Stellar Evolution:
After the Main Sequence

Chapter Twenty-One
Help me/us design a better test for you: what did you thought was the hardest part of the exam? Which aspect/question?

Leave me a note at the end of the class near the door or e-mail me
Before the final we will review the major questions that were hard!
A star’s lifetime on the main sequence is proportional to its mass divided by its luminosity.

### Table 21-1

<table>
<thead>
<tr>
<th>Mass ((M_\odot))</th>
<th>Surface temperature ((K))</th>
<th>Spectral class</th>
<th>Luminosity ((L_\odot))</th>
<th>Main-sequence lifetime ((10^6 \text{ years}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>35,000</td>
<td>O</td>
<td>80,000</td>
<td>4</td>
</tr>
<tr>
<td>15</td>
<td>30,000</td>
<td>B</td>
<td>10,000</td>
<td>15</td>
</tr>
<tr>
<td>3</td>
<td>11,000</td>
<td>A</td>
<td>60</td>
<td>800</td>
</tr>
<tr>
<td>1.5</td>
<td>7000</td>
<td>F</td>
<td>5</td>
<td>4500</td>
</tr>
<tr>
<td>1.0</td>
<td>6000</td>
<td>G</td>
<td>1</td>
<td>12,000</td>
</tr>
<tr>
<td>0.75</td>
<td>5000</td>
<td>K</td>
<td>0.5</td>
<td>25,000</td>
</tr>
<tr>
<td>0.50</td>
<td>4000</td>
<td>M</td>
<td>0.03</td>
<td>700,000</td>
</tr>
</tbody>
</table>

*The main-sequence lifetimes were estimated using the relationship \( t \propto 1/M^{2.5} \) (see Box 21-2).*

- The duration of a star’s main sequence lifetime depends on the amount of hydrogen in the star’s core and the rate at which the hydrogen is consumed.
- The more massive a star, the shorter is its main-sequence lifetime.
The Sun has been a main-sequence star for about 4.56 billion years and should remain one for about another 7 billion years.
During a star’s main-sequence lifetime, the star expands somewhat and undergoes a modest increase in luminosity.
When core hydrogen fusion ceases, a main-sequence star becomes a red giant.

The Sun as a main-sequence star
(diameter = $1.4 \times 10^6$ km $\approx \frac{1}{100}$ AU)

The Sun as a red giant
(diameter $\approx$ 1 AU)

The Sun today and as a red giant
Red Giants

- Core hydrogen fusion ceases when the hydrogen has been exhausted in the core of a main-sequence star.
- This leaves a core of nearly pure helium surrounded by a shell through which hydrogen fusion works its way outward in the star.
- The core shrinks and becomes hotter, while the star’s outer layers expand and cool.
- The result is a red giant star.
As stars age and become giant stars, they expand tremendously and shed matter into space.
Fusion of helium into carbon and oxygen begins at the center of a red giant.

- When the central temperature of a red giant reaches about 100 million K, helium fusion begins in the core.
- This process, also called the triple alpha process, converts helium to carbon and oxygen.
In a more massive red giant, helium fusion begins gradually.

In a less massive red giant, it begins suddenly, in a process called the helium flash.

<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>

Table 21-2: How Helium Core Fusion Begins in Different Red Giants
After the helium flash, a low-mass star moves quickly from the red-giant region of the H-R diagram to the horizontal branch.
Before the beginning of core helium fusion, the star’s core compresses and the outer layer expands; just after core helium fusion begins, the core expands and the outer layer compresses.
H-R diagrams and observations of star clusters reveal how red giants evolve.

The age of a star cluster can be estimated by plotting its stars on an H-R diagram.

H-R diagram of 20,853 stars—note the width of the main sequence.
Post–main-sequence evolutionary tracks of five stars with different mass.
The cluster’s age is equal to the age of the main-sequence stars at the turnoff point (the upper end of the remaining main sequence)
All of these stars have joined the main sequence.

The least massive stars evolve the slowest and have not yet joined the main sequence.

This part of the main sequence is now empty: The most massive stars have depleted the hydrogen in their cores...

...and have become red giants. The least massive stars are finally approaching the main sequence.

More of the main sequence is now empty... ...because with time, lower-mass stars have depleted the hydrogen in their cores and become red giants.
Stars of ever-lower mass have depleted their core hydrogen, so even more of the main sequence is now empty.

Much of the main sequence is now empty.

Only the least massive stars remain on the main sequence.

Age: 100 million years

Age: 4 1/4 billion years

Luminosity ($L_\odot$)

Surface temperature (K)
As a cluster ages, the main sequence is “eaten away” from the upper left as stars of progressively smaller mass evolve into red giants.
Stellar evolution has produced two distinct populations of stars

- Relatively young Population I stars are metal rich; ancient Population II stars are metal poor
- The metals (heavy elements) in Population I stars were manufactured by thermonuclear reactions in an earlier generation of Population II stars, then ejected into space and incorporated into a later stellar generation
Many mature stars pulsate

When a star’s evolutionary track carries it through a region in the H-R diagram called the instability strip, the star becomes unstable and begins to pulsate.
• Cepheid variables are high-mass pulsating variables
• RR Lyrae variables are low-mass, metal-poor pulsating variables with short periods
• Long-period variable stars also pulsate but in a fashion that is less well understood
There is a direct relationship between Cepheid periods of pulsation and their luminosities.

The light curve of δ Cephei (a graph of brightness versus time).
Radial velocity versus time for δ Cephei
(positive: star is contracting; negative: star is expanding)
When $\delta$ Cephei is at maximum brightness, the star is near its maximum surface temperature.
When $\delta$ Cephei is at maximum brightness, the star is expanding (its diameter is increasing).

Diameter versus time for $\delta$ Cephei
The graph illustrates the relationship between luminosity and period for two types of Cepheid variables.

**Type I Cepheids**
- Metal-rich Population I stars
- More luminous

**Type II Cepheids**
- Metal-poor Population I stars
- Less luminous

The luminosity is plotted on a logarithmic scale, with the period on a linear scale.
Mass transfer in a close binary system occurs when one star in a close binary overflows its Roche lobe.
Gas flowing from one star to the other passes across the inner Lagrangian point.

Mass can flow from the enlarged star to the other across the inner Lagrangian point.

Semi-detached binary: One star fills its Roche lobe.
A semidetached binary

- Large red giant
- More luminous main-sequence star

Algol

Graph showing apparent visual magnitude with
- Small star eclipses the large one.
- Large star eclipses the small one.
- 2.87 days
Mass flows from the large star onto the small one, forming an accretion disk.

**β Lyrae**

A semidetached binary with mass transfer

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**Graph:**

- **X-axis:** Time (days)
- **Y-axis:** Apparent visual magnitude

- **Label:** 12.9 days
- **Description:** Small star eclipses the large one.
- **Label:** Large star eclipses the small one.
Mass can flow from either star to the other across the inner Lagrangian point.

Contact binary: Both stars fill their Roche lobes.
This mass transfer can affect the evolutionary history of the stars that make up the binary system.

Both stars share the same outer atmosphere.

Overcontact binary: Both stars overfill their Roche lobes.
An overcontact binary

W Ursae Majoris

Both stars are about the same size, so all eclipses are roughly the same.

8.0 hours