Lecture 16: Evolution of Low-Mass Stars

Readings: 21-1, 21-2, 22-1, 22-3 and 22-4

For the protostar and pre-main-sequence phases, the process was the same for the high and low mass stars, and the main difference was the speed with which they went through the various stages.

On the main sequence, high and low mass stars are again quite similar. They fuse H to He in their cores, have cooler envelopes, and are in hydrostatic and thermal equilibrium. There are some differences: energy transport, CNO vs. proton-proton and lifetime on the main-sequence, but both high and low mass stars pass through this phase.

However, once stars leave the main-sequence, high and low mass stars have very different paths. And the key difference is whether they end their lives as white dwarfs or as neutron stars/black holes.

We look first at the evolution of low-mass stars after the main-sequence

Key Ideas

Low Mass Star = $M < 8\ M_{sun}$

Stages of Evolution of a Low Mass Star
- Main Sequence star
- Red Giant star
- Horizontal Branch star
- Asymptotic Giant Branch star
- Planetary Nebula phase
- White Dwarf

Please note that after the Red Giant phase, the names of the phases are exceedingly unhelpful and the result of history. But you'll need to learn them nonetheless.

Main Sequence Phase

Energy Source: H fusion in the core

What happens to the He from H fusion?

- Too cool to ignite He fusion

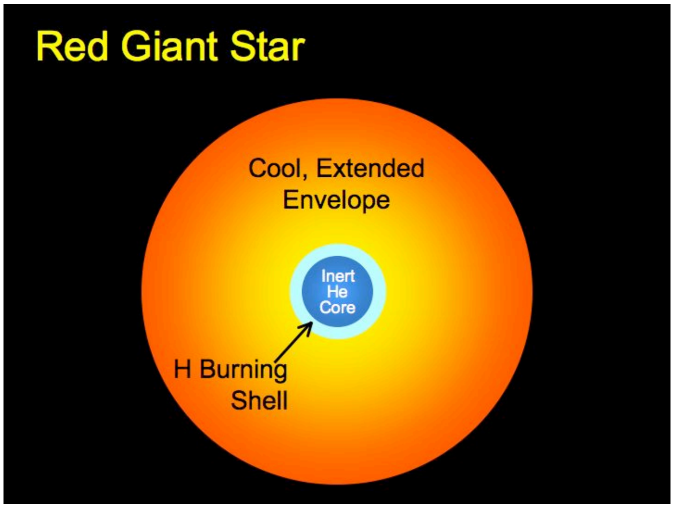
Slowly build up an inert He core

M-S Lifetime
~10 Gyr for a 1 M_{Sun}
~10 Tyr for a 0.1 M_{Sun} (red dwarf or M dwarf)

Hydrogen Exhaustion

Inside:
Loss of pressure=end of hydrostatic equilibrium
He core collapses & heats up
H burning zone shoved out into a shell
Collapsing He core heats the H shell above it, driving the fusion faster

Outside
Envelope expands and cools
Star gets *brighter* and *redder*
Becomes a **Red Giant Star**



Climbing the Red Giant Branch

See the path of the star as it moves up the red giant branch
Figure 22-1 (a)

Takes ~1 Gyr (= 1 billion years) to climb the Red Giant Branch
He core contract & heats, but no fusion

H burning to He in a shell around the core
Huge, puffy envelope ~ 0.7 AU in radius

Top of the Red Giant Branch
T_{core} reaches 100 Million K
Ignites core He burning in a Helium Flash

The Sun as a Red Giant

When the Sun becomes a Red Giant, Mercury and Venus will be vaporized, the Earth burned to a crisp. Long before the Sun reaches the tip of the red giant branch, the oceans will be boiled away and most life will be gone.

The most "Earthlike" environment at this point will be Titan, a moon of Saturn.

Helium Flash-Pt 1

Triple-alpha Process

Fusion of 3 ^{4}He nuclei into 1 ^{12}C nucleus (carbon)

$$^4\mathrm{He} + {}^4\mathrm{He} \rightarrow {}^8\mathrm{Be} + \gamma$$
$$^4\mathrm{He} + {}^8\mathrm{Be} \rightarrow {}^{12}\mathrm{C} + \gamma$$

Secondary reaction with ^{12}C makes ^{16}O

$$^4\mathrm{He} + {}^{12}\mathrm{C} \rightarrow {}^{16}\mathrm{O} + \gamma$$

So why don't we talk about He fusing into ^{8}Be? Why is there so little Be in the Universe?

^{8}Be is unstable to radioactive decay. With a half life of 7×10^{-17} seconds, it decays back to 2 ^{4}He nuclei (^{9}Be is the only stable isotope). So unless during that fraction of a second, the ^{8}Be nucleus can fuse with a ^{4}He nucleus, it will disassemble into He nuclei again and we will be back to where we started.

Degeneracy Pressure
Degeneracy pressure is important at high densities.
Degeneracy pressure depends only on the density. It is independent of the temperature.

Maximum pressure that electrons can exert.

Helium Flash – Pt 2.

When the core of stars with $M < 4M_{sun}$ reach temperatures hot enough to fuse He into C, O, degeneracy pressure is important in the cores of the stars. Therefore, when the He ignites, there is no thermostat because the pressure in the core does not depend on the temperature. So the core does not expand and the temperature does not drop.

T rises -> rate of nuclear fusion increases -> T rises -> rate of nuclear fusion increases.

Runaway nuclear reaction releases 10^{11} L_{Sun}. This provides enough energy to finally expand the core and reduce the density enough that degeneracy pressure is not important. The ideal gas law now provides the pressure and the thermostat is back in action. The energy created in the helium flash takes millions of years to leak out of the star, so this very interesting phenomenon in the center of the star does not lead to an optical flash for observers outside the star.

Leaving the Giant Branch

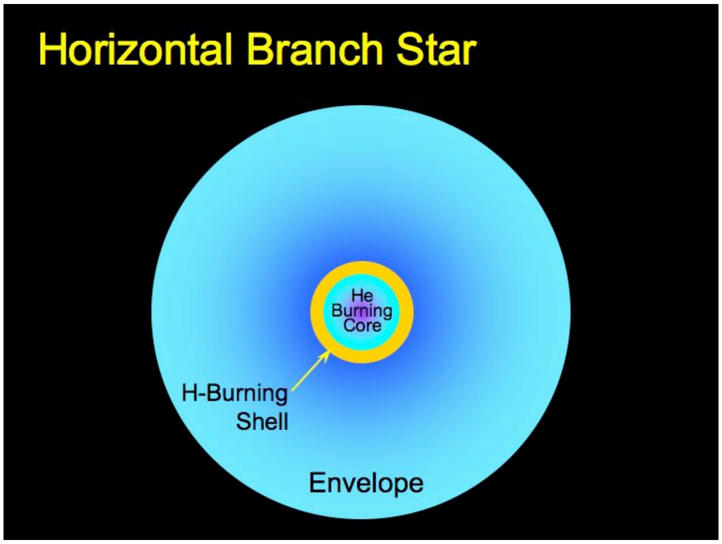
Inside

- Primary energy: He burning *core*
- Additional energy: H burning *shell*
- Inert envelope

Outside

- Gets hotter and bluer
- Star shrinks in radius, getting fainter

Moves onto the Horizontal Branch



Path on the HR diagram after the helium flash to the horizontal branch
Figure 22-1 (b)

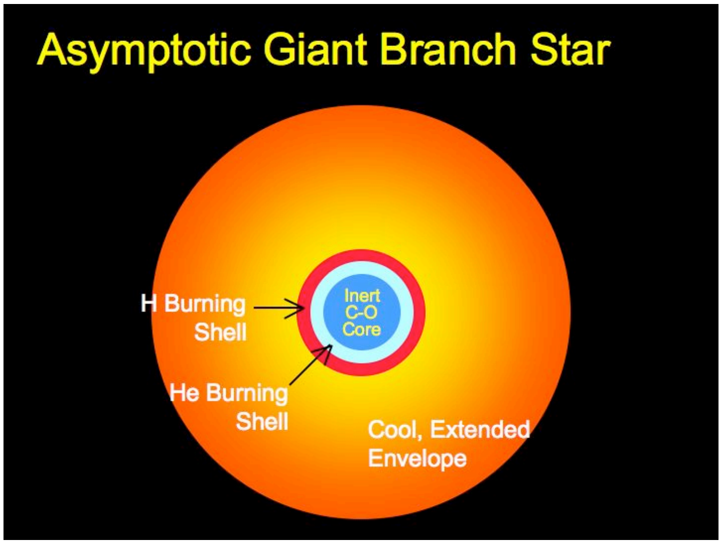
Horizontal Branch Phase
Structure:
    He-burning core
    H-burning shell
Triple-alpha Process is inefficient (mass of ^{12}C only slightly less than mass of 3 ^{4}He nuclei)
    Only lasts for ~100 Myr

Build up a massive C-O core, but it's too cool to ignite Carbon fusion

Asymptotic Giant Branch

After 100 Myr, core runs out of He
    C-O core collapses & heats up
    He burning shell
    H burning shell

Star swells and cools
    Climbs the Giant Branch again, but at higher temperature



Path of the Asymptotic Giant Branch star on the HR diagram
Figure 22-1 (c)

Higher Mass Lower Mass Stars

For stars that start with M>4 M_{Sun}, (but < 8M_{Sun}), it gets hot enough in the cores to avoid the He flash and start C fusion. They still end their lives as white dwarfs, but they are made up of O, Ne and Mg (the products of C fusion) rather than C and O. Degeneracy pressure still supports them.

The Instabilities of Old Age

He burning is very temperature sensitive
Triple-alpha fusion rate $\propto T^{40}$

Consequences:
Small changes in T lead to large changes in fusion energy output

Huge *Thermal Pulses* destabilize the outer envelope.

Core-Envelope Separation

Rapid Process: ~10^5 years

Outer envelope ejected in a fast wind

C-O Core continues to contract

- With less envelope weight above, gravity is not compressing the core and the C-O core does not heat up as much
- Never reaches the 600 million K Carbon Ignition temperature

Core and Envelope Separate

Planetary Nebula Phase

Expanding envelope forms a nebula around the contracting C-O core

- Ionized and heated by the hot central core
- Expands away to nothing in ~10^4 years

Planetary Nebula—has nothing to do with planets, but looked like a planet when observed through early telescopes because they are not points.

Hot C-O core is exposed, moves to the left on the H-R Diagram

Figure 22-10

Planetary Nebula are

- Pretty
- Emission Line objects
- They carry the elements produced in low mass stars back into space. ½ of the carbon in the solar system came from lower mass stars.

Core Collapse to White Dwarf

Contracting C-O core becomes so dense that it becomes degenerate again.

Reaches hydrostatic equilibrium when Degeneracy Pressure balances Gravity.

Collapse halts at $R \sim 0.01\ R_{sun}$ ($\sim R_{earth}$)

At this stage, the star is called a white dwarf star.

SUMMARY

Stage	Energy Source
Main Sequence	H burning Core
Red Giant	H burning Shell
Horizontal Branch	He Core + H Shell
Asymptotic Giant	He Shell + H Shell
White Dwarf	None!

The Seven Ages of the Sun

Main Sequence Star: 11 Gyr
Red Giant Star: 1.3 Gyr
Horizontal Branch Star: 100 Myr
Asymptotic Giant Branch Star: 20 Myr
Thermal Pulsation Phase: 400,00 yr
Planetary Nebula Phase: ~10,000 yr
0.54 M_{su} White Dwarf: final state…..