

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

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

## The sun - past and future

Time (10 <sup>9</sup> years)	Luminosity (L <sub>⊙</sub> )	Radius (R <sub>⊙</sub> )	T <sub>central</sub> (10 <sup>6</sup> °K)
<b>Past</b>			
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
<b>Now</b>			
4.587	1.000	1.000	15.51
<b>Future</b>			
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

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

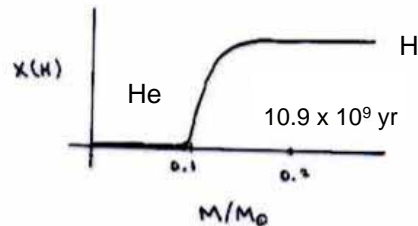
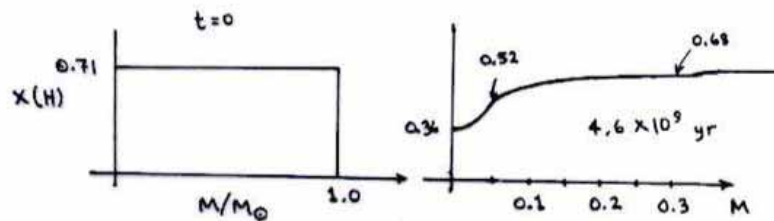
After that though, changes become rapid

\* Adapted from Turck-Chiése et al. (1988).  
Composition X = 0.7046, Y = 0.2757, Z = 0.0197.  
Present values are R<sub>⊙</sub> and L<sub>⊙</sub>.  
\*\* For time t before the present age t<sub>0</sub> = 4.6 × 10<sup>9</sup> years,  
L/L<sub>⊙</sub> ≈ 1/(1+0.4(1-t/t<sub>0</sub>))

Zero age main sequence

Red Giant

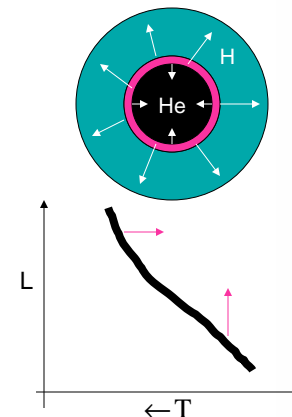
During this time the composition changes:



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

## EVOLUTION TO THE RED GIANT STAGE

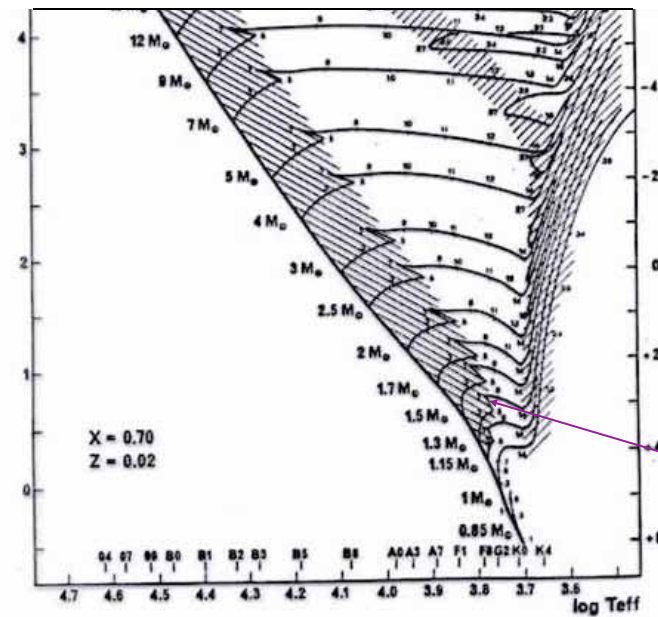
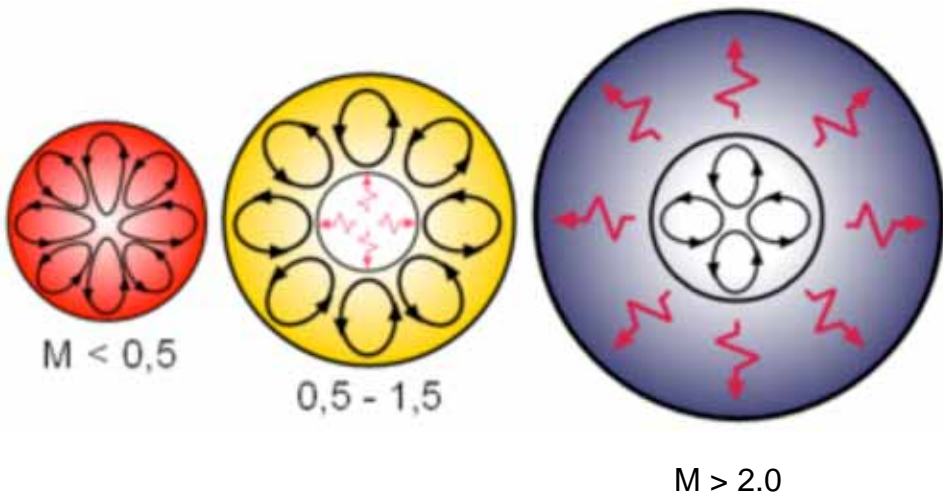
- Once hydrogen is exhausted in the center, the star is no longer a main sequence star. Hydrogen continues to burn however in a thick shell.
- (Helium) core contraction leads to heating of both the helium and the overlying hydrogen shell.
- This increases the rate of hydrogen burning in the shell ( $\epsilon \propto T^{20}$ ). 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 ( $M < 0.5 M_{\odot}$ ).
- 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  $\sim 4000$  K, but at varying luminosities. Once there, the extra luminosity of the H-shell translates into an increasing luminosity for the star itself.

All surfaces become convective

Recall convective structure on the main sequence

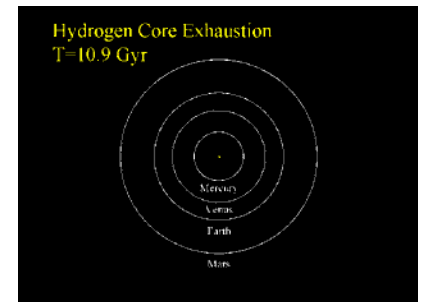
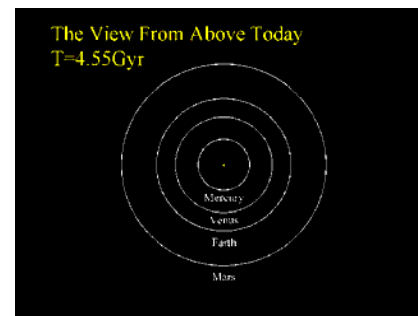
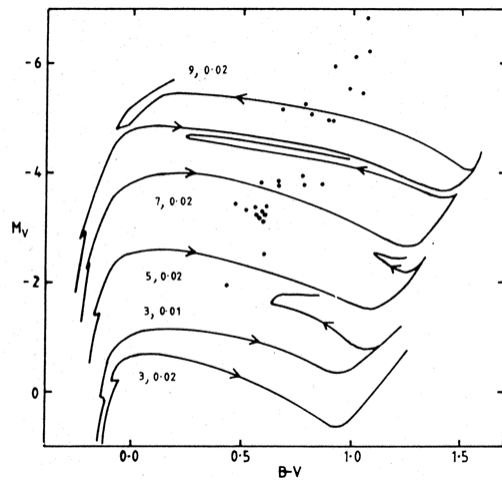


Evolution to Red Giant Stage

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

H-shell ignition

Type I Cepheids are shortlived-stages of massive stars as the cross the HR diagram on the way to becoming red giants.

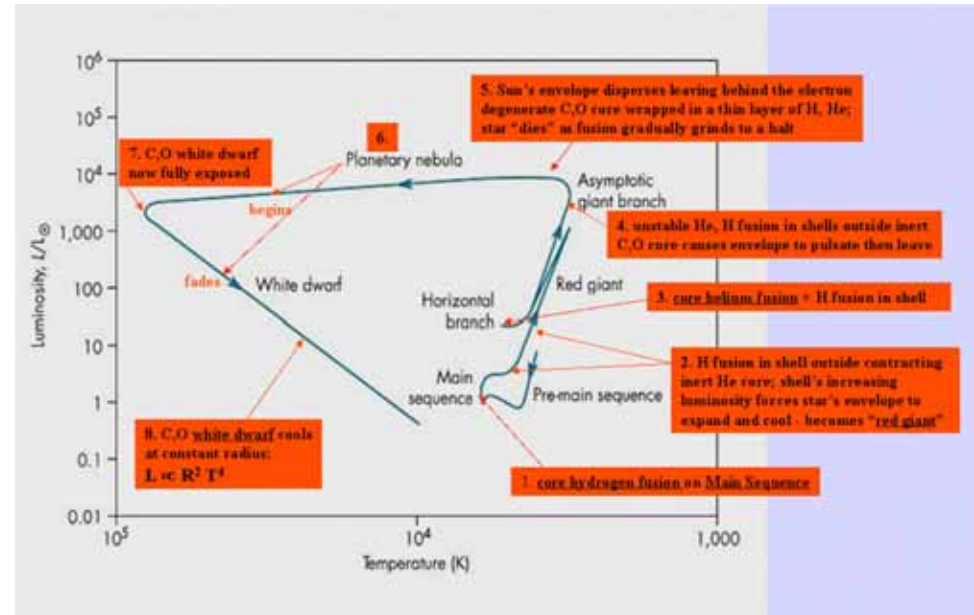


## The Seven Ages of the Sun

- 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

## Helium Burning and Beyond

## Evolution in HR Diagram

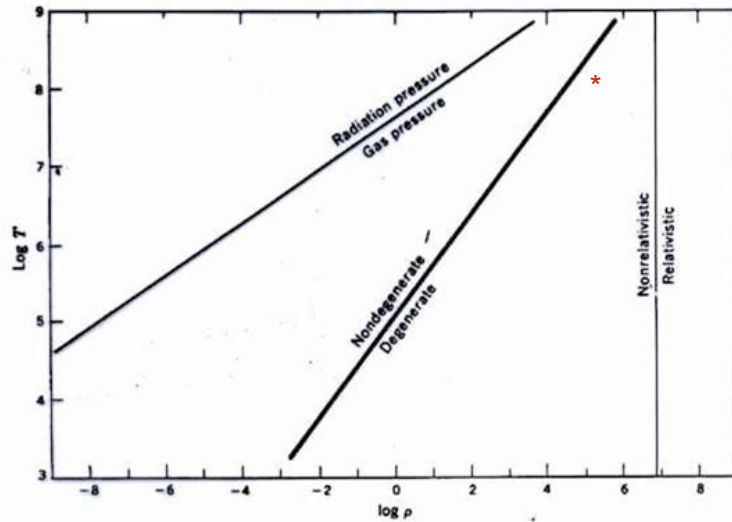


## HELIUM IGNITION

- 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*

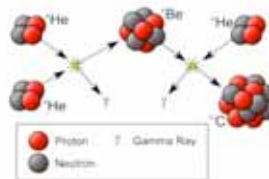
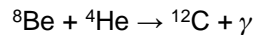
- Heavier stars ignite helium burning at about 150 million K (hotter in bigger stars). Between  $0.5$  and about  $2 M_{\odot}$ , helium ignites in a *helium flash* - a degenerate thermonuclear runaway.



- For example the sun first ignites helium burning at about  $10^5 \text{ g cm}^{-3}$ . 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.

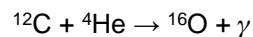
[http://en.wikipedia.org/wiki/Helium\\_flash](http://en.wikipedia.org/wiki/Helium_flash)

### Helium Burning

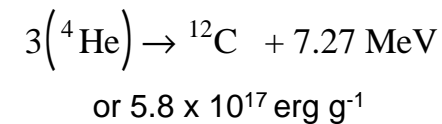


Helium burning, often called the triple alpha process occurs above temperatures of 100,000,000 K.  ${}^8\text{Be}$  is unstable and decays back into He in  $2.6 \times 10^{-16}$  secs, but in the stellar interior a small equilibrium of  ${}^8\text{Be}$  exists. The  ${}^8\text{Be}$  ground state has 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:



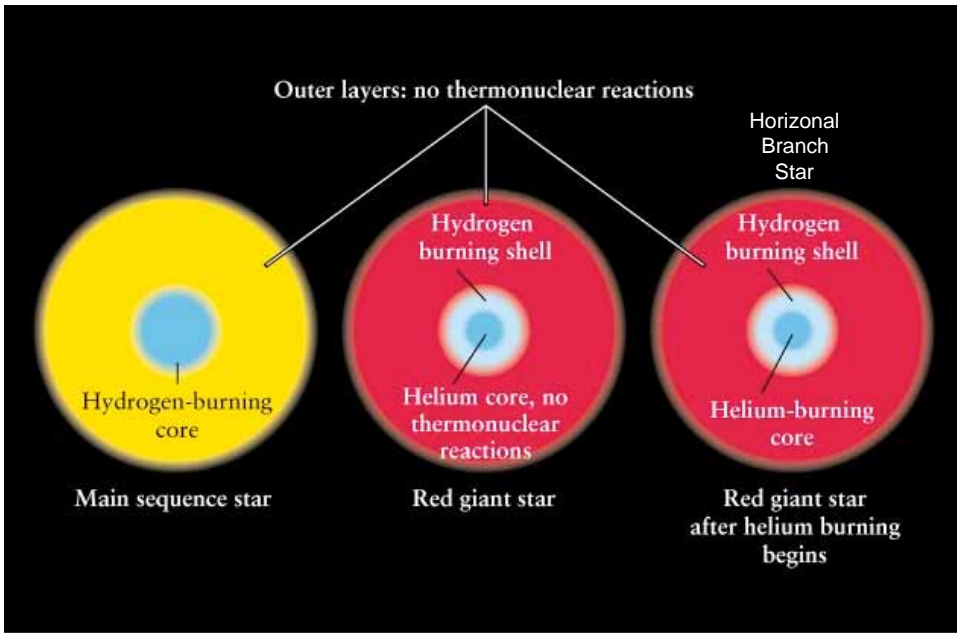
The net result is:



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.

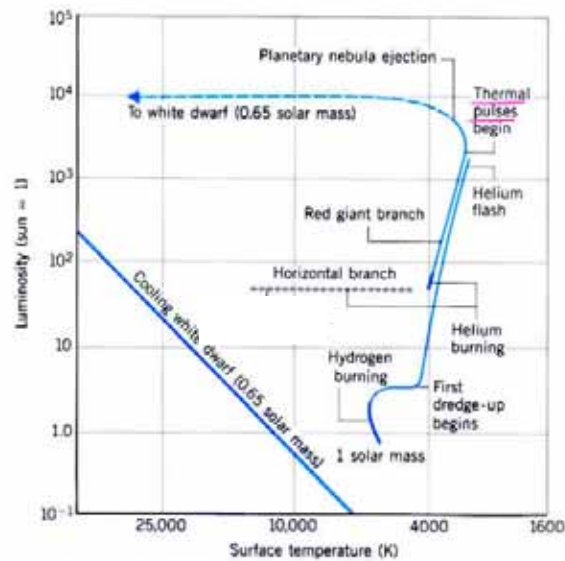




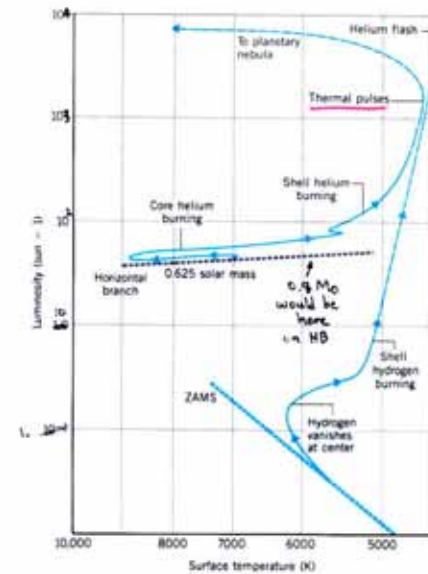
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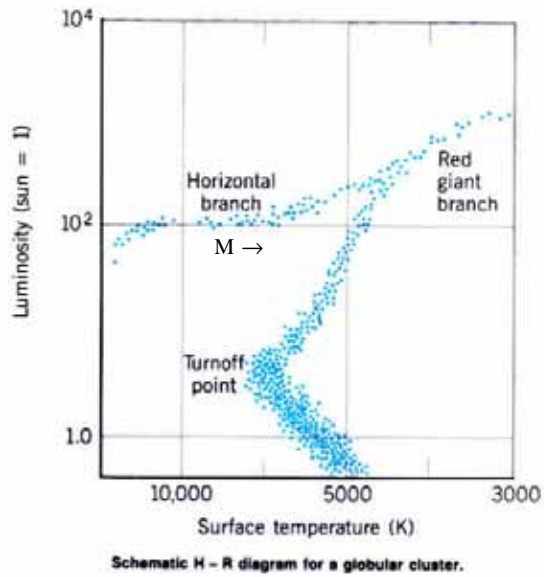
## The Sun



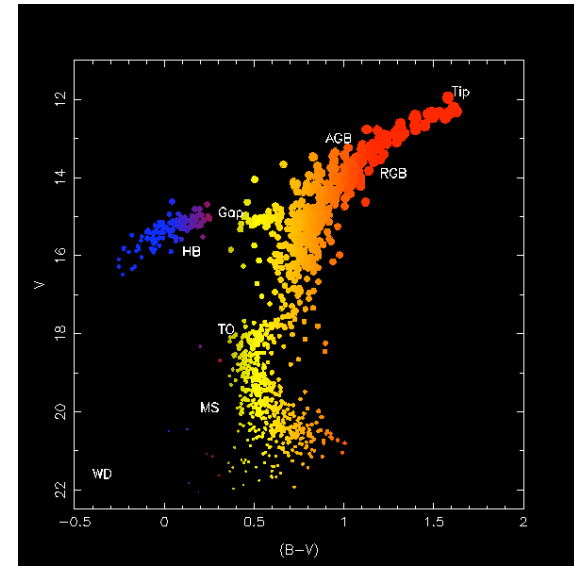
The readjustment of the red giant to a horizontal branch star takes about 2 My after the He core flash (Kelvin Helmholtz time for the hydrogen envelope)



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



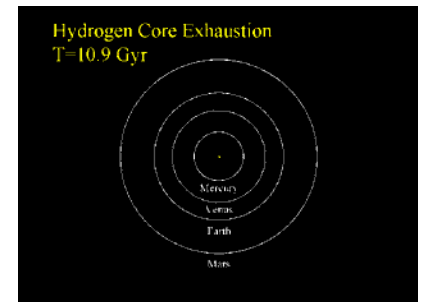
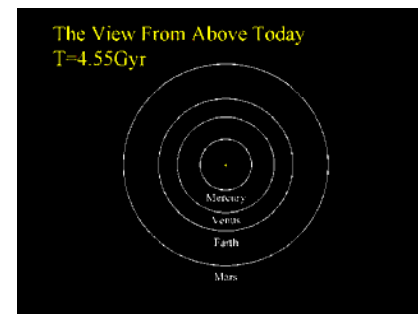
Globular Cluster M5  
[http://www.dur.ac.uk/ian.smail/gcCm/gcCm\\_intro.html](http://www.dur.ac.uk/ian.smail/gcCm/gcCm_intro.html)

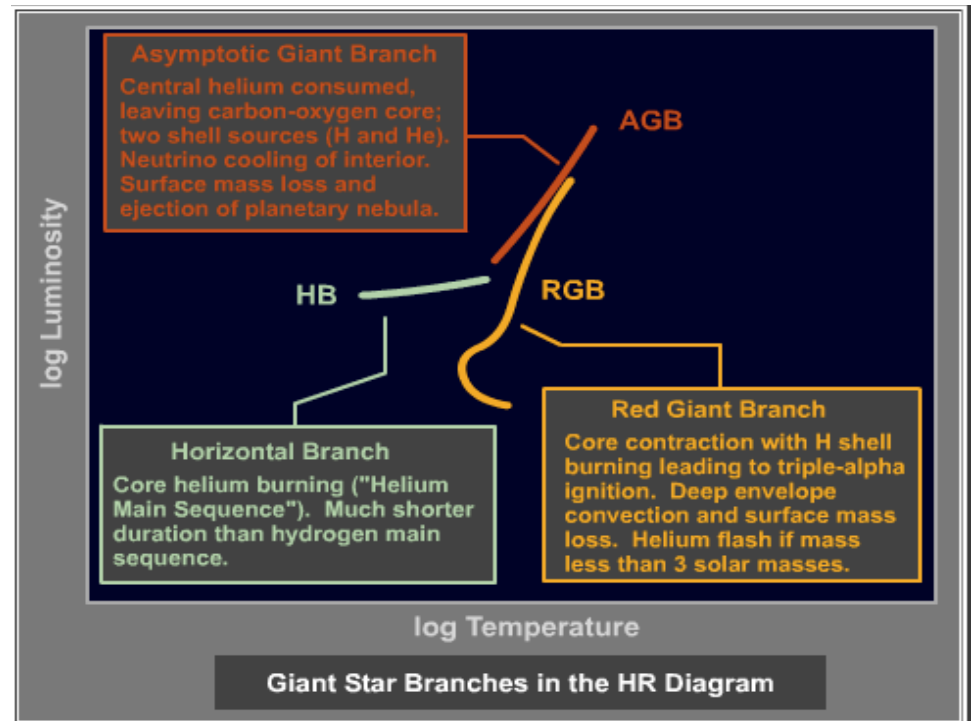
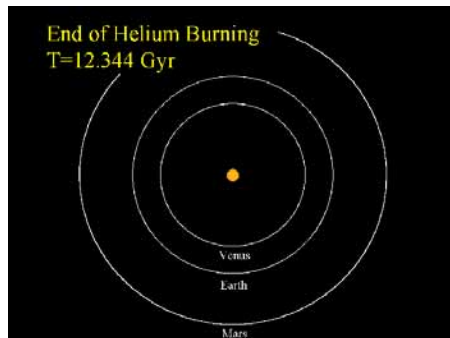
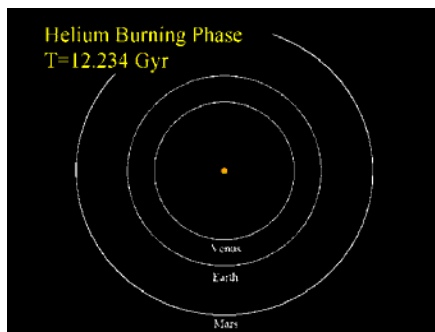


TO = “turn off mass”; HB = “horizontal branch”;  
 “Gap” is a region of atmospheric instability

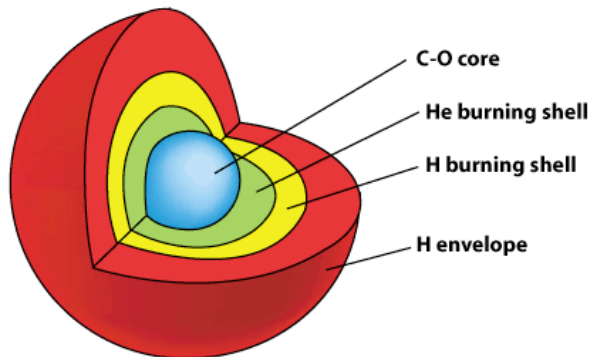


The globular cluster M10. The bright yellow and orange stars are red giants burning hydrogen or helium in a shell, but the bright blue stars are “horizontal branch” stars, burning helium in their centers. Both kinds of stars are more massive and brighter than the low mass main sequence stars in M10.





## AGB STARS



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 both at this diagram suggests. The outer layers are convective. The C-O core is degenerate and transports its radiation by conduction.

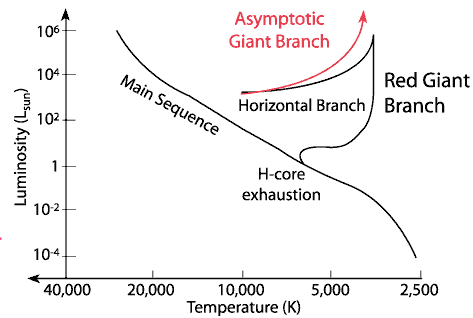
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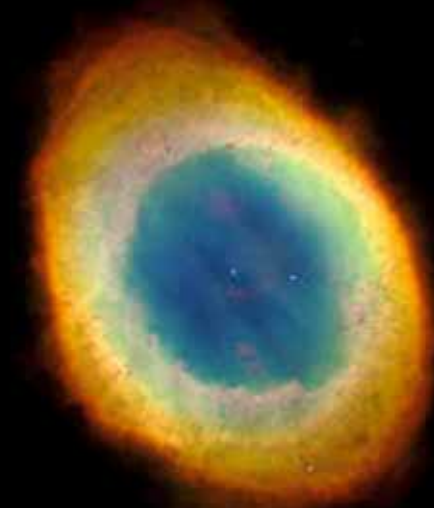
AGB stars are known to lose mass at a prodigious rate during their final stages, around  $10^{-5}$  -  $10^{-4}$  solar masses per year. This obviously cannot persist for much over 100,000 years.

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.*



[http://en.wikipedia.org/wiki/Ring\\_Nebula](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. End of life for 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  $\text{cm}^3$ ; 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

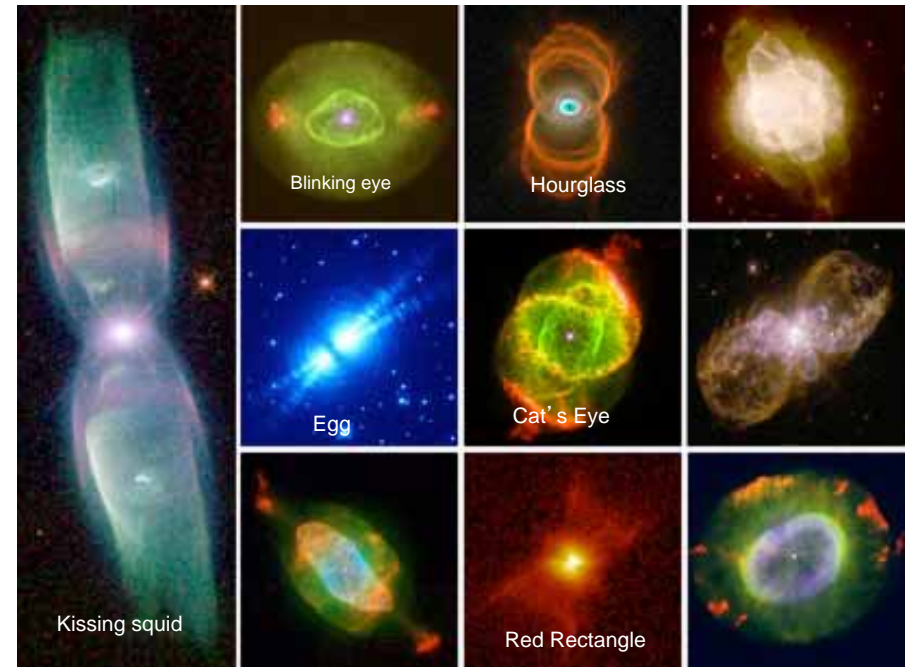
## PLANETARY NEBULAE

- 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.



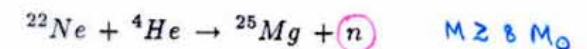
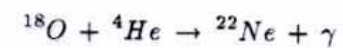
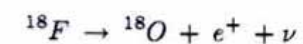
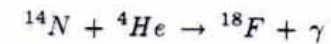
Note the consequences for nucleosynthesis here.

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. It is thought that stars in this mass range are responsible for producing most of the **nitrogen** and maybe 60 – 80% of the **carbon** in the universe.

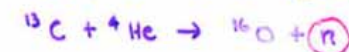
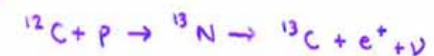
The rest of carbon and most other elements comes from massive stars.

Additional Nucleosynthesis – The s-Process.

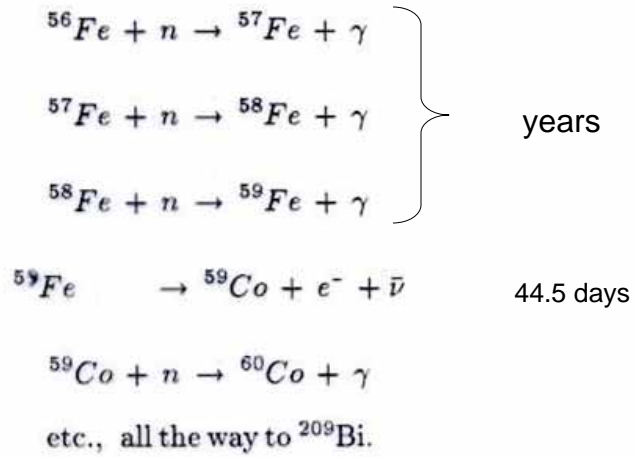
- During helium burning:



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

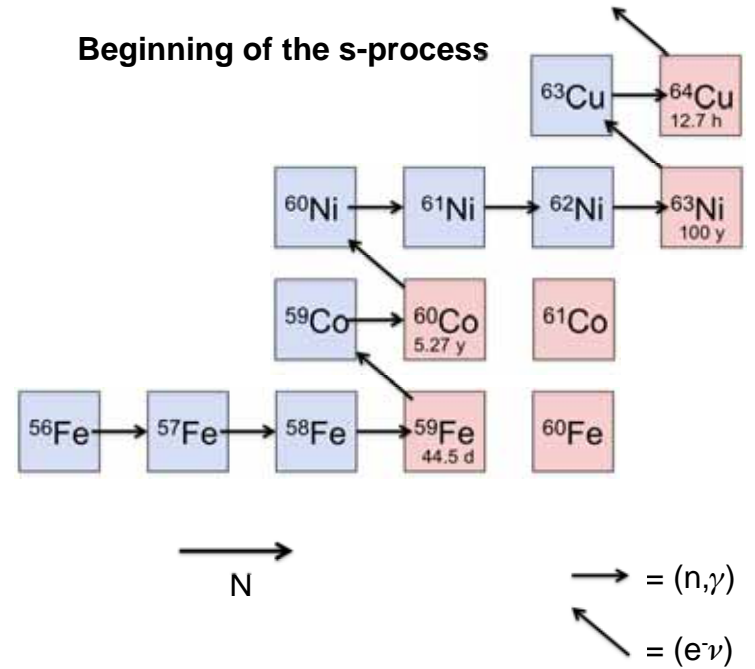


Where do the neutrons go?

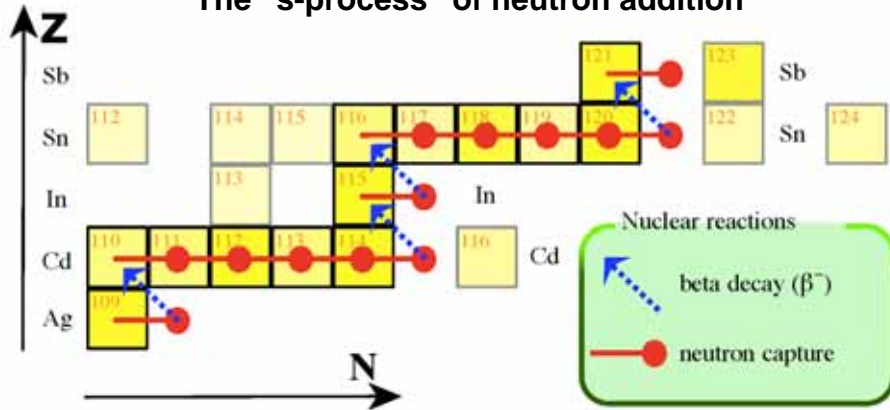


This is called the “slow” process of neutron addition or the “s-process”. (There is also a “r-process”)

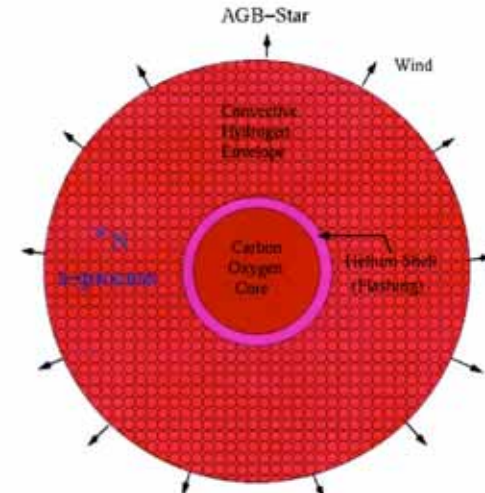
### Beginning of the s-process



### 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.



CO-core temperature about  $5 \times 10^8$  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.