Stellar evolution

2 main threads

- Coulomb barrier
- Hydrostatic equilibrium

Stellar lifetimes and HR diagram

Main sequence: H burning in core → He

- P-p chain or CNO cycle
  - (low mass)
  - (high mass)

When about 10% of star's mass burnt → He, structure changes:

- Inert He core collapses and contracts
- He heats up
- Shell burns H outside core (energy generation increases, CNO cycle init)
- outer layers expand, cool
  \( R \uparrow, T \downarrow \) so \( L \approx \) unchanged

**SUBGIANT BRANCH**

- \( ^{1}H \) shell burning gives large temperature gradient
  convective envelope

**RED GIANT**

convection hard to treat theoretically
models on shakier ground now

- core temperature rises
  density rises, becomes degenerate
  (ie pressure does not depend on \( T \))
  - only on \( P \) & density
onset of \( ^{1}H \) burning - **HE FLASH**
then settles into core \( ^{1}H \) burning, \( ^{1}H \) shell

**HORIZONTAL BRANCH**
Figure 3-13. Observed color-magnitude diagram for the metal-poor globular cluster M92, with principal sequences and other important features indicated schematically. [Adapted from (C4, Chapter 2).]
Massive stars - later evolution

Stars more massive than 5 solar masses

- very high luminosity - nuclear fusion reactions go very fast
- lifetimes short

First stages of evolution the same - hydrogen burning shell forms

Helium burning starts more gently - no helium flash

Then carbon burning:

\[
\begin{array}{cc}
\text{carbon} & \text{helium} \\
\text{O} & \text{O}
\end{array}
\]

\[
\begin{array}{cc}
^{12}_{6}\text{C} + ^{4}_{2}\text{He} & \rightarrow ^{16}_{8}\text{O} + ^{8}_{4}\text{O}
\end{array}
\]

oxygen \quad \text{gives off energy}
<table>
<thead>
<tr>
<th>Energy source</th>
<th>Temperature (K)</th>
<th>Time for exhaustion (years)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen burning</td>
<td>$1.5 \times 10^7$</td>
<td>$10^7$ years</td>
</tr>
<tr>
<td>Helium burning</td>
<td>$1.7 \times 10^8$</td>
<td>$10^6$ years</td>
</tr>
<tr>
<td>Carbon burning</td>
<td>$7 \times 10^8$</td>
<td>$10^3$ years</td>
</tr>
<tr>
<td>Neon burning</td>
<td>$1.4 \times 10^9$</td>
<td>3 years</td>
</tr>
<tr>
<td>Oxygen burning</td>
<td>$1.9 \times 10^9$</td>
<td>1 year</td>
</tr>
<tr>
<td>Silicon burning</td>
<td>$3.3 \times 10^9$</td>
<td>1 day</td>
</tr>
</tbody>
</table>
have carbon-burning core
helium-burning shell
hydrogen-burning shell

At this point the star is in the red giant region of the HR diagram.

Then the star's core goes through successive stages of burning heavier and heavier elements: neon, oxygen, silicon, etc. (also have reactions that produce magnesium, sulfur, etc.)

This stops at iron (Fe). Past iron (to make heavier elements) fusion reactions need energy, rather than giving it off.
Fig. 7-1 The binding energy per nucleon of the most stable isobar of atomic weight $A$. The solid circles represent nuclei having an even number of protons and an even number of neutrons, whereas the crosses represent odd-$A$ nuclei. (M. A. Preston, "Physics of the Nucleus," Addison-Wesley Publishing Company, Inc., Reading, Mass., 1962.)

What does the trend of binding energy with mass number imply about the energetics of fusion & fission for different elements?
Fig. 15.1. Evolutionary tracks for stars of different masses. For more massive stars the luminosities of the red giants do not increase as much as those for lower mass stars. For the more massive stars the triple-alpha reaction starts soon after they reach the red giant region. The points with the numbers indicate the position for the onset of helium burning. The other numbers indicate other stages of evolution. From Iben (1967).