The Evolution of Low Mass Stars

Key Ideas:

Low Mass = M < 4 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 star

Main Sequence Phase

Energy Source: H fusion in the core

What happens to the He created by H fusion?

• Too cool to ignite He fusion
• Slowly build up an inert He core

Lifetime:

~10 Gyr for a 1 M_{sun} star (e.g., Sun)
~10 Tyr for a 0.1 M_{sun} star (red star)
~15 Myr for a 15 M_{sun} star (blue star)

Hydrogen Exhaustion

Inside: He core collapses & heats up.

Collapsing core heats the H shell above it, starting H fusion in a shell

H burning zone shoved into a shell

More fusion, more heating. Pressure > Gravity

Outside: Envelope expands and cools

Star gets brighter and redder.

Becomes a Red Giant Star

Red Giant Star
Climbing the Red Giant Branch

- Takes ~1 Gyr to climb the Red Giant Branch
  - He core contracting & heating, but no fusion
  - H burning to He in a shell around the core
  - Huge, puffy envelope ~ size of orbit of Venus

Top of the Red Giant Branch:
  - $T_{\text{core}}$ reaches 100 Million K
  - Ignite He burning in the core in a flash.

Helium Burning

Triple-$\alpha$ Process:

- Fusion of 3 $^4\text{He}$ nuclei into $^{12}\text{C}$ (Carbon):
  \[
  ^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} + \gamma
  \]
  \[
  ^4\text{He} + ^8\text{Be} \rightarrow ^{12}\text{C} + \gamma
  \]

- Secondary reaction with $^{12}\text{C}$ makes $^{16}\text{O}$ (Oxygen):
  \[
  ^4\text{He} + ^{12}\text{C} \rightarrow ^{16}\text{O} + \gamma
  \]

Lecture 14 ended here

Helium Flash

- Electron degeneracy pressure
- Degenerate electrons do not behave like perfect gas.
- Pressure and temperature do not go hand in hand
- This leads to runaway nuclear reactions (like a bomb)

Horizontal Branch

- Outer layers: no thermonuclear reactions
- Hydrogen-fusing core
- Hydrogen-fusing shell
- Helium core, no thermonuclear reactions
- Helium-fusing core
- Red-giant star after helium fusion begins
Leaving the Giant Branch

**Inside:**
- Primary energy from He burning core.
- Additional energy from an H burning shell.

**Outside:**
- Star shrinks in radius, getting fainter.
- Gets hotter and bluer.

Moves onto the **Horizontal Branch**

Horizontal Branch Phase

**Structure:**
- He-burning core
- H-burning shell

Triple-$\alpha$ Process is inefficient, can only last for $\sim$100 Myr.

Build up a C-O core, but too cool to ignite Carbon fusion.

Asymptotic Giant Branch

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

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

**Asymptotic Giant Branch Star**
The Instabilities of Old Age

He burning is very temperature sensitive: Triple-\(\alpha\) fusion rate \(\sim T^{40}\)

Consequences:
- Small changes in T lead to
- Large changes in fusion energy output

Star experiences huge Thermal Pulses that destabilize the outer envelope.

Core-Envelope Separation

Rapid Process: takes \(\sim 10^5\) years

Outer envelope gets slowly ejected (fast wind)

C-O core continues to contract:
- with weight of envelope taken off, heats up less
- never reaches Carbon ignition temperature of 600 Million K

Core and Envelope go their separate ways.

Planetary Nebula Phase

Expanding envelope forms a ring nebula around the contracting C-O core.
- Ionized and heated by the hot central core.
- Expands away to nothing in \(\sim 10^4\) years.

Planetary Nebula

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

Core Collapse to White Dwarf

Contracting C-O core becomes so dense that a new gas law takes over. **Degenerate Electron Gas:**
- Pressure becomes independent of Temperature
- $P$ grows rapidly & soon counteracts Gravity
Collapse halts when $R \sim 0.01 \, R_{\text{sun}} \approx R_{\text{earth}}$

White Dwarf
**Mass—Radius relation of a White Dwarf**

More massive a WD, smaller it is!

**Maximum mass of a WD**

There is a limit to the mass that can be supported by the pressure of degenerate electrons:

- Chandrasekhar Limit
  \[ = 1.4 \text{ solar masses} \]

→ All white dwarfs must have mass less than 1.4 solar masses.

**Summary of life of a low-mass star:**

<table>
<thead>
<tr>
<th>Stage</th>
<th>Energy Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proto-star</td>
<td>Gravitational contraction</td>
</tr>
<tr>
<td>Main Sequence</td>
<td>H Burning Core</td>
</tr>
<tr>
<td>Red Giant</td>
<td>H Burning Shell</td>
</tr>
<tr>
<td>Horizontal Branch</td>
<td>He Core + H Shell</td>
</tr>
<tr>
<td>Asymptotic Giant</td>
<td>He Shell + H Shell</td>
</tr>
<tr>
<td>White Dwarf</td>
<td>None!</td>
</tr>
</tbody>
</table>

**What happens to the helium-rich core of a star after the core runs out of hydrogen (mention the main stage)**

A) It contracts and heats up  
B) It expands and cools down  
C) It heats up and expands  
D) It cools down and contracts

**When is electron-degeneracy pressure important in a low-mass star?**

1) When He is burning in the core  
2) During core H-burning  
3) Just before the start of core He burning  
4) In a proto-star evolving toward the main sequence

**What makes a red giant star so large?**

A) It has many times more mass than the Sun  
B) The He-rich core has expanded, pushing the outer layers of the star outward.  
C) Centrifugal force pushes the surface outwards.  
D) The H-burning shell heats the envelop making it expand.
What happens to a low-mass star after the start of core He-burning?

It becomes:
A) Larger & cooler
B) Smaller & hotter
C) Larger & hotter
D) Smaller & cooler

In terms of a low-mass star’s evolutionary life, an asymptotic giant branch star is in the phase of:

A) He shell burning
B) He core burning
C) H core burning
D) C core burning

What is the event that follows the asymptotic giant branch phase in the life of a low-mass star?

A) He-flash
B) Onset of C burning
C) The ejection of a planetary nebula
D) Supernova explosion

A planetary nebula is:

A) An expanding gas shell surrounding a hot white dwarf
B) A gas cloud around a newly formed star in which planets are forming
C) A nebula caused by the explosion of a star
D) A gas cloud surrounding a planet