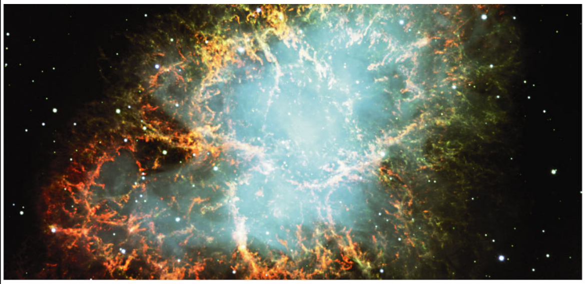
Chapter 17
Star Stuff



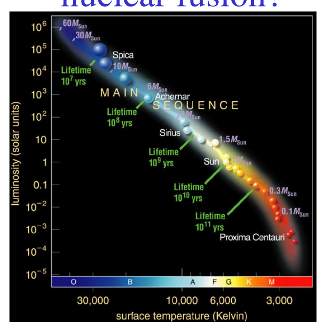
Agenda

- Announce
  - Tutorial
  - Projects (Theme: Biographies? Fiction?)
- Ch. 17—Star Stuff
- GR Exercise

17.1 Lives in the Balance

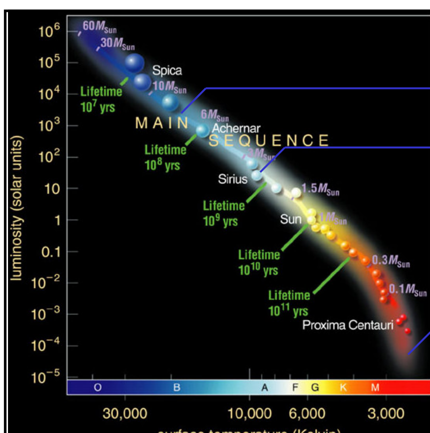
- Our goals for learning
- How does a star's mass affect nuclear fusion?

How does a star's mass affect nuclear fusion?



Stellar Mass and Fusion

- The mass of a main sequence star determines its core pressure and temperature
- Stars of higher mass have higher core temperature and more rapid fusion, making those stars both more luminous and shorter-lived
- Stars of lower mass have cooler cores and slower fusion rates, giving them smaller luminosities and longer lifetimes



High-Mass Stars $> 8\ M_{Sun}$

Intermediate-Mass Stars

Low-Mass Stars $< 2\ M_{Sun}$

Brown Dwarfs

Star Clusters and Stellar Lives

- Our knowledge of the life stories of stars comes from comparing mathematical models of stars with observations
- Star clusters are particularly useful because they contain stars of different mass that were born about the same time

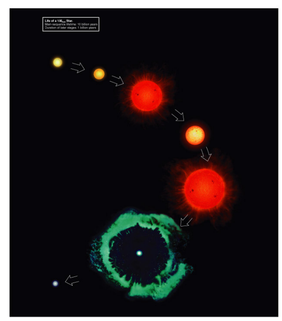
What have we learned?

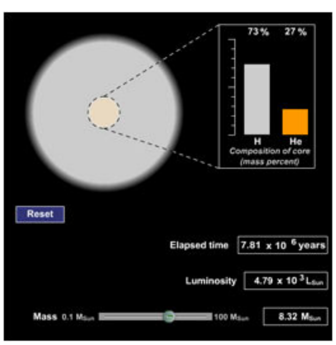
- How does a star's mass affect nuclear fusion?
  – A star's mass determines its core pressure and temperature and therefore determines its fusion rate
  – Higher mass stars have hotter cores, faster fusion rates, greater luminosities, and shorter lifetimes

17.2 Life as a Low-Mass Star

- Our goals for learning
- What are the life stages of a low-mass star?
- How does a low-mass star die?

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





A star remains on the main sequence as long as it can fuse hydrogen into helium in its core

Thought Question

What happens when a star can no longer fuse hydrogen to helium in its core?

A. Core cools off
B. Core shrinks and heats up
C. Core expands and heats up
D. Helium fusion immediately begins

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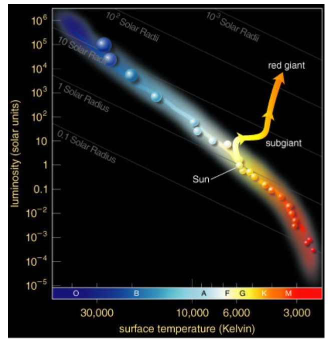
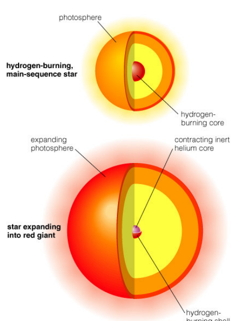
Life Track after Main Sequence

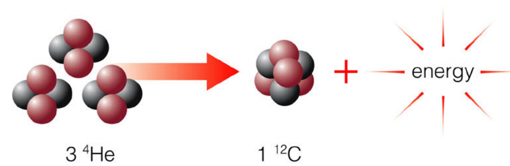


- Observations of star clusters show that a star becomes larger, redder, and more luminous after its time on the main sequence is over

Broken Thermostat



- As the core contracts, H begins fusing to He in a shell around the core
- Luminosity increases because the core thermostat is broken—the increasing fusion rate in the shell does not stop the core from contracting



Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion

Fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon

Thought Question

What happens in a low-mass star when core temperature rises enough for helium fusion to begin?

A. Helium fusion slowly starts up
B. Hydrogen fusion stops
C. Helium fusion rises very sharply

Hint: Degeneracy pressure is the main form of pressure in the inert helium core

Thought Question

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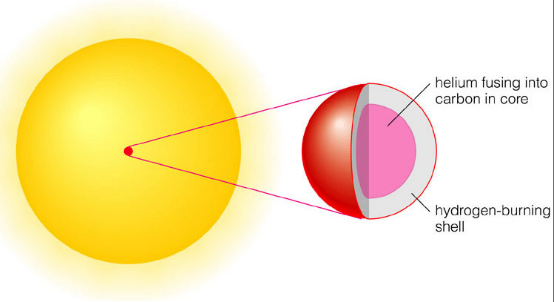
Hint: Degeneracy pressure is the main form of pressure in the inert helium core

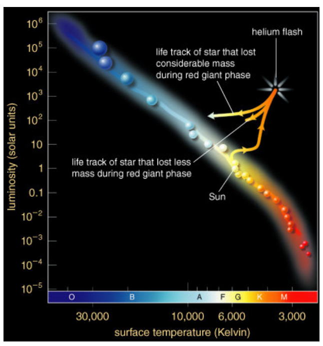
Helium Flash

- Thermostat is broken in low-mass red giant because degeneracy pressure supports core
- Core temperature rises rapidly when helium fusion begins
- Helium fusion rate skyrockets until thermal pressure takes over and expands core again



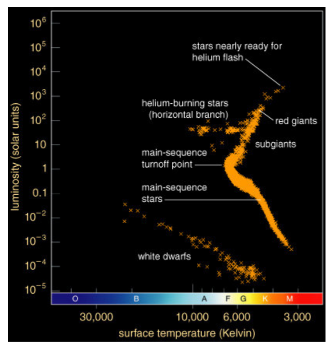
Helium burning stars neither shrink nor grow because core thermostat is temporarily fixed.

Life Track after Helium Flash

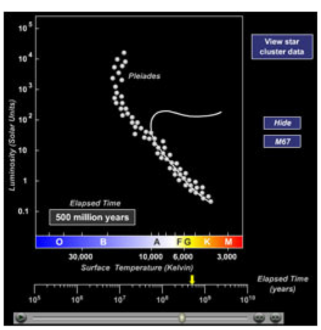


- Models show that a red giant should shrink and become less luminous after helium fusion begins in the core

Life Track after Helium Flash

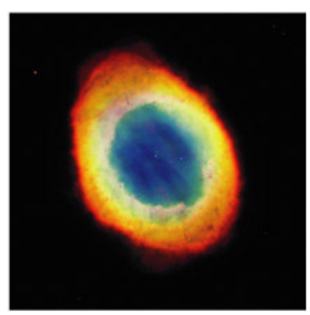


- Observations of star clusters agree with those models
- Helium-burning stars are found in a *horizontal branch* on the H-R diagram



Combining models of stars of similar age but different mass helps us to age-date star clusters

How does a low-mass star die?



Thought Question

What happens when the star's core runs out of helium?

A. The star explodes
B. Carbon fusion begins
C. The core cools off
D. Helium fuses in a shell around the core

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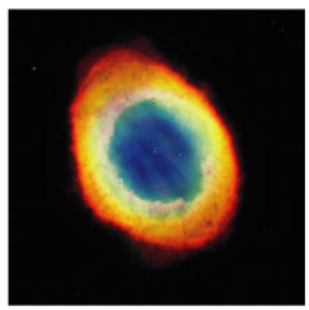
Double Shell Burning

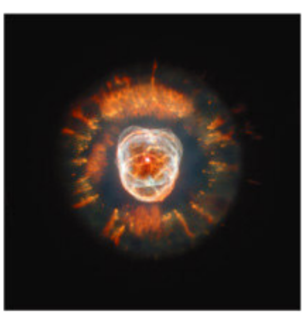
- After core helium fusion stops, He fuses into carbon in a shell around the carbon core, and H fuses to He in a shell around the helium layer
- This double-shell burning stage never reaches equilibrium—fusion rate periodically spikes upward in a series of *thermal pulses*
- With each spike, convection dredges carbon up from core and transports it to surface

Planetary Nebulae



- Double-shell burning ends with a pulse that ejects the H and He into space as a *planetary nebula*
- The core left behind becomes a white dwarf

Planetary Nebulae



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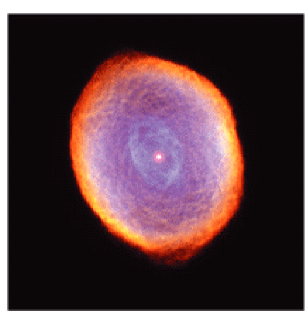

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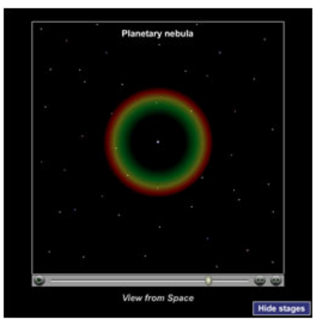
- The core left behind becomes a white dwarf

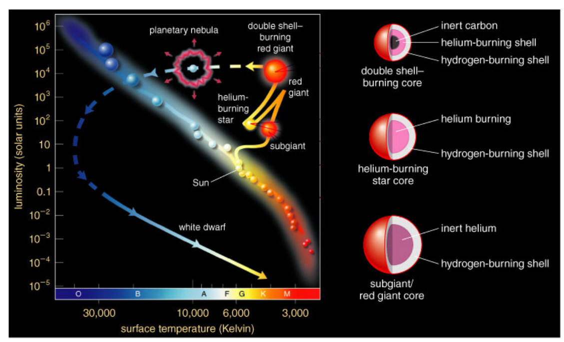
End of Fusion

- Fusion progresses no further in a low-mass star because the core temperature never grows hot enough for fusion of heavier elements (some He fuses to C to make oxygen)
- Degeneracy pressure supports the white dwarf against gravity

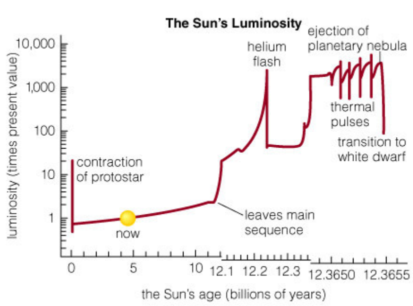


Life stages of a low-mass star like the Sun

Life Track of a Sun-Like Star

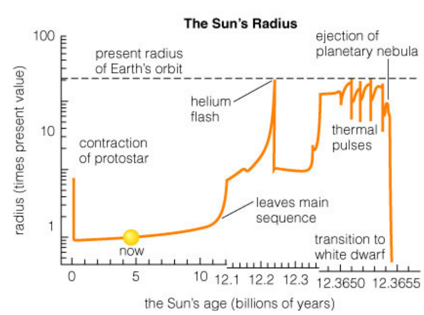


Earth's Fate



- Sun's luminosity will rise to 1,000 times its current level—too hot for life on Earth

Earth's Fate



- Sun's radius will grow to near current radius of Earth's orbit

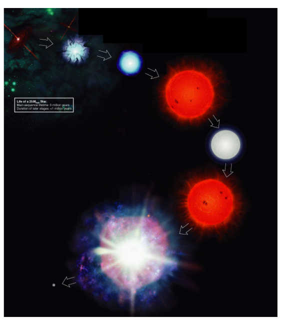
What have we learned?

- What are the life stages of a low-mass star?
  - H fusion in core (main sequence)
  - H fusion in shell around contracting core (red giant)
  - He fusion in core (horizontal branch)
  - Double-shell burning (red giant)
- How does a low-mass star die?
  - Ejection of H and He in a planetary nebula leaves behind an inert white dwarf

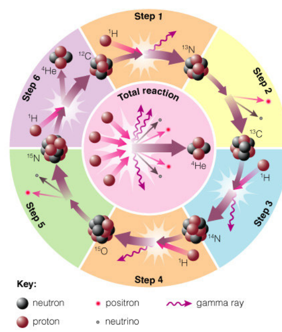
17.3 Life as a High-Mass Star

- 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?



CNO Cycle

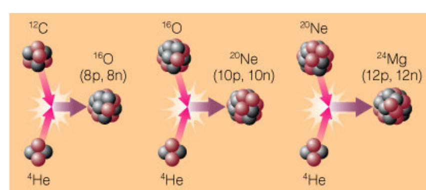


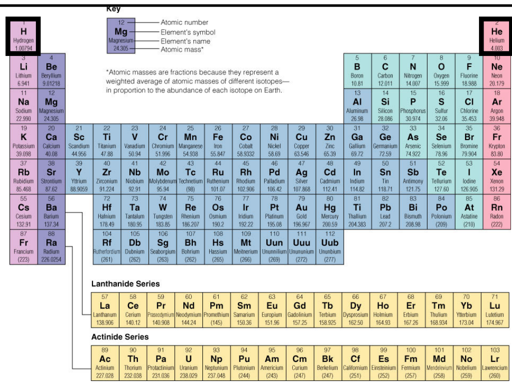
- High-mass main sequence stars fuse H to He at a higher rate using carbon, nitrogen, and oxygen as catalysts
- Greater core temperature enables H nuclei to overcome greater repulsion

Life Stages of High-Mass Stars

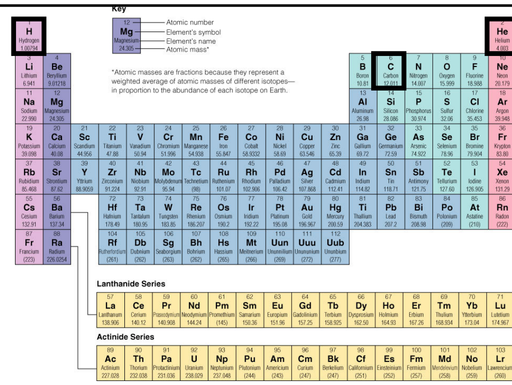
- Late life stages of high-mass stars are similar to those of low-mass stars:
  - Hydrogen core fusion (main sequence)
  - Hydrogen shell burning (supergiant)
  - Helium core fusion (supergiant)

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

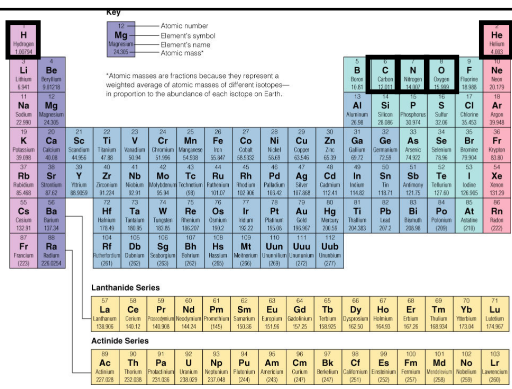




Big Bang made 75% H, 25% He – stars make everything else

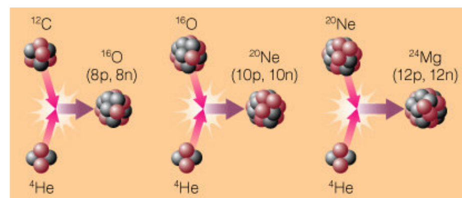


Helium fusion can make carbon in low-mass stars

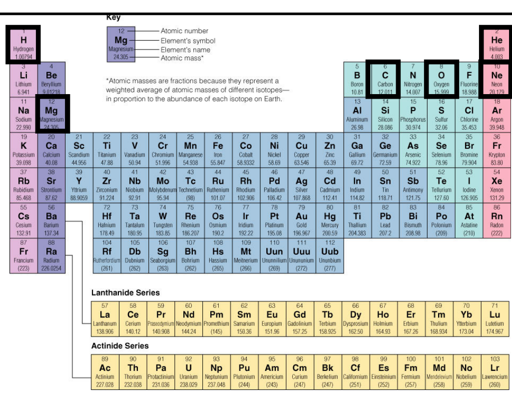


CNO cycle can change C into N and O

Helium Capture

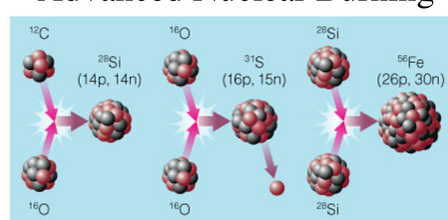


- High core temperatures allow helium to fuse with heavier elements

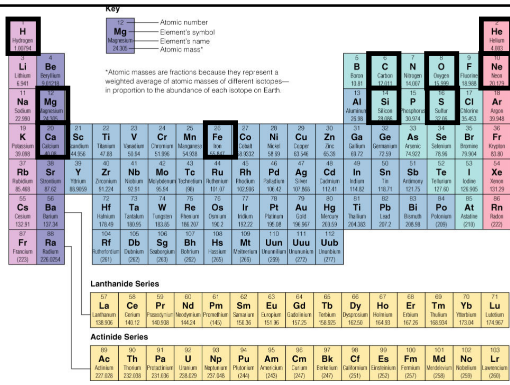


Helium capture builds C into O, Ne, Mg, …

Advanced Nuclear Burning

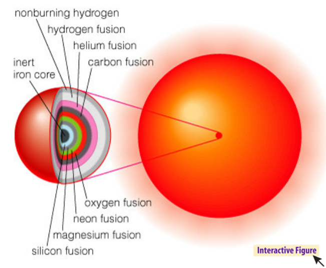


- Core temperatures in stars with $>8M_{\mathrm{Sun}}$ allow fusion of elements as heavy as iron

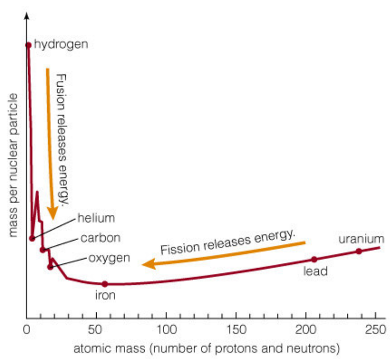


Advanced reactions in stars make elements like Si, S, Ca, Fe

Multiple Shell Burning

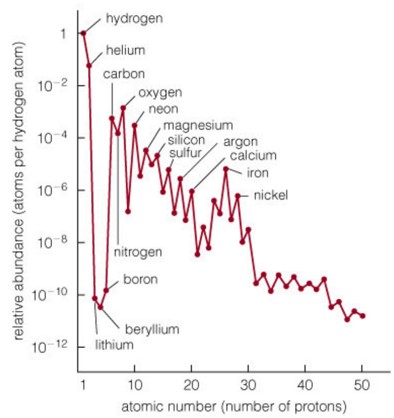


- Advanced nuclear burning proceeds in a series of nested shells



Iron is dead end for fusion because nuclear reactions involving iron do not release energy

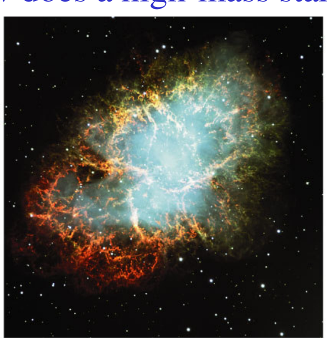
(Fe has lowest mass per nuclear particle)

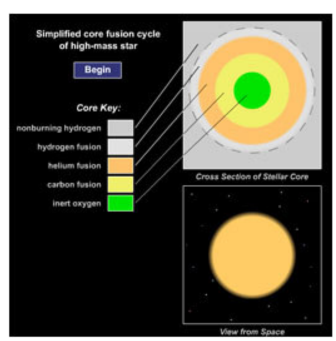


Evidence for helium capture:

Higher abundances of elements with even numbers of protons

How does a high-mass star die?

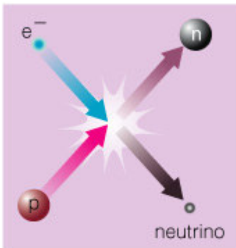




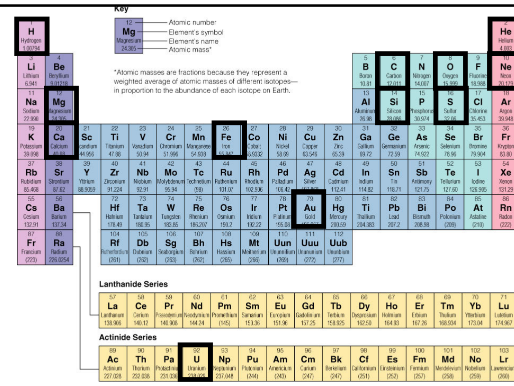
Iron builds up in core until degeneracy pressure can no longer resist gravity

Core then suddenly collapses, creating supernova explosion

Supernova Explosion

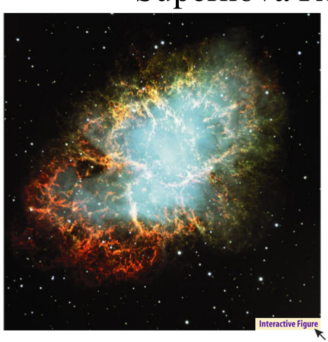


- Core degeneracy pressure goes away because electrons combine with protons, making neutrons and neutrinos
- Neutrons collapse to the center, forming a **neutron star**



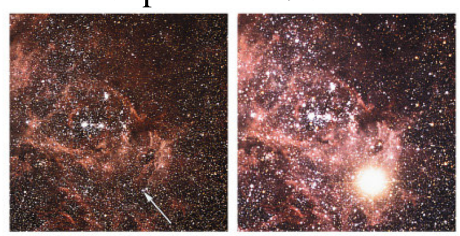
Energy and neutrons released in supernova explosion enable elements heavier than iron to form, including Au and U

Supernova Remnant



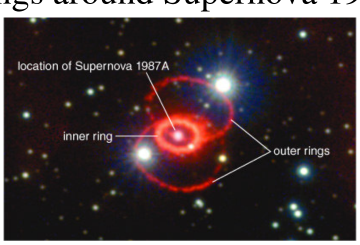
- Energy released by collapse of core drives outer layers into space
- The Crab Nebula is the remnant of the supernova seen in A.D. 1054

Supernova 1987A



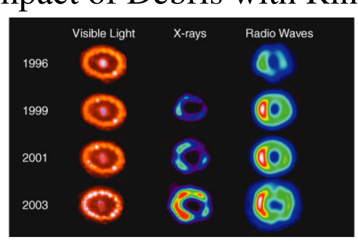
- The closest supernova in the last four centuries was seen in 1987

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 are showing the inner ring light up as debris crashes into it

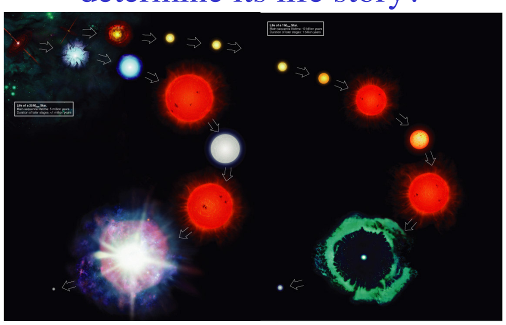
What have we learned?

- 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?
  - Iron core collapses, leading to a supernova

17.4 The Roles of Mass and Mass Exchange

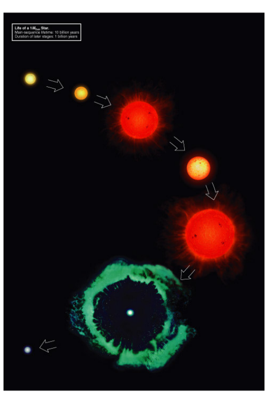
- Our goals for learning
- How does a star's mass determine its life story?
- How are the lives of stars with close companions different?

How does a star's mass determine its life story?



Role of Mass

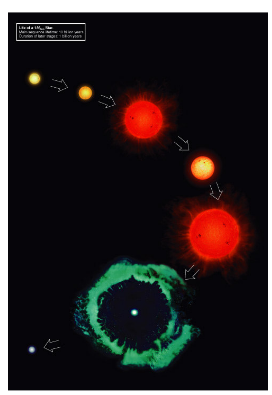
- A star's mass determines its entire life story because it determines its core temperature
- High-mass stars with $>8M_{Sun}$ have short lives, eventually becoming hot enough to make iron, and end in supernova explosions
- Low-mass stars with $<2M_{Sun}$ have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs
- Intermediate mass stars can make elements heavier than carbon but end as white dwarfs



Not to scale!

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 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

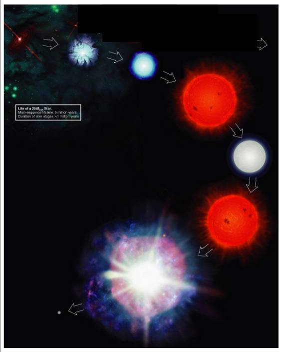


Not to scale!

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 while core is not hot enough for fusion (shell burning)
- Core fusion can't happen if degeneracy pressure keeps core from shrinking

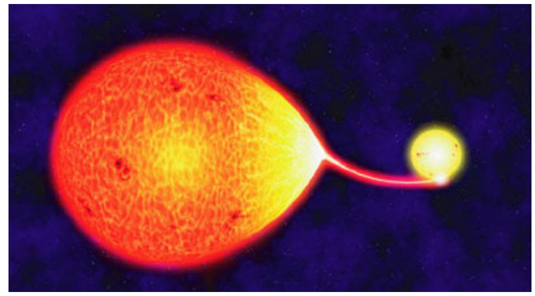
Life Stages of High-Mass Star



Not to scale!

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 while H fuses to He in shell
4. Multiple Shell Burning: Many elements fuse in shells
5. Supernova leaves neutron star behind

How are the lives of stars with close companions different?

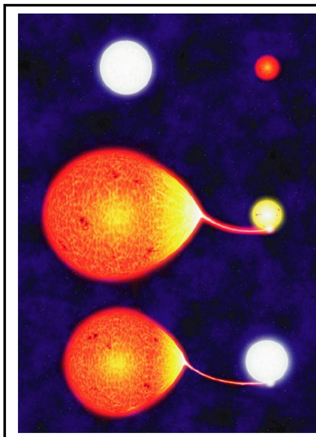


Thought Question

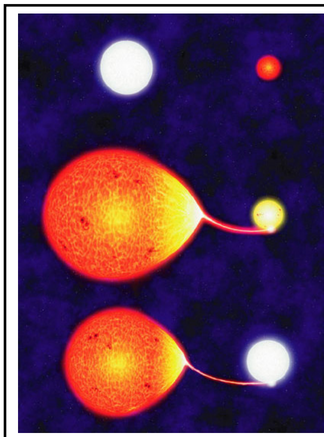
The binary star Algol consists of a 3.7 M_{Sun} main sequence star and a 0.8 M_{Sun} subgiant star.

What's strange about this pairing?

How did it come about?



Stars in Algol are close enough that matter can flow from subgiant onto main-sequence star



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

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