Lecture 9: Post-main sequence evolution of stars

- Lifetime on the main sequence
- Shell burning and the red giant phase
- Helium burning - the horizontal branch and the asymptotic giant branch
- The death of low mass stars - planetary nebulae and white dwarfs
- Summary - the evolution of our Sun

Lifespan on the main sequence

Lifetime of core H burning phase (where *f*=fraction of mass converted to energy) $t = \frac{fMc^2}{L}$

From the mass-luminosity relation $L \propto M^{3.5}$

It follows that $t \propto \frac{M}{M^{3.5}} \propto M^{-2.5}$

So, since the MS lifetime of the sun is ~12 Gyr, $t \approx 12 \left[\frac{M}{M_\odot}\right]^{-2.5}$ Gyr

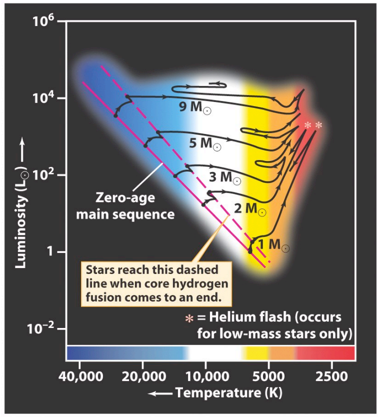
table 21-1 Approximate Main-Sequence Lifetimes

Mass ($M_\odot$)	Surface temperature (K)	Spectral class	Luminosity ($L_\odot$)	Main-sequence lifetime (10^6 years)
25	35,000	O	80,000	4
15	30,000	B	10,000	15
3	11,000	A	60	800
1.5	7000	F	5	4500
1.0	6000	G	1	12,000
0.75	5000	K	0.5	25,000
0.50	4000	M	0.03	70,000

The main-sequence lifetimes were estimated using the relationship $t \propto 1/M^{2.5}$ (see Box 21-2).

Evolution on the main sequence

- The evolution can be understood using the virial theorem
$$<T>= \frac{\eta G M \mu}{3kR}$$
- As H is converted into He in the stellar core the mean particle mass μ rises
- The mean internal temperature is approximately constant, since the nuclear reactions are very temperature sensitive
- Hence if μ rises at constant <T>, it follows that R must increase, and hence L ($\propto R^2$) also rises

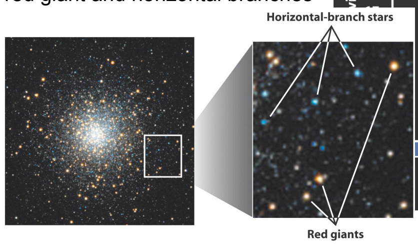


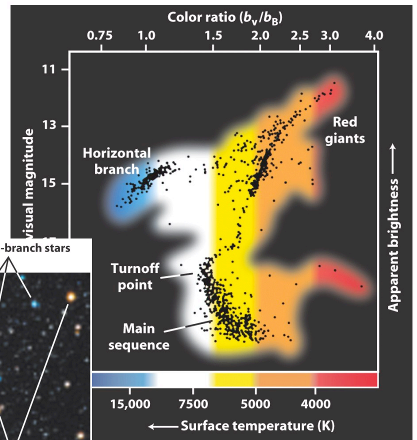
Post–main-sequence evolutionary tracks of five stars with different mass

Evolution after the main sequence

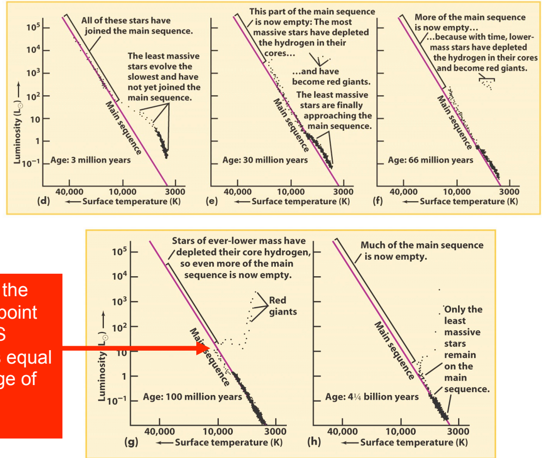
Clues to what happens to stars once their core hydrogen is exhausted, come from studying the H-R diagram of an old star cluster (e.g. a globular cluster).

The bottom of the main sequence is still present, but more massive stars have evolved off onto the red giant and horizontal branches





Evolution of cluster H-R diagrams

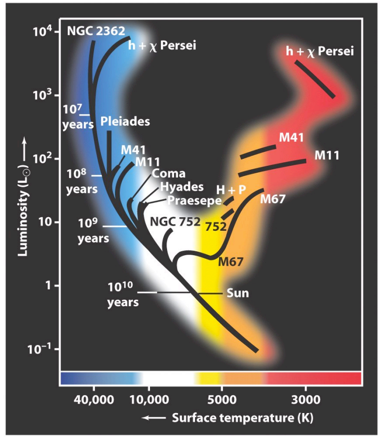


Stars at the turn-off point have MS lifetimes equal to the age of the star cluster

H-R diagrams for clusters of different ages - a range of MS turn-off points

Older clusters have progressively shorter main sequences, and lower turn-off points.

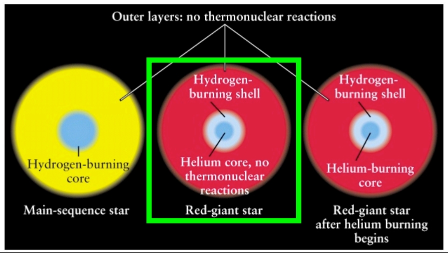
How do stars actually move on the H-R diagram once they turn off the main sequence?

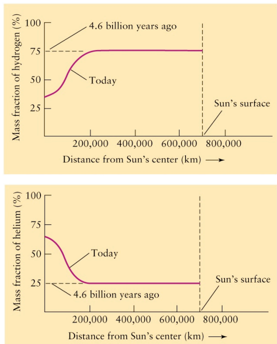


Life after the main sequence

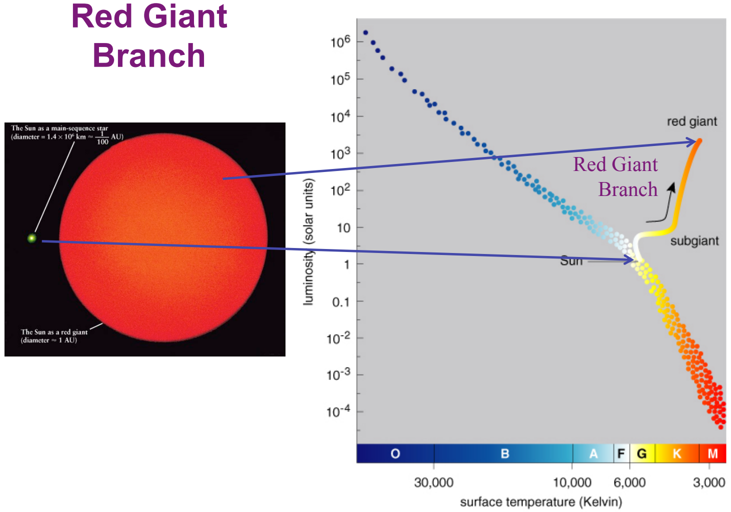
When all H in the core has been exhausted, the fusion reaction switches to an H-burning shell surrounding the now inert He core.

This core contracts (having no internal energy source), and so T_0 rises, and the extra energy released in the H-burning shell causes the outer envelope of the star to expand - the star becomes a red giant.



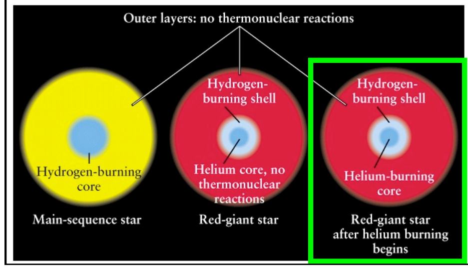


Red Giant Branch



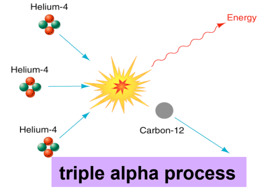
Onset of helium burning

- As the inert core of a red giant star progressively shrinks, its temperature rises (the virial theorem again)
- When the central temperature reaches about 10^8 K, helium fusion begins in the core
- This process, also called the triple alpha process, converts helium to carbon and oxygen

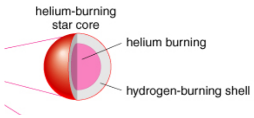


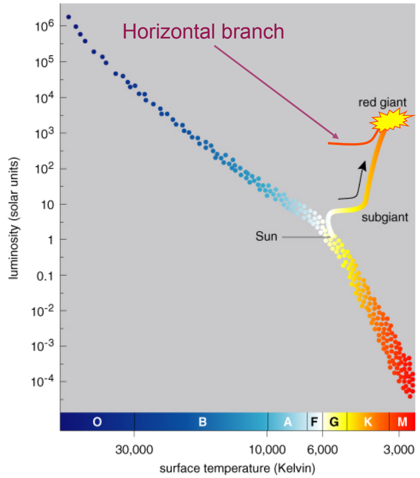
- In stars with masses less than 2-3 $M_\odot$, the start of He burning is explosive, and is called the helium flash
- This leads to a sudden change in the star's structure

Helium flash and the horizontal branch



Following helium ignition the star becomes smaller and hotter, settling onto the horizontal branch, fusing He→C in its core and H→He in a shell.

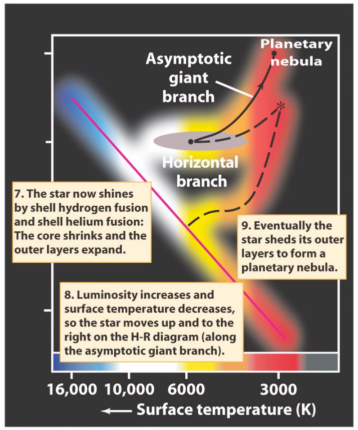




Exhaustion of core helium and ascent of the asymptotic giant branch

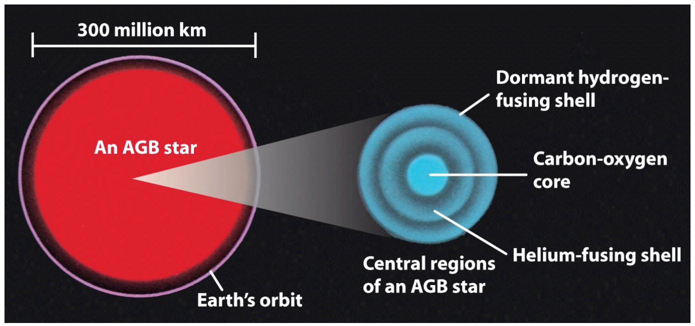
When He is exhausted in the core (converted to C and O), helium burning switches to a surrounding shell.

The star then swells in much the same way as in the earlier red giant phase, and ascends the asymptotic giant branch on the H-R diagram.



After core helium fusion ends: An AGB star

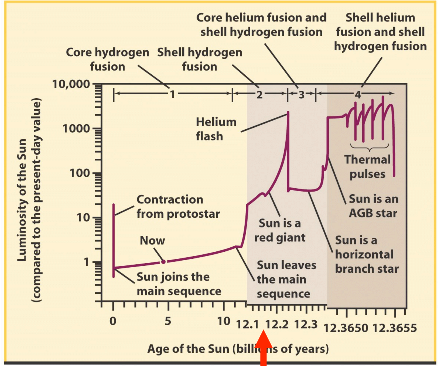
Dredge-ups bring the products of nuclear fusion to a giant star's surface



- During the AGB phase, convection occurs over a larger portion of the star's volume
- This takes heavy elements formed in the star's interior and distributes them throughout the star

The death of low-mass stars, and creation of planetary nebulae

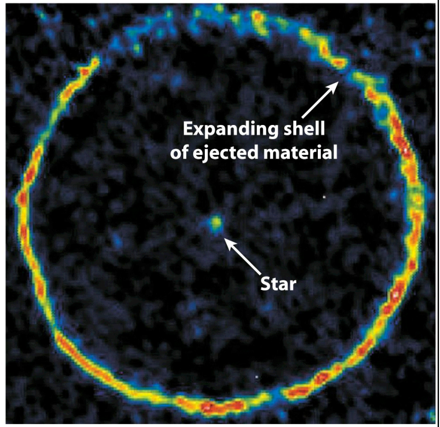
- Helium shell flashes in an old, low-mass star produce thermal pulses during which more than half the star's mass may be ejected into space



note the changes in timescale here

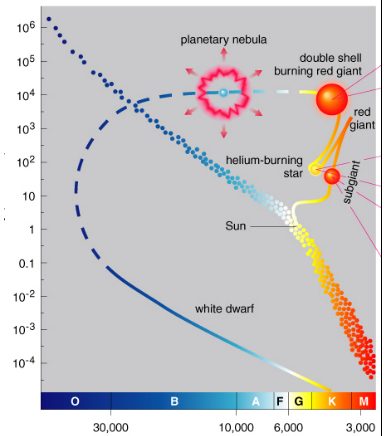
The death of low-mass stars, and creation of planetary nebulae

- Helium shell flashes in an old, low-mass star produce thermal pulses during which more than half the star's mass may be ejected into space
- This exposes the hot carbon-oxygen core of the star
- Ultraviolet radiation from the exposed core ionizes and excites the ejected gases, producing a planetary nebula



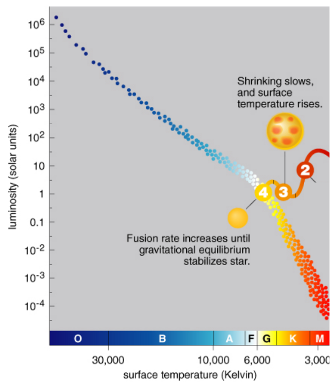
The end of the road...

- Ejection of the stellar atmosphere leaves the compact carbon-oxygen core.
- The drastic shrinkage of the star leads to a dramatic drop in luminosity.
- What remains is a white dwarf star, in the lower left portion of the H-R diagram.

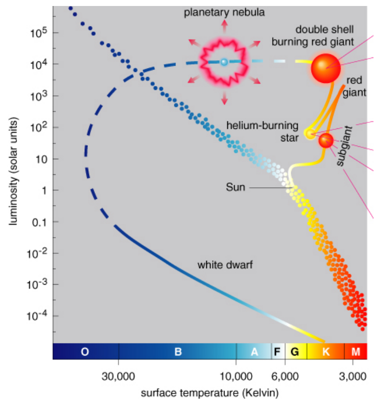


Our Sun's evolution: summary

Past



Future



Our Sun's Evolution

- 5.0 billion years ago: the Solar Nebula begins to form out of a cloud of cold interstellar gas and dust
- 10,000-100,000 years later: Sun is a protostar, a protoplanetary disk forms around it
- 30-40 million years later: Sun begins fusing hydrogen to helium in its core; at around the same time planetesimals in the solar nebula begin to form planets
- 10-20 million years later: Sun settles onto the main sequence as a G2 star with a surface temperature of 5800 K
- 5 billion years from now: our sun begins to leave the main sequence. The He core shrinks and H to He fusion occurs in a shell around the hot He core. The Sun is now a red giant.
- ~100 million years later: He flash: the sun's core will fuse He to C in the core and settle onto the horizontal branch.
- ~100 million years later: When the core runs out of helium, the sun will extend up the asymptotic branch. The sun will become so luminous that it will blow off its outer envelope.
- 10,000 years later: nuclear reactions in the carbon core stop and we are left with a white dwarf. The outer envelope is illuminated by the white dwarf producing a planetary nebula.