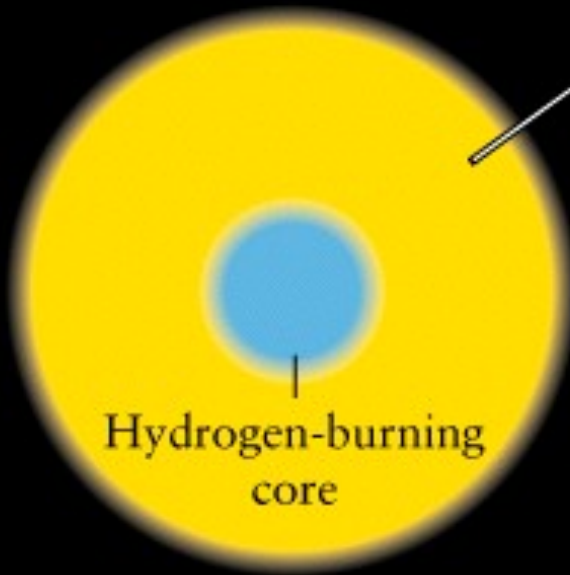
The extra burning to oxygen, ${}^{12}\text{C}(\alpha, \gamma){}^{16}\text{O}$ raises this to $7.5 \times 10^{17} \text{ erg g}^{-1}$, or about 10% of what hydrogen burning gave.

Because helium burning produces less energy and because the luminosities are actually greater, helium burning is a shorter stage in the life of a star than the main sequence.

In the end more oxygen is made than carbon. This is how carbon and oxygen are produced in nature.

Stages in the Sun's Life (incomplete)

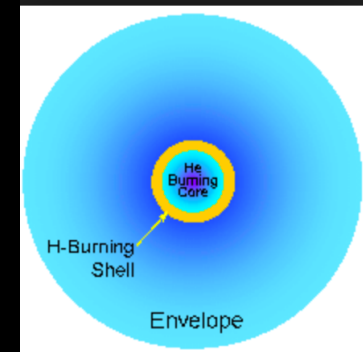
Outer layers: no thermonuclear reactions



Main sequence star



Red giant star



Horizontal branch star

The Seven Ages of the Sun

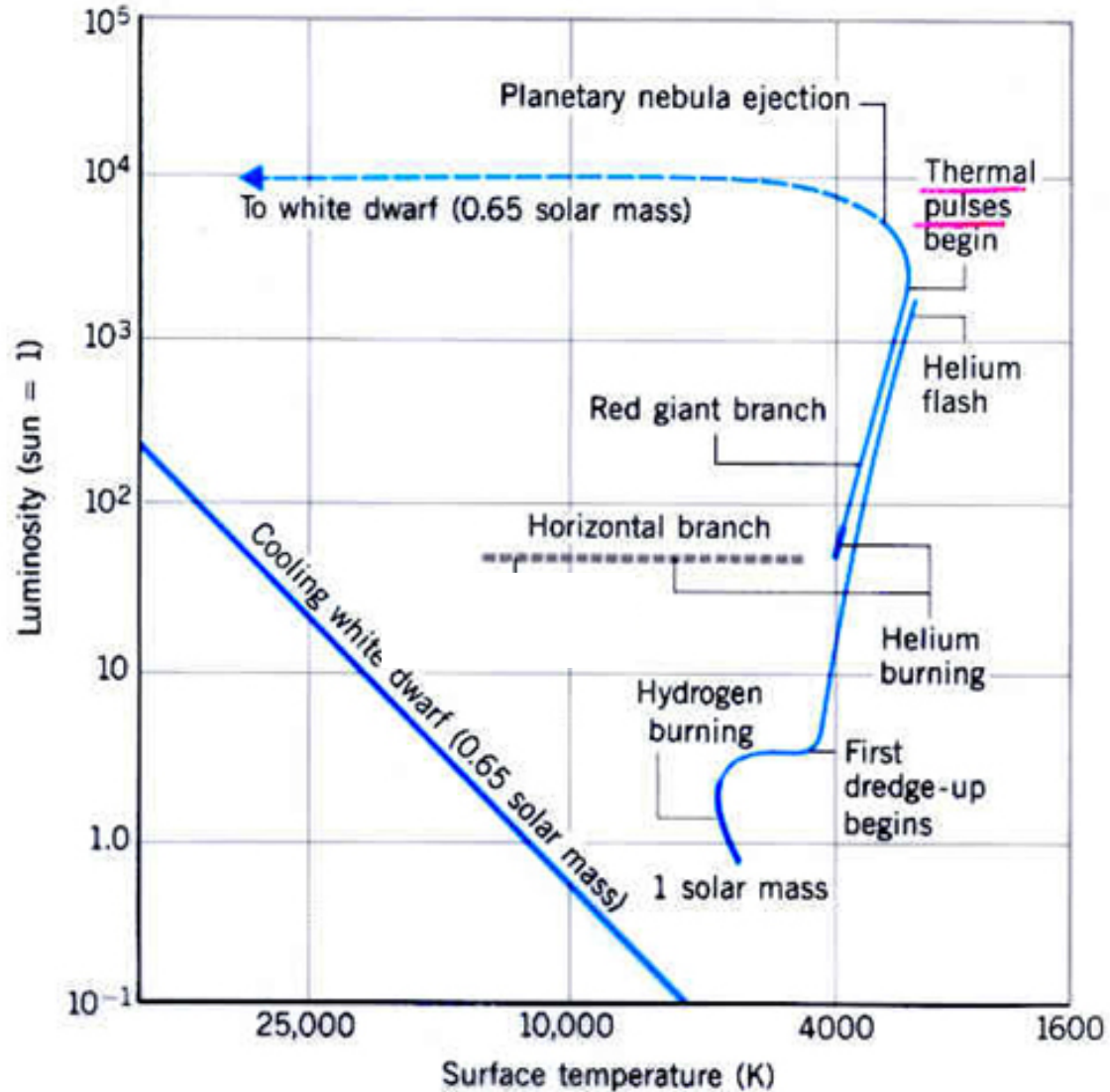
- Main sequence 10.9 Gy
- First red giant 1.3 Gy
- Helium burning 120 My horizontal branch



- Second red giant 20 My
- Unstable pulsation 400 Ky
- Planetary nebula 10 Ky
- White dwarf forever

The Sun

The readjustment of the red giant to a horizontal branch star takes about 2 My after the He core flash (Kelvin Helmholtz time for the helium core.)



Evolutionary track on an H-R diagram for a 1-solar-mass star (Population I).

All low mass stars ignite helium with about the same mass – close to 0.5 solar masses

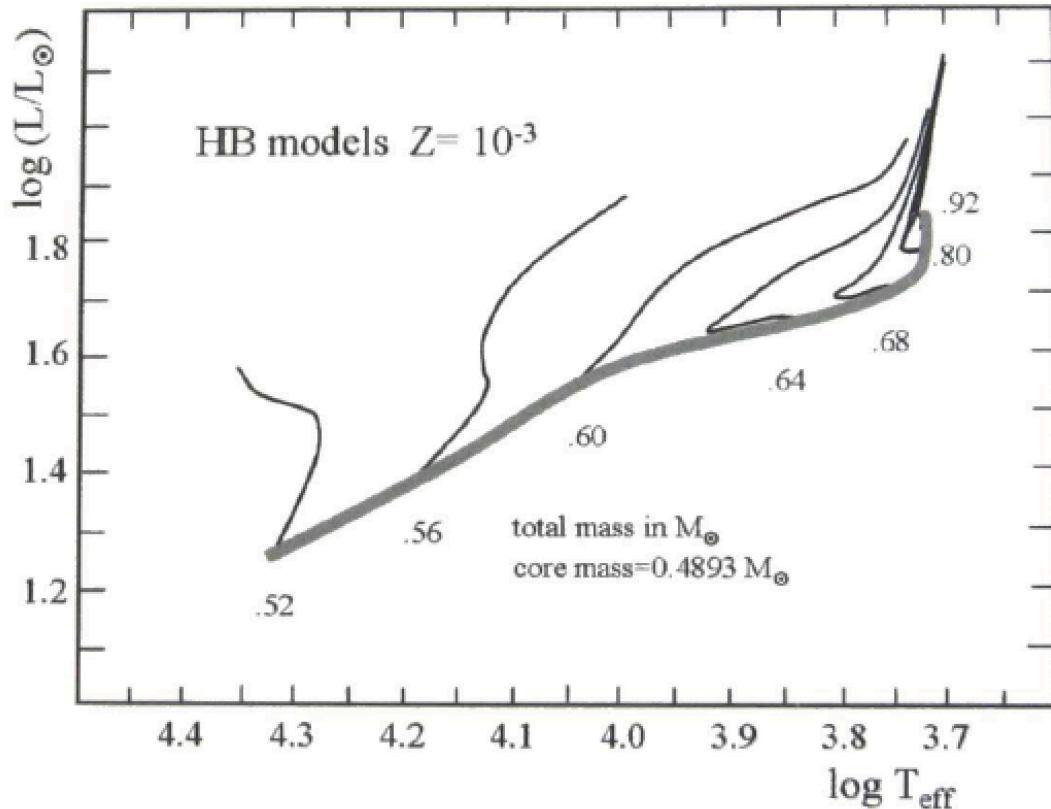
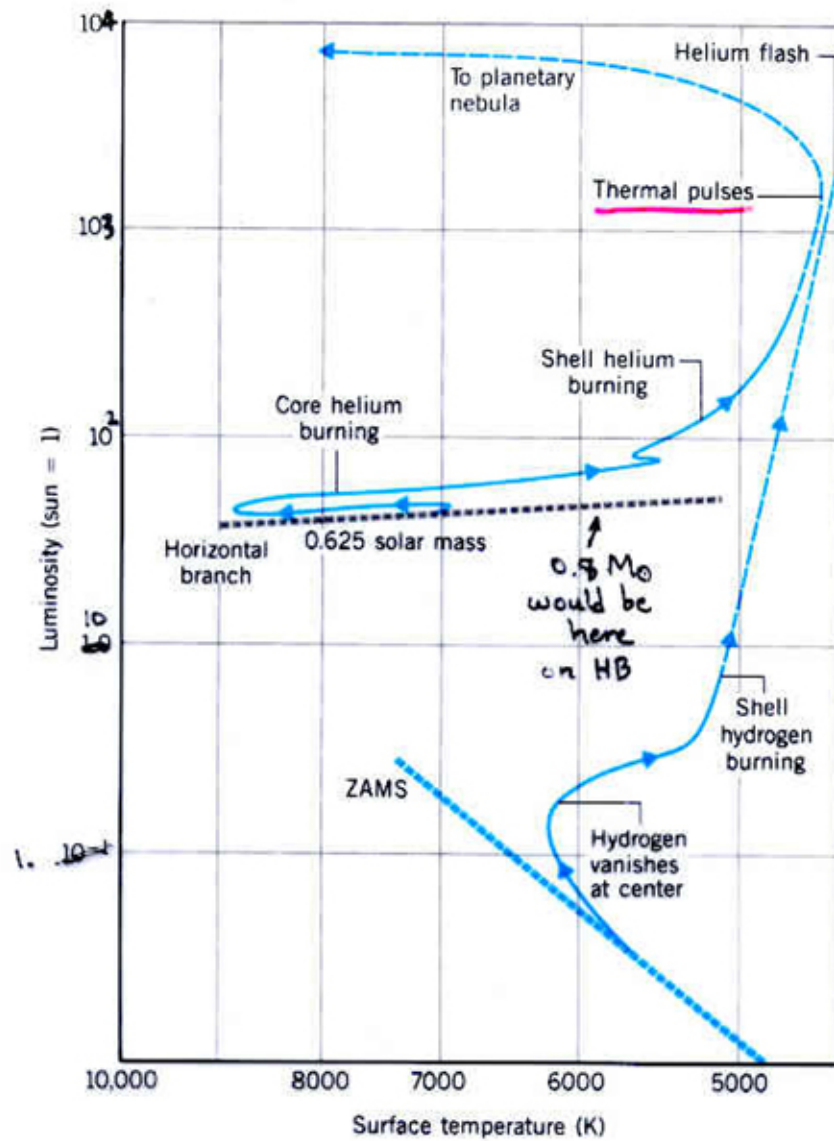


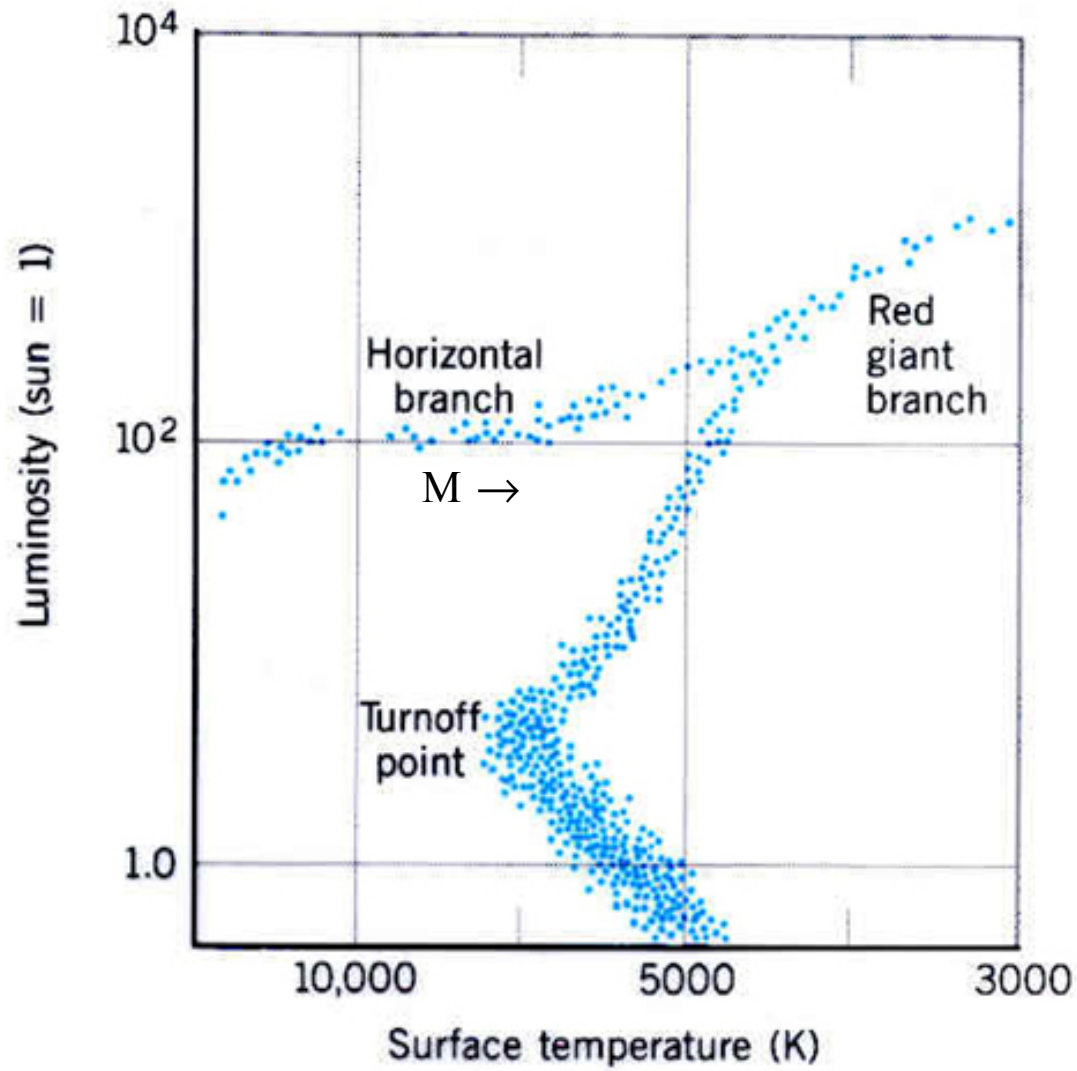
Figure 10.9. Location of the zero-age horizontal branch (think gray line) for a metallicity $Z = 0.001$ typical of globular clusters. These models have the same core mass ($0.489 M_{\odot}$) but varying total (i.e. envelope) mass, which determines their position in the H-R diagram. Evolution tracks during the HB for several total mass values are shown as thin solid lines. Figure from MAEDER.

Having a bigger envelope mass makes the radius bigger at about the same luminosity – hence redder. The duration of He burning is about 120 My, again independent of mass (because they all have the same He core mass).



Lower mass HB stars are hotter (bluer) than higher mass ones

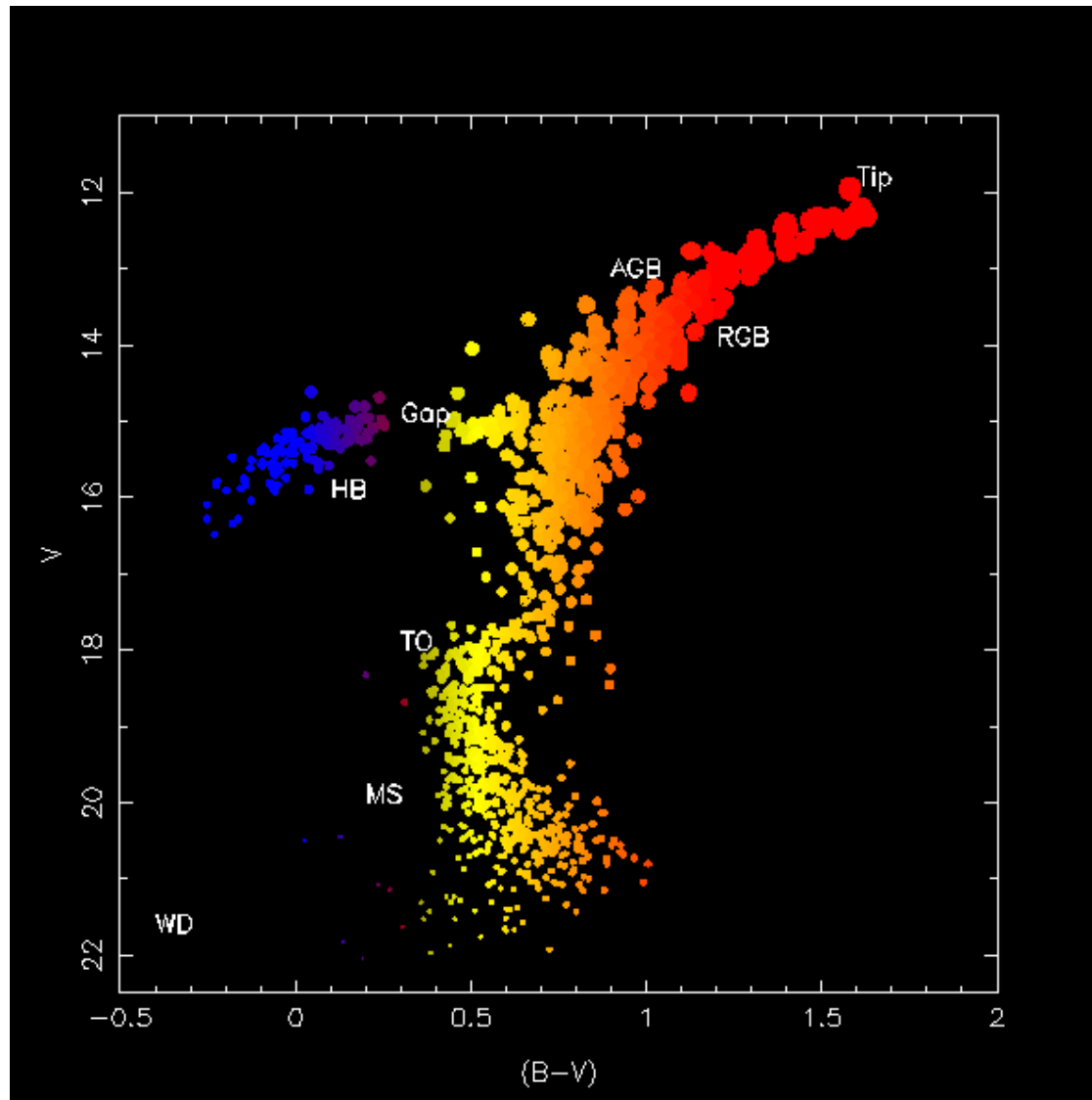
Theoretical evolutionary track on an H - R diagram for a 0.7-solar-mass star off the main sequence.



Schematic H - R diagram for a globular cluster.

Globular Cluster M5

http://www.dur.ac.uk/ian.smil/gcCm/gcCm_intro.html

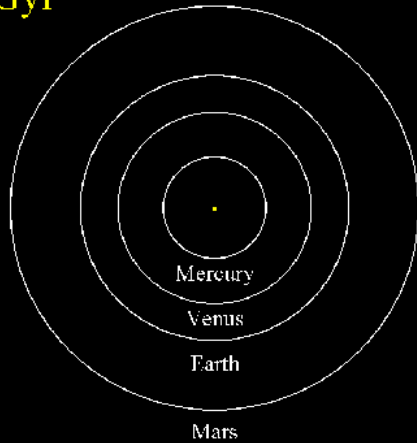


TO = “turn off mass”; HB = “horizontal branch”;
“Gap” is a region of atmospheric instability

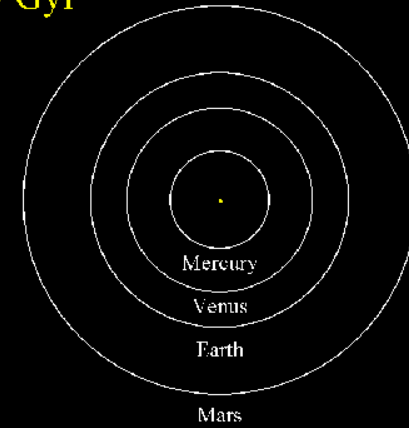


The globular cluster M10. The bright yellow and orange stars are red giants burning hydrogen or helium in a shell, but the bright blue stars are “horizontal branch” stars, burning helium in their centers. Both kinds of stars are more massive and brighter than the low mass main sequence stars in M10.

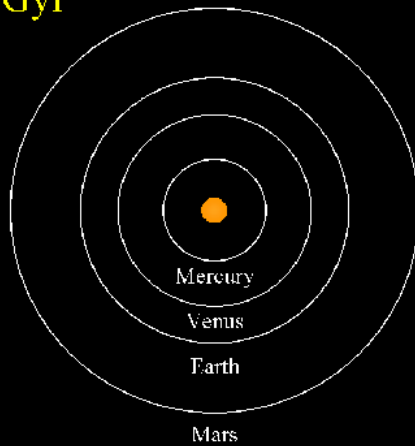
The View From Above Today
T=4.55Gyr



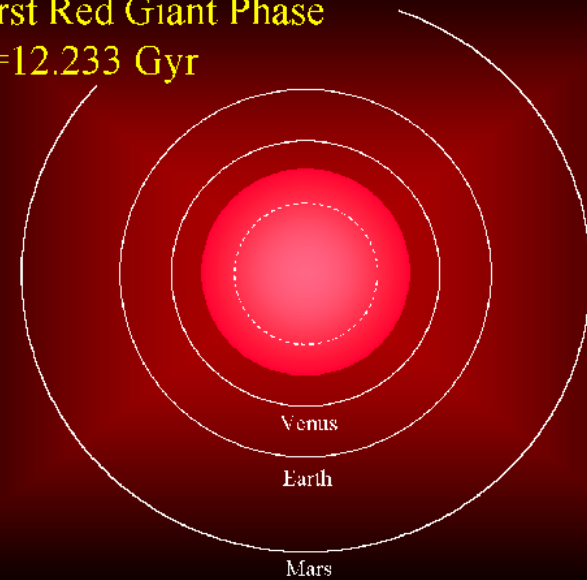
Hydrogen Core Exhaustion
T=10.9 Gyr



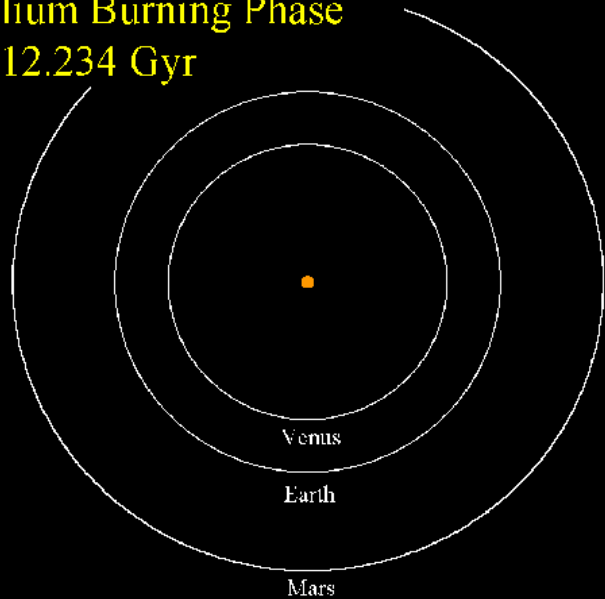
Subgiant Phase
T=11.6 Gyr



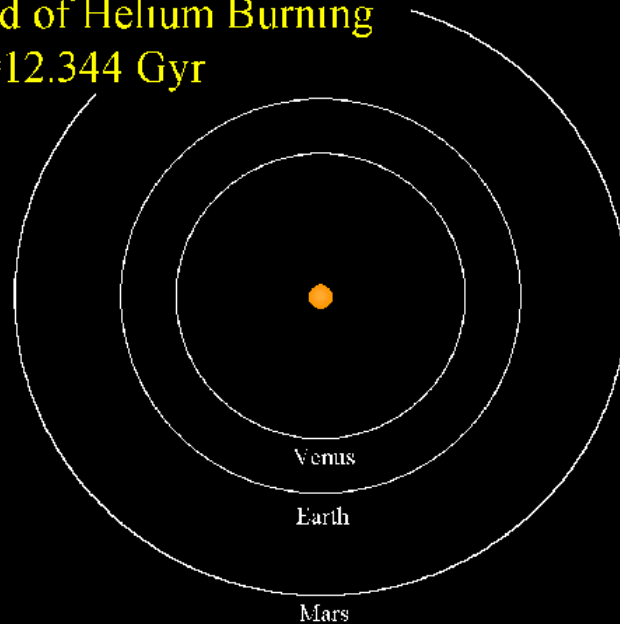
First Red Giant Phase
T=12.233 Gyr



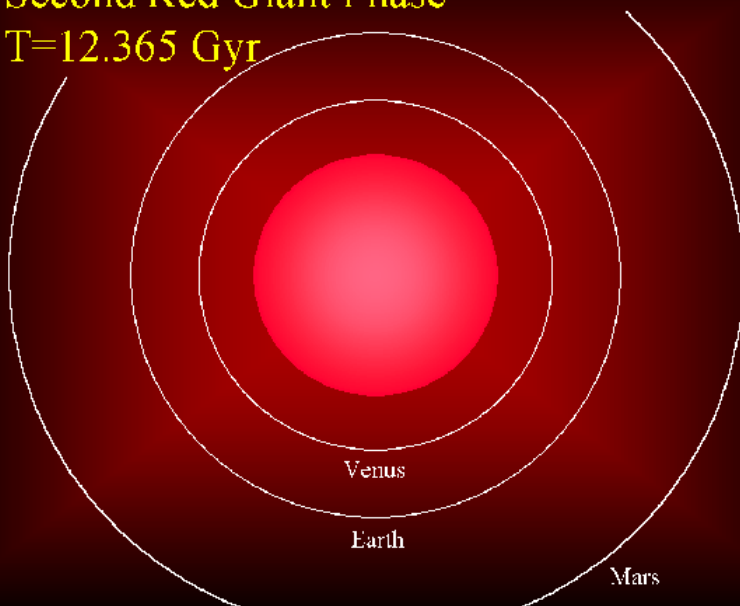
Helium Burning Phase
T=12.234 Gyr



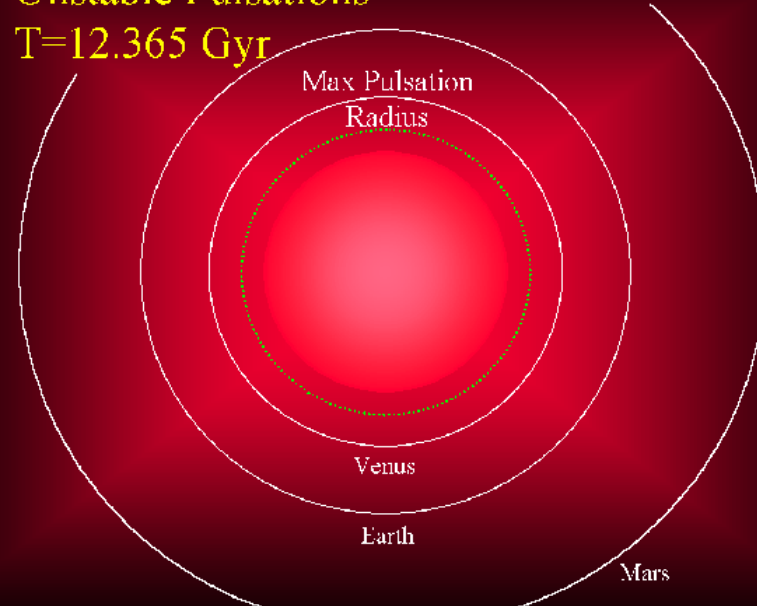
End of Helium Burning
T=12.344 Gyr



Second Red Giant Phase
T=12.365 Gyr



Unstable Pulsations
T=12.365 Gyr



log Luminosity

Asymptotic Giant Branch

Central helium consumed, leaving carbon-oxygen core; two shell sources (H and He). Neutrino cooling of interior. Surface mass loss and ejection of planetary nebula.

AGB

HB

RGB

Horizontal Branch

Core helium burning ("Helium Main Sequence"). Much shorter duration than hydrogen main sequence.

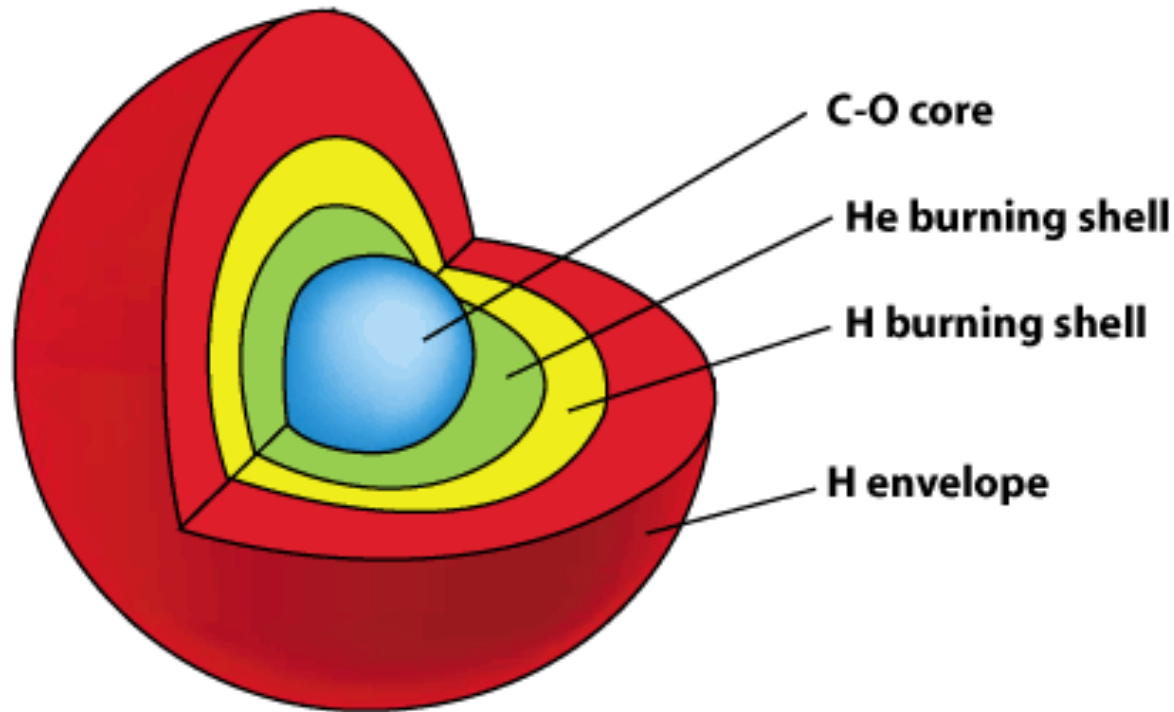
Red Giant Branch

Core contraction with H shell burning leading to triple-alpha ignition. Deep envelope convection and surface mass loss. Helium flash if mass less than 3 solar masses.

log Temperature

Giant Star Branches in the HR Diagram

AGB STARS 0.5 to $8 M_{\odot}$



Cutaway drawing of the interior structure of an “Asymptotic Giant Branch” or AGB star. Hydrogen and helium burning shells are both active, though not necessarily both at the same time. The He and H burning regions are much thinner than this diagram suggests. The outer layers are convective. The C-O core is degenerate and transports its radiation by conduction.

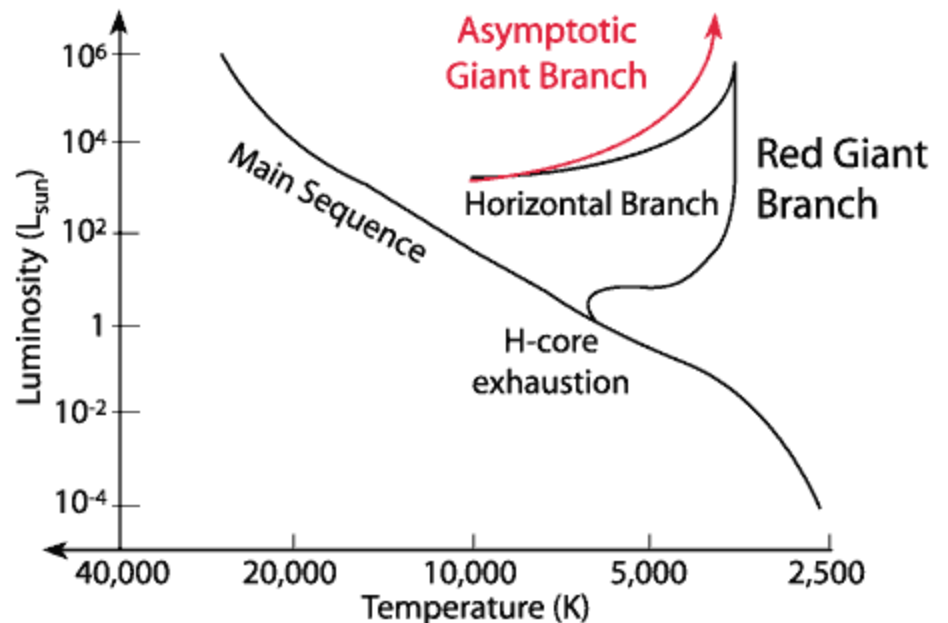
The Seven Ages of the Sun

- Main sequence 10.9 Gy
 - First red giant 1.3 Gy
 - Helium burning 100 My
 - Second red giant 20 My
 - Unstable pulsation 400 Ky
-
- Planetary nebula 10 Ky
 - White dwarf forever

AGB stars are known to lose mass at a prodigious rate during their final stages, around 10^{-5} - 10^{-4} solar masses per year. This obviously cannot persist for much over 100,000 years.

The mass loss is driven in part by the pulsational instability of the thin helium shell. These pulses grow more violent with time. Also, and probably more importantly, the outer layers of the star get so large and cool owing to the high luminosity, that they form dust. The dust increases the opacity and material is blown away at speeds $\sim 10 - 30 \text{ km s}^{-1}$

The evolution is terminated as the outer layers of the star are blown away.



Thin shell instability:

Suppose star is supported by ideal gas but the burning region is a very thin shell. $\Delta r \ll R$.

Then the pressure on the top and bottom are almost the same and burning cannot change the pressure appreciably

$$P \propto \rho T$$

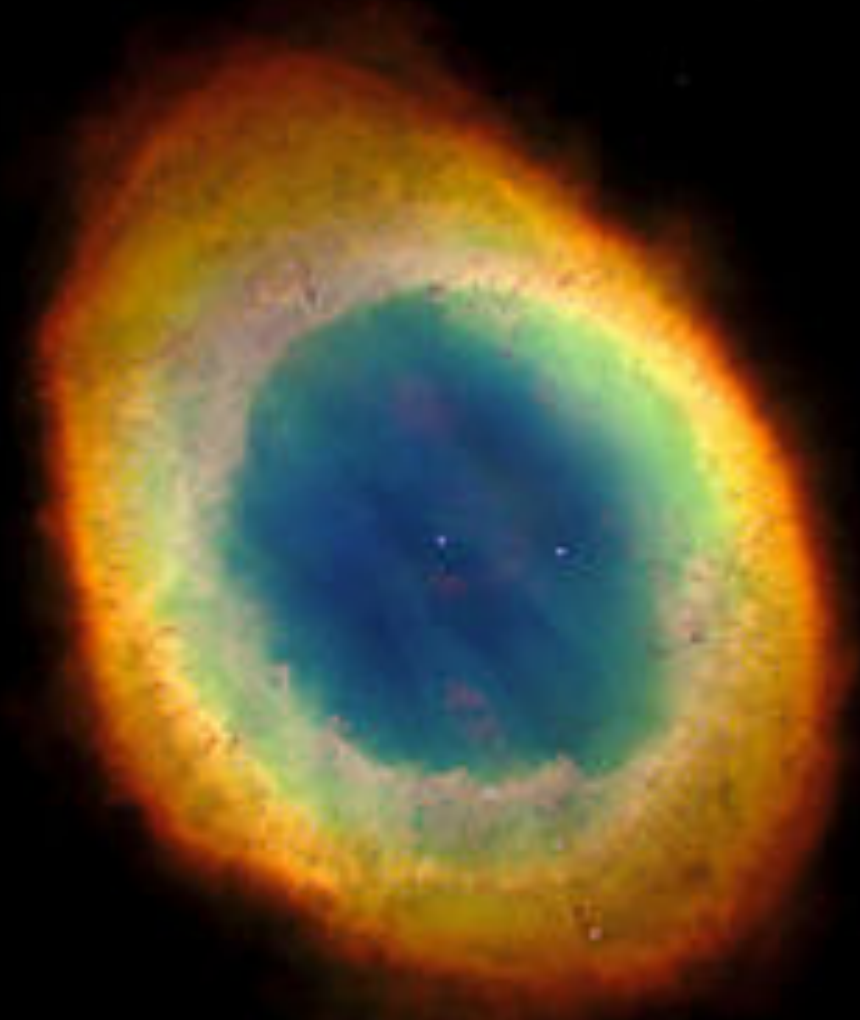
$T \uparrow$ but P stays constant

$\rho \downarrow$ but energy generation depends
on T^n with n a big number

Energy generation continues to rise so $T \uparrow$ some more.

This continues until the fuel is gone or the shell expands a great deal

http://en.wikipedia.org/wiki/Ring_Nebula



The Ring Nebula in Lyra (M57)
700 pc; magnitude 8.8

PLANETARY NEBULAE

- Transition phase from a star to a white dwarf. Occurs for all stars under 8 solar masses
- About 3000 known in our galaxy though most stars go through this phase
- Short lived – about 10,000 years
- Densities $\sim 100 - 10,000$ particles per cm^3 ; roughly one light year across. Velocities $20 - 50 \text{ km s}^{-1}$
- Masses $0.1 - 1$ solar masses, a substantial fraction of the star's mass
- Definitely not a site of planet (or star) formation

PLANETARY NEBULAE

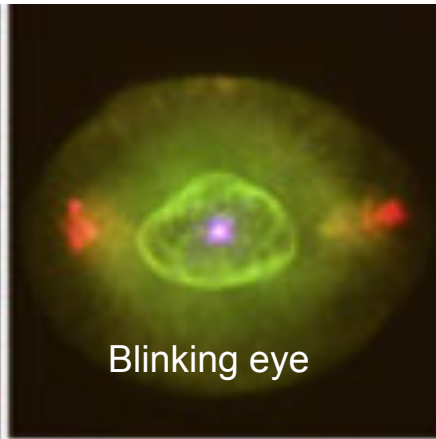
- UV radiation from central star heats to about 10,000 K
- Rich in carbon, nitrogen and oxygen. May be the source of most of the carbon and nitrogen in the universe
- Only about 20% are spherically symmetric. Rest are deformed by asymmetric outflow, binary companions, magnetic fields, etc.
- Emission lines e.g., of O III, O II, and N II
- Central stars 20,000 – 100,000 K



NGC 2440 – White dwarf ejecting envelope. One of the hottest white dwarfs known is in the center of the picture About 200,000 K and 250 times the sun's luminosity



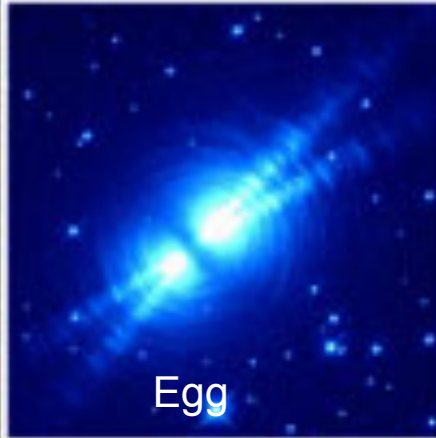
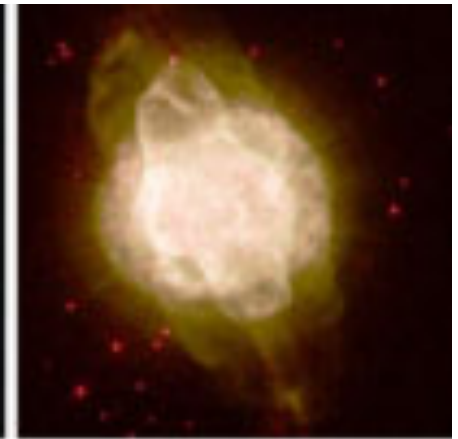
Kissing squid



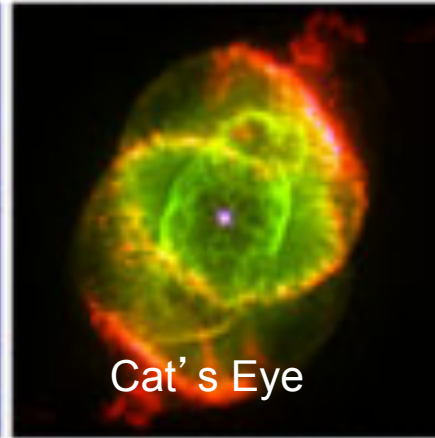
Blinking eye



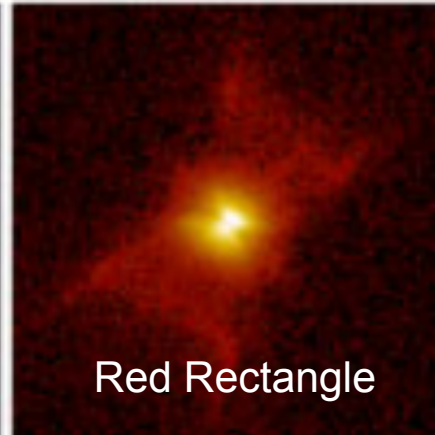
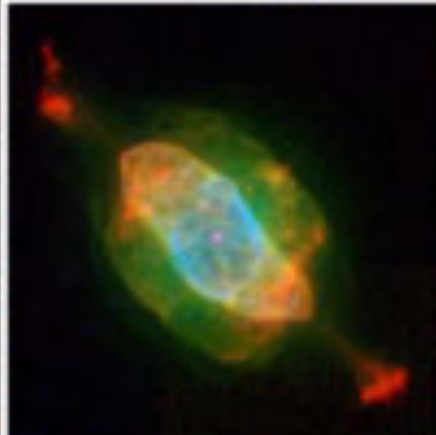
Hourglass



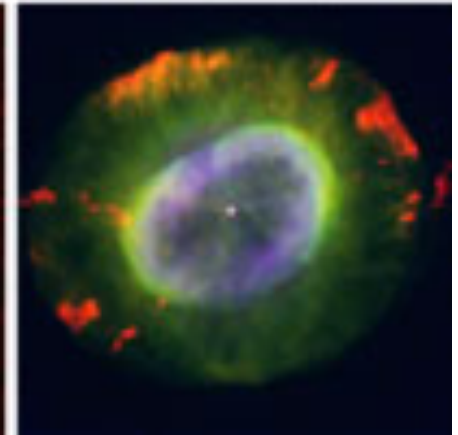
Egg



Cat's Eye



Red Rectangle



Note the consequences for nucleosynthesis here.

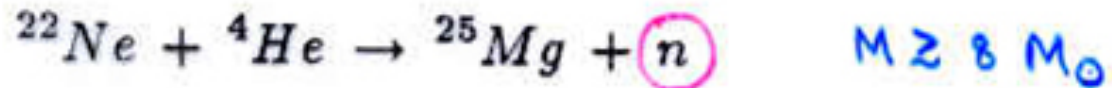
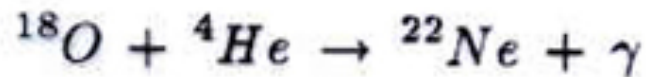
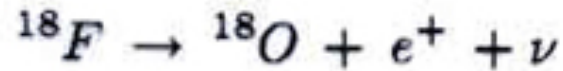
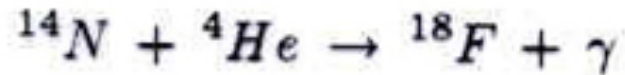
The outer layers of the star contain hydrogen and helium to be sure, but also nitrogen from CNO processing and C and O from helium burning. Much of this is lost to the interstellar medium by winds during the red giant and AGB phases and as a planetary nebula.

It is thought that stars in this mass range are responsible for producing most of the **nitrogen** and maybe 40 – 80% of the **carbon** in the universe.

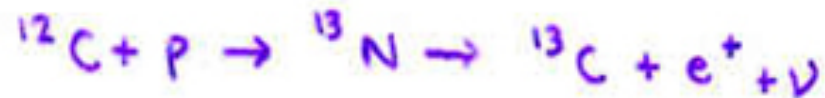
The rest of carbon and most other elements comes from massive stars.

Additional Nucleosynthesis – The s-Process.

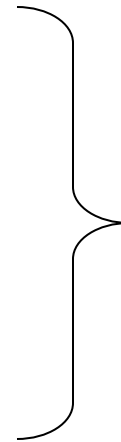
- During helium burning:



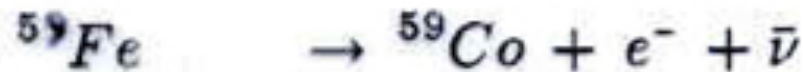
In $M \leq 8 M_{\odot}$ during "AGB" stage,
a little H may get mixed into the thin He-burning
shell. Then



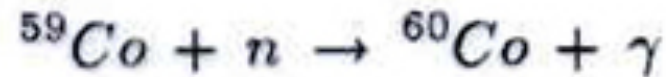
Where do the neutrons go?



years



44.5 days

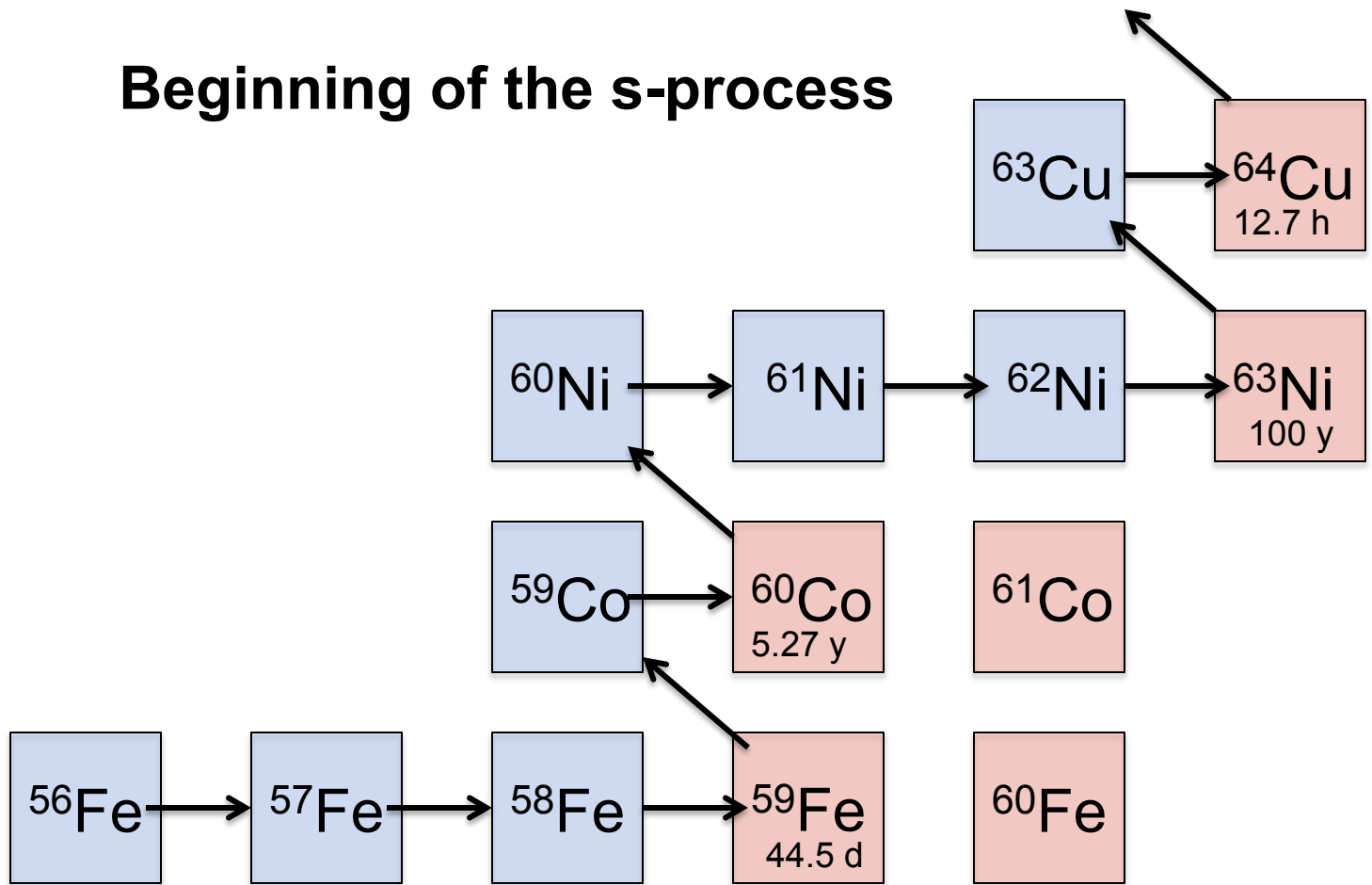


etc., all the way to ${}^{209}\text{Bi}$.

This is called the “slow” process of neutron addition or the “s-process”. (There is also a “r-process”)

Beginning of the s-process

Z ↑

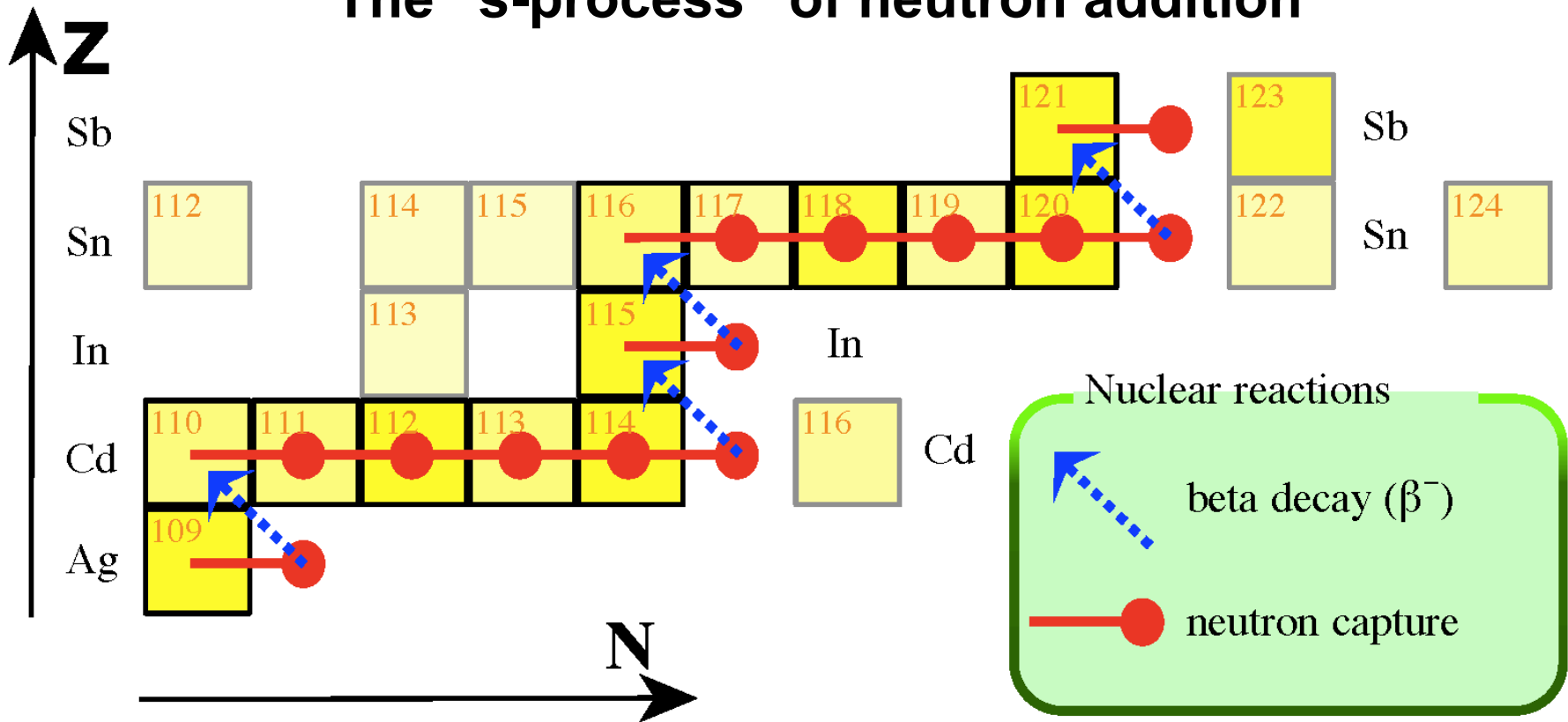


N →

→ = (n, γ)

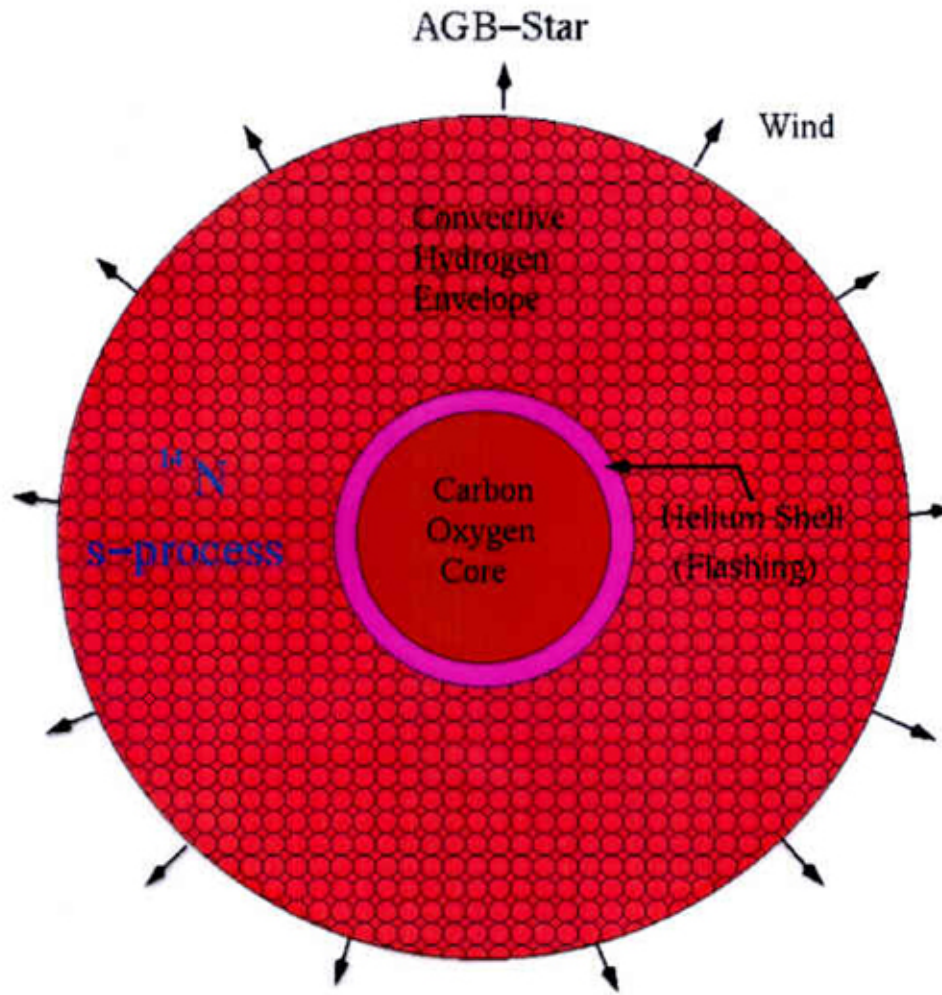
↖ = (e^-, ν)

The “s-process” of neutron addition



Each neutron capture takes you one step to the right in this diagram. Each decay of a neutron to a proton inside the nucleus moves you up a left diagonal.

This goes all the way up to lead – element number 82



On top of the He burning shell there is also a thin H burning shell

CO-core temperature about 5×10^8 K
 He-shell flash $T = 3 \times 10^8$ K

Convective hydrogen envelope dredges up ashes of helium shell flashes to the surface where they are lost to wind and planetary nebula formation.