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

\[ t = \frac{f Mc^2}{L} \]

From the mass-luminosity relation

\[ L \propto M^{3.5} \]

It follows that

\[ t \propto M^{-2.5} \]

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

<table>
<thead>
<tr>
<th>Mass (M_\odot)</th>
<th>Spectral class</th>
<th>Luminosity (L_\odot)</th>
<th>Main-sequence lifetime (10^6 years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>8</td>
<td>O</td>
<td>30,000</td>
<td>4</td>
</tr>
<tr>
<td>3</td>
<td>A</td>
<td>10,000</td>
<td>11</td>
</tr>
<tr>
<td>1.5</td>
<td>F</td>
<td>5</td>
<td>4500</td>
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<tr>
<td>1.0</td>
<td>G</td>
<td>1</td>
<td>12,000</td>
</tr>
<tr>
<td>0.75</td>
<td>K</td>
<td>0.5</td>
<td>23,000</td>
</tr>
<tr>
<td>0.5</td>
<td>M</td>
<td>0.05</td>
<td>78,000</td>
</tr>
</tbody>
</table>

The main sequence lifetimes were estimated using the relationship \( t = 5.2t^2 \) (see Box 21.2).

Evolution on the main sequence

- The evolution can be understood using the virial theorem

\[ \langle T \rangle = \frac{\eta GM\mu}{3kR} \]

- As H is converted into He in the stellar core the mean particle mass \( \mu \) rises
- The mean internal temperature is approximately constant, since the nuclear reactions are very temperature sensitive
- Hence if \( \mu \) rises at constant \( \langle T \rangle \), it follows that \( R \) must increase, and hence \( L \propto R^2 \) also rises

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

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.

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?

Red Giant Branch

- Red giant branch
- Red giant
- Core
- H-burning shell
- Main-sequence star
- Red-giant star after helium burning begins
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.

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.

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.

• 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.

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

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.