Late Stages of Stellar Evolution

- The star enters the Asymptotic Giant Branch with an active helium shell burning and an almost dormant hydrogen shell.
- Again the stars size and luminosity increase, leading to a deepening of the convective zone (dredge-up).
- The hydrogen shell reignites, possibly several times, leading to pulsation of the star.
- Eventually the outer layers will be blown off and a planetary nebula forms.

Late Stages of Stellar Evolution

- Development of an intermediate mass star with \(5 \, M_\odot\) after leaving the zero-age main-sequence (ZAMS).
- Hydrogen and helium core burning co-exist until the core, now containing mostly carbon and oxygen contracts and the envelope expands and cools.
- A helium burning shell forms and star moves to the asymptotic giant branch (AGB).
Late Stages of Stellar Evolution

- Early AGB star of $5 \, M_\odot$ shown with its shell structure
- Expanding and cooling of the hydrogen shell leads to fusion temporarily turning off
- This leads to a pulsation of the star with periods of the order of years (up to thousand of years for low mass stars)

In the third dredge-up phase, carbon from the core reaches the surface through convection
- Stars with masses larger than $8 \, M_\odot$ will begin nuclear burning of the CO core
- Eventually the hydrogen and helium burning shells are exhausted and the star begins to loose mass
- The hot central core will cool down and develop into a white dwarf star
The Sun Today and as a Giant

- Present day Sun has hydrogen-fusing core of 200,000 km diameter
- Giant Sun will have only 30,000 km diameter helium core surrounded by hydrogen-fusing shell of 20 million km diameter
Depending on the size of the initial star, different fractions of the stellar matter will be ejected as a planetary nebula.
Planetary Nebulae

• The glow of planetary nebula shells is caused by ultra-violet light emitted by the dwarf star
• The radiation excites the gas with de-exciting gas atoms sending out light also in the visible spectrum
• Planetary nebulae will dissipate into the interstellar matter within 50,000 years

Sirius and its White Dwarf Companion

Sirius B, a white dwarf, at the five o’clock position

Both are hot blackbodies and strong emitters of X rays
Nova Herculis 1934

- In a binary star system, mass falling gravitationally onto a white dwarf star can lead to an explosion called Nova

 Shortly after peak brightness as a magnitude −3 star Two months later, magnitude +12

Structure of an Old High-Mass Star

A supergiant star

- Hydrogen-fusing shell
- Helium-fusing shell
- Carbon-fusing shell
- Neon-fusing shell
- Oxygen-fusing shell
- Silicon-fusing shell
- Iron core

Jupiter's orbit

1.6 billion kilometers

Central regions of a supergiant star
Evolution of a 25-M\(_\odot\) Star

*TABLE 13-1 Evolutionary Stages of a 25-M\(_\odot\) Star*

<table>
<thead>
<tr>
<th>Stage</th>
<th>Central temperature (K)</th>
<th>Central density (kg/m(^3))</th>
<th>Duration of stage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hydrogen fusion</td>
<td>4 \times 10^7</td>
<td>5 \times 10^3</td>
<td>7 \times 10^6 yr</td>
</tr>
<tr>
<td>Helium fusion</td>
<td>2 \times 10^8</td>
<td>7 \times 10^3</td>
<td>5 \times 10^5 yr</td>
</tr>
<tr>
<td>Carbon fusion</td>
<td>6 \times 10^9</td>
<td>2 \times 10^3</td>
<td>600 yr</td>
</tr>
<tr>
<td>Neon fusion</td>
<td>1.2 \times 10^9</td>
<td>4 \times 10^3</td>
<td>1 yr</td>
</tr>
<tr>
<td>Oxygen fusion</td>
<td>1.5 \times 10^9</td>
<td>1 \times 10^{10}</td>
<td>6 mo</td>
</tr>
<tr>
<td>Silicon fusion</td>
<td>2.7 \times 10^9</td>
<td>3 \times 10^{10}</td>
<td>1 d</td>
</tr>
<tr>
<td>Core collapse</td>
<td>5.4 \times 10^9</td>
<td>3 \times 10^{12}</td>
<td>0.2 s</td>
</tr>
<tr>
<td>Core bounce</td>
<td>2.3 \times 10^{10}</td>
<td>4 \times 10^{17}</td>
<td>milliseconds</td>
</tr>
<tr>
<td>Supernova explosion</td>
<td>about 10^9</td>
<td>varies</td>
<td>hours</td>
</tr>
</tbody>
</table>

Stellar Clusters

- Clusters are categorized into three populations
  - **Population I**
    - Low velocities relative to the Sun
    - Found predominantly in the Milky Way disk
    - Stars metal-rich, relatively large abundance of higher Z elements
    - Open clusters formed fairly recently
    - Small number of stars (Pleiades)
  - **Population II**
    - Relatively fast velocities with respect to Sun
    - Found often away from the Milky Way disk in the halo
    - Stars metal-poor, Z small or close to zero
    - Formed when the Milky Way was very young
    - Some of the oldest globular clusters with large numbers of stars
  - **Population III**
    - Hypothetical
    - Formed early after the Big Bang
    - Virtually no metal, Z = 0
• Globular clusters (M10 about 70 ly across) contain a few hundred thousand stars of different masses and stage of development (assuming the cluster congregated at the same time)
• They are found at the halo of the Milky Way

Age of Stellar Clusters

• With the initial collapse of the molecular cloud, a large number of stars with different masses form
• The most massive stars will arrive on the main-sequence first
• When the lightest stars arrive at the main-sequence, the heaviest stars will have left the main-sequence already
• Hydrogen-burning lifetimes are inversely related to the star masses
• The main-sequence turn-off point will move to the red in the Hertzsprung-Russel diagram as the cluster ages
H-R Diagram of Globular Cluster M55

Las Campanas 1 m reflector

H-R Diagram for Stellar Clusters

41,453 stars measured by the Hipparcos satellite (ESA)