Guiding Questions

1. How will our Sun change over the next few billion years?
2. Why are red giants larger than main-sequence stars?
3. Do all stars evolve into red giants at the same rate?
4. How do we know that many stars lived and died before our Sun was born?
5. Why do some giant stars pulsate in and out?
6. Why do stars in some binary systems evolve in unusual ways?
A star’s lifetime on the main sequence is proportional to its mass divided by its luminosity.

**Table 21-1** Approximate Main-Sequence Lifetimes

<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\ 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.
- N.B. - 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.
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.
• When the central temperature of a red giant reaches about 100 million K, helium fusion begins in the core.
• A process 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.
After the helium flash, a low-mass star moves quickly from the red-giant region of the H-R diagram to the horizontal branch.
- 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.

- Zero-age main sequence
- Stars reach this dashed line when core hydrogen fusion comes to an end.
- * = Helium flash (occurs for low-mass stars only)
The cluster’s age can be estimated by 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

(f) Surface temperature (K)

Age: 4 ¼ billion years

(h) 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.
Populations (generations) 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.
Variable Stars

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.

(a) Mira at minimum
(b) Mira at maximum

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 variable stars.
- RR Lyrae variables are lower-mass, metal-poor variable stars 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.
When δ Cephei is at maximum brightness, the star is expanding most rapidly.

Radial velocity versus time for δ Cephei
(positive: star is contracting; negative: star is expanding)
When δ Cephei is at maximum brightness, the star is near its maximum surface temperature.
When δ Cephei is at maximum brightness, the star is expanding (its diameter is increasing).
Type I Cepheids
- Metal-rich Population I stars
- More luminous

Type II Cepheids
- Metal-poor Population I stars
- Less luminous
Mass transfer can affect the evolution of close binary star systems.

Mass transfer in a close binary system occurs when one star in a close binary overflows its Roche lobe.

Detached binary: Neither star fills 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

Small star eclipses the large one.

2.87 days

Large star eclipses the small one.
A semidetached binary with mass transfer

Mass flows from the large star onto the small one, forming an accretion disk.

Small star eclipses the large one.

Large star eclipses the small one.

12.9 days
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.
W Ursae Majoris

An overcontact binary

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

8.0 hours
Key Words

- alpha particle
- Cepheid variable
- close binary
- color-magnitude diagram
- contact binary
- core helium fusion
- core hydrogen fusion
- degeneracy
- degenerate-electron pressure
- detached binary
- globular cluster
- helium flash
- helium fusion
- horizontal-branch star
- ideal gas
- inner Lagrangian point
- instability strip
- long-period variable
- main-sequence lifetime
- mass loss
- mass transfer
- metal-poor star
- metal-rich star
- overcontact binary
- Pauli exclusion principle
- period-luminosity relation
- Population I and Population II stars
- pulsating variable star
- red giant
- Roche lobe
- RR Lyrae variable
- semidetached binary
- shell hydrogen fusion
- triple alpha process
- turnoff point
- Type I and Type II Cepheids
- zero-age main sequence (ZAMS)
- zero-age main-sequence star