Chapter 12:
The Life Cycle of Stars (cont’d)
12.3 Life as a High-Mass Star

Learning Goals

• 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?
High-Mass Stars
$> 8 \text{ M}_{\text{Sun}}$

Intermediate-Mass Stars
($\sim 2-8 \text{ M}_{\text{Sun}}$)

Low-Mass Stars
$< 2 \text{ M}_{\text{Sun}}$

Brown Dwarfs (no H-burning)
$< 0.08 \text{ M}_{\text{Sun}}$
High-Mass Star’s Life

Early stages are similar to those of low-mass star:

1. **Main Sequence:**
   H fuses to He in core *(but through a different process)*

3. **Red Supergiant:**
   H fuses to He in shell around inert He core

3. **Helium Core Burning:**
   He fuses to C in core
Low-mass Main Sequence stars fuse H into He via the proton-proton chain.

High-mass Main Sequence stars have higher core temperatures. H fusion occurs via the CNO chain.

CNO cycle is just another way to fuse H into He, using carbon, nitrogen, and oxygen as catalysts.
High-mass stars become **supergiants** after core H runs out.

Process is much faster than with low mass stars.

*Luminosity doesn’t change much but radius gets much larger.*
How do high mass stars make the elements necessary for life?
Big Bang made 75% H, 25% He. Stars make everything else

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

Helium fusion can make carbon in low-mass stars
How do high mass stars make the elements necessary for life?

High-mass stars can change C into N and O
Helium-capture reactions add two protons at a time. Build even heavier elements in this fashion.
Helium capture builds C into O, Ne, Mg, …
Observational evidence for helium capture: 
higher abundances of elements with even numbers of protons
Advanced nuclear reactions make heavier elements
• Advanced nuclear fusion reactions require extremely high temperatures: *only happens in high-mass stars.*

• Process continues up to the formation of **iron.**
Advanced nuclear burning in high mass stars occurs in multiple shells (*layers of an onion*)
Iron is the dead end for fusion because nuclear reactions involving iron do not release energy.

Iron has lowest mass per nuclear particle.

Hence, star’s core cannot make any more energy once it has made iron.
How does a high mass star die?

- Iron builds up in core until degeneracy pressure can no longer resist gravity.
- Core then suddenly collapses in a few seconds, creating a **supernova** explosion.
- Can temporarily be as bright as a whole galaxy!
Electron degeneracy pressure in the iron core disappears at very high densities because electrons combine with protons, making neutrons and neutrinos.

These neutrons collapse to the center, forming a neutron star (supported by neutron degeneracy pressure).

The iron core has a starting mass of \( \sim 1 \, M_{\text{Sun}} \) and size of the Earth. Collapses into a ball of neutrons only a few km across!!
A neutron star is about the same size as a small city.
Energy and neutrons released in supernova explosion enables elements heavier than iron to form.
Elements made during supernova explosion.
Supernova 1987A is the nearest supernova observed in the last 400 years.

Occurred in the Large Magellanic Cloud, a small galaxy orbiting the Milky Way, about 150,000 light years away.
SN 1987A: Change with time
SN 2005cs in the nearby galaxy M51

Discovered June 2005 by a German amateur astronomer.
Crab Nebula: Remnant of supernova observed in 1054 A.D.
The next nearby supernova? (500 light-years away)
Summary
**Low-Mass Star Summary**

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 and H fuses to He in shell

4. **Double Shell Burning**: H and He both fuse in shells

5. **Planetary Nebula** leaves …

6. **White Dwarf** behind
Reasons for Life Stages

- Core shrinks and heats until it’s hot enough for fusion
- Nuclei with larger charge require higher temperature for fusion
- Core thermostat is broken when core not hot enough for fusion (during shell burning)
- Core fusion can’t happen if degeneracy pressure keeps core from shrinking
Life of a High-Mass Star

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**: He fuses to C in core and H fuses to He in shell

4. **Multiple Shell Burning**: Many elements fuse in shells

5. **Supernova** occurs, leaving a **neutron star** behind
Life of a ~1 \( M_{\odot} \) Sun star

- Yellow main-sequence star: Star is fueled by hydrogen fusion in its core, which converts four hydrogen nuclei into one helium nucleus. A low-mass star, hydrogen fusion proceeds by the proton-proton chain.
- Red giant star: After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red giant.
- Helium core-burning star: Helium fusion in which three helium nuclei fuse to form a single carbon nucleus, begins when enough helium has accumulated in the core. The core then expands, slowing the fusion rate and allowing the star's outer layers to shrink somewhat, hydrogen shell burning continues at a reduced rate.
- Double shell-burning red giant: After core helium is exhausted, the core again shrinks and heats, helium shell burning begins around the inert carbon core and the star enters its second red giant phase. Hydrogen shell burning continues.
- White dwarf: The remaining white dwarf is made primarily of carbon and oxygen because the core never grew hot enough to fuse these elements into anything heavier.

Ends as a white dwarf.

Life of a >8 \( M_{\odot} \) Sun star

- Blue main-sequence star: Star is born by hydrogen fusion in its core. In high-mass stars, hydrogen fusion proceeds by the series of reactions known as the CNO cycle.
- Red supergiant: After core hydrogen is exhausted, the core shrinks and heats. Hydrogen shell burning begins around the inert helium core, causing the star to expand into a red supergiant.
- Helium core-burning supergiant: Helium fusion begins when enough helium has accumulated in the core. The core then expands, slowing the fusion rate and allowing the star's outer layers to shrink somewhat, hydrogen shell burning continues at a reduced rate.
- Multiple shell-burning supergiant: After core helium is exhausted, the core shrinks until carbon fusion begins, while helium and hydrogen continue to burn in shells surrounding the core. Later in life, the star uses heavier elements like carbon and oxygen in shells while iron reflects in the inert core.
- Neutron star: During the core collapse of the supernova, neutrons combine with protons to make neutrons. The former core is therefore made almost entirely of neutrons.
- Supersnova: Iron cannot provide fusion energy, so it accumulates in the core until degenerate pressure sets in, in order to support it. Then the core collapses, leading to the catastrophic explosion of the star.

Ends in a supernova, leaving a neutron star or black hole.
We are “star stuff”

For every 10,000 atoms …

<table>
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All elements heavier than helium were made in stars.
Question 1 [12.27]

The following question refers to the sketch below of an H-R diagram for a star cluster.

Consider the star to which the arrow points. How is it currently generating energy?
- by hydrogen shell burning around an inert helium core
- by gravitational contraction
- by core hydrogen fusion
- by both hydrogen and helium shell burning around an inert carbon core
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Question 2 [12.28]

Consider the star to which the arrow points. Which one of the following statements in NOT true

- It is brighter than the Sun
- Its core temperature is higher than the Sun’s
- It is significantly less massive than the Sun.
- Its surface temperature is lower than the Sun's
- It is larger in radius than the Sun.
Question 2

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- It is larger in radius than the Sun.
Question 3 [12.29]

What is the CNO cycle

• the period of a massive star's life when carbon, nitrogen, and oxygen are fusing in different shells outside the core
• a type of hydrogen fusion that uses carbon, nitrogen, and oxygen atoms as catalysts
• the process by which helium is fused into carbon, nitrogen, and oxygen
• the period of a low-mass star's life when it can no longer fuse carbon, nitrogen, and oxygen in its core
• the process by which carbon is fused into nitrogen and oxygen
Question 3

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- the process by which carbon is fused into nitrogen and oxygen
Question 4 [12.30]

Which element has the lowest mass per nuclear particle and therefore cannot release energy by either fusion or fission?

- hydrogen
- silicon
- oxygen
- iron
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Question 5 [12.31]

What happens when the gravity of a massive star is able to overcome neutron degeneracy pressure?

• The star explodes violently, leaving nothing behind.
• The core contracts and becomes a white dwarf.
• Gravity is not able to overcome neutron degeneracy pressure
• The core contracts and becomes a black hole.
• The core contracts and becomes a ball of neutrons.
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Question 6 [12.8]

When does a star become a main-sequence star?
• when the protostar assembles from its parent molecular cloud
• the instant when hydrogen fusion first begins in the star's core
• when a star becomes luminous enough to emit thermal radiation
• when the rate of hydrogen fusion in the star's core is high enough to sustain gravitational equilibrium
• when hydrogen fusion is occurring throughout the star's interior
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