Announcements

- Welcome back!
Announcements

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Today:
- How stars evolve
  - Main-sequence evolution
  - Giants
  - Planetary nebula
- *Stellar Evolution, Chaps. 21 & 22*
Main-sequence evolution (1/2)

- H is being converted into He through fusion
- \( PV = NkT \) \( \ldots \) 4 particles are converted to 1, pressure drops!
- Smaller fraction of Hydrogen fuel requires higher temperature to produce energy
- Core collapses and temperature rises

![Diagram: Mass fraction of hydrogen vs. distance from Sun's center]

(a) Hydrogen in the Sun’s interior
Main-sequence evolution (1/2)

- H is being converted into He through fusion
  - \( PV = NkT \) ... 4 particles are converted to 1, pressure drops!
- Smaller fraction of Hydrogen fuel requires higher temperature to produce energy
- Core collapses and temperature rises

![Diagram of Helium in the Sun’s interior](image)

A114: Lecture 19—26 Mar 2007  Read: Ch. 21,22  Astronomy 114—3/13
Main-sequence evolution (1/2)

- H is being converted into He through fusion
  - $PV = NkT$ ... 4 particles are converted to 1, pressure drops!
  - Smaller fraction of Hydrogen fuel requires higher temperature to produce energy
- Core collapses and temperature rises

This heats and expands the outer envelope
Process begins at onset of Hydrogen ‘burning’
Main-sequence evolution (2/2)

Process continues slowly for billions of years

- 5 billion years ago (zero-age Sun)
  - Beginning of its life on main-sequence
  - Sun had 1/3 luminosity its current luminosity

- 5 billion years from now (old Sun)
  - End of its life on main-sequence
  - Sun will have twice its current luminosity

[Estimates based on computer modeling]
### Table 21-1: 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>3</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>500</td>
</tr>
<tr>
<td>1.5</td>
<td>7000</td>
<td>F</td>
<td>5</td>
<td>3,000</td>
</tr>
<tr>
<td>1.0</td>
<td>6000</td>
<td>G</td>
<td>1</td>
<td>10,000</td>
</tr>
<tr>
<td>0.75</td>
<td>5000</td>
<td>K</td>
<td>0.5</td>
<td>15,000</td>
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<tr>
<td>0.50</td>
<td>4000</td>
<td>M</td>
<td>0.03</td>
<td>200,000</td>
</tr>
</tbody>
</table>

- Luminosity increases *steeply* with mass
- Main-sequence age decreases *steeply* with mass
Main-sequence luminosity & lifetimes (2/2)

![Graph showing the relationship between luminosity and mass on a log-log scale. The x-axis represents mass in solar masses, ranging from 0.1 to 100, and the y-axis represents luminosity in solar luminosity, also on a log scale.]
Main-sequence luminosity & lifetimes (2/2)

\[ L = M^{3.5} \]
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Main-sequence luminosity & lifetimes (2/2)

\[ L = M^{3.5} \]

\[ t/10^{10} = M^{-2.5} \]
Main-sequence luminosity & lifetimes (2/2)

$L = M^{3.5}$

$t/10^{10} = M^{-2.5}$

Read: Box 21-2 in Freedman & Kaufmann
Life after the main-sequence

What happens next depends on mass . . .

Solar mass (low mass) star:

- When H is exhausted, the core shrinks
- Core heats up but can not yet burn He, needs $10^6$ K!
- The high temperatures ignites a fusion shell of H
- The increased pressure drives the envelope of the star outward
- Creates a giant star

A114: Lecture 19—26 Mar 2007 Read: Ch. 21,22 Astronomy 114—7/13
Giants

Bloated stars: very large radii

g Large luminosity: $L = 4\pi R^2 \sigma T^4$
Giants

- **Bloated stars: very large radii**
- **Large luminosity:** \( L = 4\pi R^2 \sigma T^4 \)
- **\( T_{\text{core}} \) reaches** \( 10^8 \) K
The Helium Flash

When $T_{\text{core}} \approx 10^8$ K, He begins to burn

1. $He^4 + He^4 \Rightarrow Be^8 + \gamma$
2. $He^4 + Be^8 \Rightarrow C^{12} + \gamma$
3. Triple-alpha process
4. He fusion in the core and H shell burning
The Helium Flash

- When $T_{\text{core}} \approx 10^8$ K, He begins to burn

  $$He^4 + He^4 \Rightarrow Be^8 + \gamma$$

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

- Triple-alpha process
- He fusion in the core and H shell burning

- Star leaves giant branch and moves onto the horizontal branch
Horizontal branch

- Hotter and bluer
- Shrinks and gets fainter
Horizontal branch

- Hotter and bluer
- Shrinks and gets fainter
- He-burning in core, H-burning shell
- After $10^8$ years, core He exhausted
Asymptotic giant branch

- Core collapses (again)
- Envelope expands and cools (again)
- Ascends the giant branch (again)
- Hotter this time around
Asymptotic giant branch

- Core collapses (again)
- Envelope expands and cools (again)
- Ascends the giant branch (again)
- Hotter this time around
- After $10^8$ years, core He exhausted
Formation and evolution summary

- **Most massive protostars**
- **Least massive protostars**
- **The most massive protostars are approaching the main sequence.**
- **The most massive protostars have joined the main sequence. This means that hydrogen fusion is taking place in their cores.**
Formation and evolution summary

- 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.

Read: Ch. 21, 22
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.
Globular cluster HR diagram

Horizontal-branch stars

Red giants