Lecture 24
Life as a Low Mass Giant

Dating the Stars
Shell vs Core Fusion
Helium Fusion
Planetary Nebulae

Reprise: Evolution Timescale

• To estimate the duration of any stage that depends on an energy source:
  – Energy available = Mass × Efficiency
  – Rate of energy use = Luminosity (Watts)

\[
\text{Lifetime} = \frac{\text{Energy Available}}{\text{Rate of Use}}
= \frac{\text{Efficiency} \times \text{Mass}}{\text{Luminosity}}
\]

• For the sun,
  – detailed models show it has 10% of its H available
  – we find M.S. lifetime = $10 \times 10^9$ yrs ("10 Gyr")

• For the rest of the main sequence, can do ratio with sun:

\[
\frac{\text{M.S. Lifetime}}{\text{Solar M.S. Lifetime}} = \frac{M}{M_{\text{sun}}} \times \frac{L}{L_{\text{sun}}}
\]
Reprise: Main Sequence Lifetime

So can complete our table for main sequence stars:

<table>
<thead>
<tr>
<th>Mass (M_{\odot})</th>
<th>Lum (L_{\odot})</th>
<th>Radius (R_{\odot})</th>
<th>Temp (deg K)</th>
<th>MS life (yrs)</th>
<th>Spec</th>
<th>Example</th>
</tr>
</thead>
<tbody>
<tr>
<td>40</td>
<td>5x10^5</td>
<td>18</td>
<td>40,000</td>
<td>8 Myr</td>
<td>O5</td>
<td>Zeta Pup</td>
</tr>
<tr>
<td>3.2</td>
<td>80</td>
<td>2.5</td>
<td>9900</td>
<td>400 Myr</td>
<td>A0</td>
<td>Vega</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>5800</td>
<td>10 Gyr</td>
<td>G2</td>
<td>Sun</td>
</tr>
<tr>
<td>0.1</td>
<td>8x10^{-4}</td>
<td>.13</td>
<td>2400</td>
<td>1000 Gyr</td>
<td>M7</td>
<td>Wolf 359</td>
</tr>
</tbody>
</table>

More massive stars last a much shorter time!

Evolution on the Main Sequence

- While on Main Sequence, there are slow changes:
- Zero-Age Main Sequence: first ignition of H in core.
- Evolution:
  - As 4H \rightarrow He in core, the number of gas particles is reduced.
  - For a "perfect gas" it takes a higher core temperature to maintain the same pressure.
  - As core temperature rises, fusion rate rises, so luminosity increases somewhat.
  - This is very important for understanding origin of life on earth. Sun's luminosity has grown at least 50% since birth of Earth. Planetary scientists having difficult time understanding why Earth was not in permanent ice age then!
After the Main Sequence

• When H runs out in core (core is about 10% of mass),
  – core starts contracting, heats up, starts H fusion in "shell" around core. Outer layers bloat out and cool off:
  – Star moves to right in HR diagram: Red Giant stage
  – It checks! Next most numerous stars to main sequence are Red Giants: correspond nicely to this stage.
  Duration of stage, 20% of Main Sequence lifetime.

• For sun, (in about 5 billion years)
  – Radius -> 1 AU (incinerating Mercury, Venus, and Earth)
  – Surface Temp -> 3500 K (very red)

Main sequence Turnoff: Cluster Age

**Verification**: Clusters. Can easily check this story by looking at HR diagrams of star clusters of different ages:

• As cluster ages, most massive stars run out of core Hydrogen first, moving to Red Giant stage: The point where stars are just leaving the Main Sequence is called "main sequence turnoff" point. [http://www.astro.ubc.ca/~scharein/a311/Sim.html](http://www.astro.ubc.ca/~scharein/a311/Sim.html)

  **The age of a cluster is just the main sequence lifetime of the stars at the main sequence turnoff**

  • This is about the only way astronomers have to estimate the age of objects outside the solar system!
  • Theoretical Cluster HR diagrams: age (in the computer) stars of a range of masses to the age of an observed cluster
Cluster facts

- **Young clusters** are always found near active star formation sites. (Seems logical)
- Middle-age clusters are usually "open" clusters: 100-1000 stars loosely bound together by gravity.
- **The oldest observed clusters are 13 billion years old.** They are **globular clusters**: Tight assemblages of 100's of thousands of stars.

Late Stages of Stellar Evolution

What happens next? Pretty complicated, but a few general things are clear:

- Stellar core staves off collapse for a while by fusion of heavier elements
- Some of stellar envelope ejected, either gradually or explosively
- Some kind of collapsed "remnant" left behind.
Helium fusion: Yellow Supergiant

As Hydrogen "shell" fusion continues, helium "ash" left behind in core continues to collapse and heat up.

- The core temperature gets to about 100 million K (!) and the He begins to fuse to still heavier elements C,O
  
  $^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be}$ (Beryllium)
  
  $^8\text{Be} + ^4\text{He} \rightarrow ^{12}\text{C}$ (Carbon)

- Since Helium nuclei are known to physicists as "alpha particles" this is called the "triple-alpha process".
- Also get Oxygen from
  
  $^{12}\text{C} + ^4\text{He} \rightarrow ^{16}\text{O}$

- On H-R: star becomes less bloated when He ignites in the core (smaller, higher surface temperature) but still to right of main sequence: **Yellow Supergiant**

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Fusing Helium in shell: Red Supergiant

The details of the rest of the story quite uncertain - the subject of current research!

- After Helium in core exhausted: Just as when Hydrogen ran out, core (now carbon) shrinks, heats up, star envelope expands, cools.
- Becomes Red supergiant, radius > 2 AU (there goes Mars!).
- Start fusing Helium in shell around carbon core.
  
  - current models say this is unsteady, in "shell flashes", which stir up insides, bringing up fused elements to surface: observed in “carbon stars”
Low Mass Stars: The End

What happens next depends on mass of star:

**Low Mass (< about 8 M$_{\text{sun}}$) Fate (eg, Sun)**

- Carbon core (ashes of helium fusion) shrinks, never gets hot enough for Carbon fusion.
- Outer envelope (maybe 50% of stellar mass) gets so distended that part of it drifts off into space, giving "**Planetary Nebula**".
- This uncovers the hot compact Carbon core, which is now to the left of the Main Sequence ("**hot subdwarf**"). Short stage, but many are seen.
- Nebula drifts off in maybe 50,000 years, core cools into "**white dwarf**".
- **Summary:** H-R “evolutionary track”

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**Timescales**

- H core fusion: Main sequence lifetime
- H shell fusion: red giant. 5% of MS lifetime:
- He core fusion plus He shell: yellow -> red supergiant. 1% of M.S. lifetime
- Planetary nebula: 50,000 yrs
- **White Dwarf: forever...**

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Figure 7.17, p229, Arny
Main sequence -> Red Giant

- Hydrogen burning in core
- As fuel is exhausted, outward pressure in core drops, and gravity compresses it. Core contracts. Outer layers expand. Rising heat in contracting core creates pressure that causes outer layers to expand. Shell of H outside core ignites.

Mature Cluster HR Diagram

- Zero-Age Main Sequence ("ZAMS")
- More massive stars have run out of H in core

Figure 7.10, p222, Arny

Figure 7.23, p238, Arny
Young Star Cluster

Figure 7.9, p219, Amy

“Open” Cluster

Pleiades
Globular Cluster

Planetary Nebulae
More Planetary Nebulae..

Sun on the H-R Diagram

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