17.3 Life as a High-Mass Star

Our goals for learning:

What are the life stages of a high-mass star?

How do high-mass stars make the elements necessary for life?

How does a high-mass star die?
What are the life stages of a high-mass star?

**Life of a High-Mass Star (≥8 M☉)**

1. **Protostar**: A star is born from a cloud of interstellar gas that collapses under gravity.
2. **Blue main-sequence star**: In the core of a high-mass star, four hydrogen nuclei fuse into a single helium nucleus by the process of proton-proton chain or the CNO cycle.
3. **Red supergiant**: After core hydrogen is exhausted, the core contracts and heats up, and hydrogen shell burning begins around the hot helium core, causing the star to expand into a red supergiant.
4. **Helium-burning supergiant**: Hydrogen fusion begins where the core temperature is high enough to fuse helium into carbon. The core then expands, clearing the mass of hydrogen shell burning material in the star’s outer layers to form a white dwarf.
5. **Multiple shell burning supergiant**: After the core runs out of helium, it shrinks and mass is used up. Fusion begins from the bottom up, the star forms many different elements in a series of shells where they collect in the core.
6. **Supernova**: Iron cannot provide heat energy, and all accumulated in the core until degenerate pressure can no longer support. The core collapses, leading to a catastrophic explosion of the star.
7. **Neutron star or black hole**: The core collapses to form a ball of neutrons, which may collapse into a black hole or continue to form a neutron star.

**Actual Length of Stage**

- 40,000 years
- 6 million years
- 100,000 years
- 1 million years
- 10,000 years
- a few months
- Indefinite

**Time on Cosmic Calendar**

- 12:00 PM - 12:25 AM
- 12:30 PM - 12:55 AM
- 1:00 PM - 1:25 AM
- 1:30 PM - 1:55 AM
- 2:00 PM - 2:25 AM
- 2:30 PM - 2:55 AM
- 3:00 PM - 3:25 AM
- 3:30 PM - 3:55 AM
- 4:00 PM - 4:25 AM
- 4:30 PM - 4:55 AM
- 5:00 PM - 5:25 AM
- 5:30 PM - 5:55 AM
- 6:00 PM - 6:25 AM
- 7:00 PM - 7:25 AM
- 8:00 PM - 8:25 AM
- 9:00 PM - 9:25 AM
- 10:00 PM - 10:25 AM
- 11:00 PM - 11:25 AM

These times correspond to the life stages of a 20 M☉ star formed at the end of a typical day of the cosmic calendar.
High-mass main-sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts.

Greater core temperature enables hydrogen nuclei to overcome greater repulsion.
Late life stages of high-mass stars are similar to those of low-mass stars:

- Hydrogen core fusion (main sequence)
- Hydrogen shell burning (supergiant)
- Helium core fusion (supergiant)
How do high-mass stars make the elements necessary for life?

Helium-capture reactions.
Big Bang made 75% H, 25% He; stars make everything else.
Helium fusion can make carbon in low-mass stars.
CNO cycle can change carbon into nitrogen and oxygen.
High core temperatures allow helium to fuse with heavier elements.
Helium capture builds carbon into oxygen, neon, magnesium, and other elements.
Core temperatures in stars with $>8M_{\text{Sun}}$ allow fusion of elements as heavy as iron.
Advanced reactions in stars make elements like Si, S, Ca, Fe.
Multiple Shell Burning

Advanced nuclear burning proceeds in a series of nested shells.
Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(This is because iron has lowest mass per nuclear particle.)
Evidence for helium capture:

- Higher abundances of elements with even numbers of protons
How does a high-mass star die?
- Iron builds up in core until degeneracy pressure can no longer resist gravity.
- The core then suddenly collapses, creating a supernova explosion.
Supernova Explosion

- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos.

- Neutrons collapse to the center, forming a neutron star.
Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including gold and uranium.
Supernova Remnant

- Energy released by the collapse of the core drives the star's outer layers into space.

- The Crab Nebula is the remnant of the supernova seen in A.D. 1054.
Supernova 1987A

The closest supernova in the last four centuries was seen in 1987.
Rings around Supernova 1987A

The supernova's flash of light caused rings of gas around the supernova to glow.
Impact of Debris with Rings

More recent observations show the inner ring lighting up as debris crashes into it.
What have we learned?

- What are the life stages of a high-mass star?
  - They are similar to the life stages of a low-mass star.

- How do high-mass stars make the elements necessary for life?
  - Higher masses produce higher core temperatures that enable fusion of heavier elements.

- How does a high-mass star die?
  - Its iron core collapses, leading to a supernova.
17.4 The Roles of Mass and Mass Exchange

Our goals for learning:

- How does a star’s mass determine its life story?
- How are the lives of stars with close companions different?
How does a star's mass determine its life story?

1. Protoplanetary disk: A star forms from a cloud of interstellar gas and dust, collapsing under gravity.
2. Star formation: The cloud collapses, forming a protostar, which eventually becomes a main-sequence star.
3. Red giant: After core helium burning, the star expands, becoming a red giant, where the core is still burning hydrogen at the center.
4. Helium core: As the core runs out of helium, the star becomes a helium core, which collapses and forms a white dwarf.
5. Planetary nebula: The star's outer layers are expelled, creating a planetary nebula around the central white dwarf.
6. Supernova: If the star is massive enough, it can undergo a supernova explosion, releasing its outer layers into space.

Table: Life of a Star

<table>
<thead>
<tr>
<th>Mass Range</th>
<th>Actual Length of Stage</th>
<th>Time on Cosmic Calendar</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1 - 8 solar masses</td>
<td>10 - 10,000 years</td>
<td>12:00 AM - 12:30 AM</td>
</tr>
<tr>
<td>8 - 20 solar masses</td>
<td>100,000 - 1 million years</td>
<td>12:30 AM - 1:00 AM</td>
</tr>
<tr>
<td>&gt; 20 solar masses</td>
<td>1 million - 10 billion years</td>
<td>1:00 AM - 1:30 AM</td>
</tr>
</tbody>
</table>

Note: The actual length of stage times are approximate and can vary depending on the star's mass and initial conditions.
Role of Mass

- A star's mass determines its entire life story because it determines its core temperature.
- High-mass stars with $> 8M_{\text{Sun}}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars with $< 2M_{\text{Sun}}$ have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.
- Intermediate-mass stars can make elements heavier than carbon but end as white dwarfs.
1. Main sequence: H fuses to He in core.
2. Red giant: H fuses to He in shell around He core.
3. Helium core burning: He fuses to C in core while H fuses to He in shell.
4. Double shell burning: H and He both fuse in shells.
5. Planetary nebula leaves white dwarf behind.
Core shrinks and heats until it's hot enough for fusion.

Nuclei with larger charge require higher temperature for fusion.

Core thermostat is broken while core is not hot enough for fusion (shell burning).

Core fusion can't happen if degeneracy pressure keeps core from shrinking.
1. **Main sequence:** H fuses to He in core.
2. **Red supergiant:** H fuses to He in shell around He core.
3. **Helium core burning:**
4. **He fuses to C in core while H fuses to He in shell.**
5. **Multiple shell burning:**
6. **Many elements fuse in shells.**
7. **Supernova leaves neutron star behind.**
How are the lives of stars with close companions different?

Algol at onset of mass transfer. When the more massive star expanded into a red giant, it began losing some of its mass to its normal, hydrogen core fusion companion.
Thought Question

- The binary star Algol consists of a $3.7M_{\text{Sun}}$ main-sequence star and a $0.8M_{\text{Sun}}$ subgiant star.

- What's strange about this pairing?

- How did it come about?
The stars in Algol are close enough that matter can flow from the subgiant onto the main-sequence star.
The star that is now a subgiant was originally more massive.

As it reached the end of its life and started to grow, it began to transfer mass to its companion (mass exchange).

Now the companion star is more massive.
Images of Algol
What have we learned?

- **How does a star's mass determine its life story?**
  - Mass determines how high a star's core temperature can rise and therefore determines how quickly a star uses its fuel and what kinds of elements it can make.

- **How are the lives of stars with close companions different?**
  - Stars with close companions can exchange mass, altering the usual life stories of stars.