Post Main Sequence Evolution of “Low-Mass” Stars
Chapter 19.1-19.3, then 20.1-20.4, then 19.4-19.6

Key points

- At each stage, what element is fusing and where?
- How does that change the structure of the star?
- The evolutionary path of the star on the H-R diagram. How do $L$, $T$, $R$ change at each stage?
- Although evolution is complex, it’s driven by a few basic physical concepts.
- Star clusters and their H-R diagrams
- Variable stars and distance indicators

"Stellar Midlife" - Main Sequence

In stars more massive than about $1M_{\odot}$ ($T_{\text{core}} > 1.6 \times 10^7$ K), H $\Rightarrow$ He fusion more efficient through “CNO cycle”: chain of six reactions where C, N and O are catalysts, but end result same as p-p chain.

\[
\begin{align*}
^{12}\text{C} + ^{1}\text{H} & \rightarrow ^{13}\text{N} + \text{energy} \\
^{13}\text{N} & \rightarrow ^{12}\text{C} + e^+ + \nu \\
^{13}\text{C} + ^{1}\text{H} & \rightarrow ^{14}\text{N} + \text{energy} \\
^{14}\text{N} + ^{1}\text{H} & \rightarrow ^{15}\text{O} + \text{energy} \\
^{15}\text{O} & \rightarrow ^{14}\text{N} + e^+ + \nu \\
^{15}\text{N} + ^{1}\text{H} & \rightarrow ^{12}\text{C} + ^{4}\text{He} + \text{energy}
\end{align*}
\]

Nuclear reactions are highly sensitive to core $T$:
- p-p chain: $\propto T^4$
- CNO cycle: $\propto T^{20}$

MS stars fuse H to He in cores. There is some evolution of $L$ and $T$ on MS (so may sometimes see ZAMS or Zero-Age Main Sequence referred to – indicates stars’ positions at beginning of MS life).
Post main sequence evolution: “evolved” stars. Focus on $0.4 \, M_\odot < M < 7(?) \, M_\odot$ case

(This is a condensed version of what’s in the textbook, and is what you need to know).

1. During the MS, $H \Rightarrow He$ in core
   $\Rightarrow$ core runs out of fuel at some point.

   Can it immediately “burn” He?

   No, the Coulomb (electrical charge) barrier is too high.
   $\Rightarrow$ core energy production drops.
   $\Rightarrow$ internal pressure drops.

   Hydrostatic equilibrium is being lost.

   Core hydrogen exhaustion

2. Core contracts (eventually by factor of about 3 in radius)
   $\Rightarrow$ heats up
   $\Rightarrow$ inner part of “envelope” (everything outside core) contracts too, heats up
   $\Rightarrow$ now a zone around He core is hot enough for H burning – “H-burning shell”

3. $T$, density higher in shell than in core during MS
   $\Rightarrow$ faster fusion!

4. Faster fusion results in both higher pressure, which pushes out envelope above it, and more radiation

5. Outer envelope expands and therefore cools $\Rightarrow$ redder.
   Luminosity rises due to vigorous shell fusion.

6. Result is a Red Giant (ignore subgiant/Red Giant distinction in text for this class)

Radius increases roughly 100 times.

Lasts about 1 Gyr for 1 $M_\odot$ stars
(c.f. $t_{\text{MS}} \sim 10$ Gyr).

Strong winds

Evolving along the red giant branch ($1 \, M_\odot$ case)

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(Aside: evolution of stars < 0.4 $M_\odot$, down to brown dwarf limit)

These are fully convective: convection zone extends from center to surface => all gas cycles into core where fusion occurs and out again.

Eventually, all H in star converted to He. This takes 100’s of billions of years.

Never hot enough for He fusion.

Result will be dead He star.

Back to Red Giant. Eventually, core hot enough (T almost $10^8$ K) to ignite helium:

Helium burning (Sec 19.3, 20.1)

1) He burning starts via:

- The “triple alpha” process:

  $^4\text{He} + ^4\text{He} \rightarrow ^8\text{Be} + \gamma$

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

- Some C goes on to make O by fusing with another helium nucleus:

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

Low-mass (<2-3 $M_\odot$) stars: Electron degeneracy and the Helium Flash (not required to learn)

- In cores of low-mass red giants conditions are extreme: very high temperature and density, gas is completely ionized.

- With core contracting, density rises to about $10^7$ kg m$^{-3}$.

- Electrons and nuclei of the ionized gas are tightly squeezed.

- Electrons reach a limit set by quantum mechanics where they greatly resist further compression. This is a “degenerate” gas, different from an ideal gas. Its pressure depends on density only, not on temperature, and it dominates the normal, ideal gas pressure.

<table>
<thead>
<tr>
<th>Mass of star</th>
<th>Onset of helium burning in core</th>
</tr>
</thead>
<tbody>
<tr>
<td>Less than 2–3 solar masses</td>
<td>Explosive (helium flash)</td>
</tr>
<tr>
<td>More than 2–3 solar masses</td>
<td>Gradual</td>
</tr>
</tbody>
</table>

Why is the onset of helium burning explosive in lower mass stars?

To understand that, we need the concept of degeneracy, and degenerate matter.
• Whether you have an ideal gas or a degenerate gas depends on both density and temperature.

\[ \log \rho (\text{kg m}^{-3}) \]

\[ \log T (\text{K}) \]

7 8
5 6 7 8

X

(core at start of He fusion)

ideal gas
degenerate gas

• Now the rapidly rising temperature causes pressure to rapidly rise, and core to violently re-expand. Re-expansion of core takes a few hours.

• Note: no flash at surface of star!

2. Expansion of core causes it to cool, and pushes out H-burning shell, which also cools

3. Fusion rate drops. Envelope contracts and luminosity drops

4. Moves onto Horizontal Branch of H-R diagram. Stable core He burning (and shell H burning)

HB lasts about \(10^8\) years for 1 M\(\odot\) star. All HB stars < 3 M\(\odot\) have luminosity of almost 100 L\(\odot\).
Higher-mass stars: helium burning onset

- In higher mass stars, cores hotter and less dense. He fusion can start before core contracts to such a high density, so never gets degenerate.

  => H burning shell, then steady onset of He burning

- Moves more horizontally across the H-R diagram, especially for stars > 5 \(M_\odot\) or so.

- But structure is same, with He -> C, O fusion in core, and H -> He in shell.

Helium Runs out in Core (Sec 20.1)

1. All He -> C, O in core. Not hot enough for C, O fusion.
2. Core shrinks (to \(~1R_{\text{Earth}}\)) states up, becomes degenerate again. Shell also contracts and heats up.
3. Get new, intense He-burning shell (inside H-burning shell).
4. High rate of burning, star expands, luminosity way up!
5. H shell also pushed out by He shell fusion, eventually turns off

- Called Asymptotic Giant Branch (AGB) phase.
- Only \(~10^6\) years for 1 \(M_\odot\) star.

Helium Shell Flashes

1. As He in shell used up, shell contracts, so H shell must contract too and heat up
2. H shell reignites, creating new supply of He. He shell gains mass, shrinks, heats up, becomes “degenerate”.
3. Eventually He shell reignites, but in a flash
4. H shell re-expands, fusion stops
5. Cycle repeats

\[L \text{ and } R \text{ vary on } \sim 10^3 - 10^5 \text{ year timescales, depending on mass.}\]

Strong winds
Planetary Nebulae

- Pulsations become more violent. Eventually envelope ejected, at speeds of a few 100 km s\(^{-1}\), taking up to 40\% of mass
- Envelope eventually visible as a nebula with emission lines
- Remaining C-O core is a White Dwarf

Remnant Core – a White Dwarf

- Mass 0.25 \(M_\odot\) – 1.4 \(M_\odot\), depending on mass of progenitor star
- Supported by electron degeneracy pressure
- With no further fusion, they cool to oblivion over billions of years
- Radius about 1 \(R_\odot\)
- Hence enormous densities, \(\sim 10^9\) kg m\(^{-3}\)
- Composition C, O.
- Residual H, He atmosphere seen in spectra of most WDs
How did this understanding come about? Had to connect expectations from physics of stellar interiors with observations, refine thinking, etc.

Powerful test of theory: compare theoretical “evolutionary tracks” on the H-R diagram with real stars – specifically star clusters.