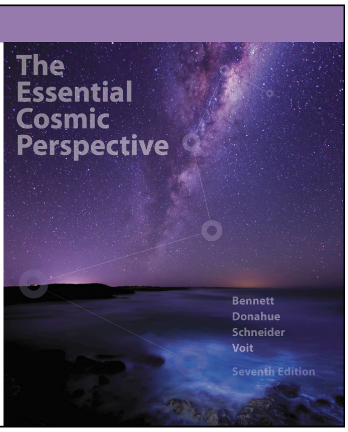
## Lecture Outline

## Chapter 13: Life of Stars



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## 13.1 Star Birth

Our goals for learning:

- How do stars form?
- How massive are newborn stars?

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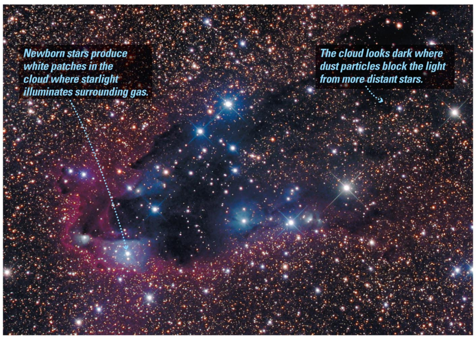
## •How do stars form?



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## Star-Forming Clouds

- Stars form in dark clouds of dusty gas in interstellar space.
- The gas between the stars is called the **interstellar medium.**

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## Gravity Versus Pressure

- Gravity can create stars only if it can overcome the force of thermal pressure in a cloud.
- Gravity within a contracting gas cloud becomes stronger as the gas becomes denser.

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## Mass of a Star-Forming Cloud

- A typical molecular cloud ($T \sim 30$ K, $n \sim 300$ particles/cm$^3$) must contain at least a few hundred solar masses for gravity to overcome pressure.
- The cloud can prevent a pressure buildup by converting thermal energy into infrared and radio photons that escape the cloud.

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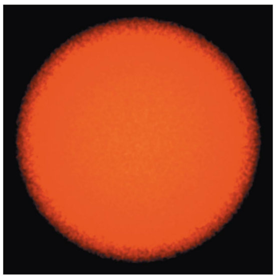
## Fragmentation of a Cloud



**a** The simulation begins with a turbulent gas cloud 1.2 light-years across, containing $50M_{Sun}$ of gas.

- This simulation begins with a turbulent cloud containing 50 solar masses of gas.

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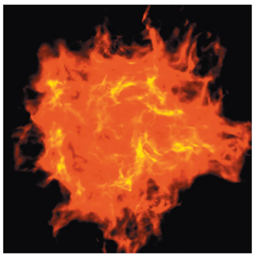
## Fragmentation of a Cloud



**b** Random motions in the cloud cause it to become lumpy, with some regions denser than others. If gravity can overcome pressure in these dense regions, they can collapse to form even denser lumps of matter.

- The random motions of different sections of the cloud cause it to become lumpy.

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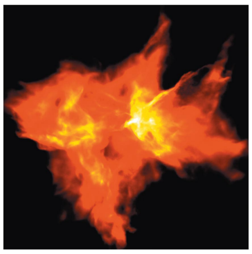
## Fragmentation of a Cloud



**c** The large cloud therefore fragments into many smaller lumps of matter, and each lump can go on to form one or more new stars.

- Each lump of the cloud in which gravity can overcome pressure can go on to become a star.
- A large cloud can make a whole cluster of stars.

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## Glowing Dust Grains

MA INTERACTIVE FIGURE

- As stars begin to form, dust grains that absorb visible light heat up and emit infrared light.

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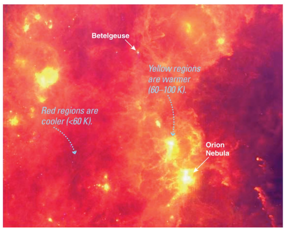
## Glowing Dust Grains



- Long-wavelength infrared light is brightest from regions where many stars are currently forming.

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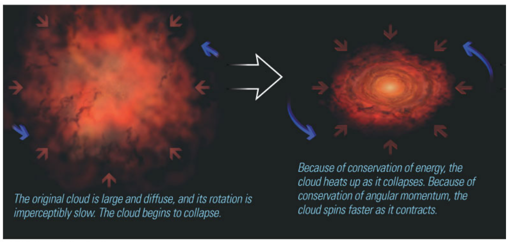
## Solar system formation is a good example of star birth.



The original cloud is large and diffuse, and its rotation is imperceptibly slow. The cloud begins to collapse.

Because of conservation of energy, the cloud heats up as it collapses. Because of conservation of angular momentum, the cloud spins faster as it contracts.

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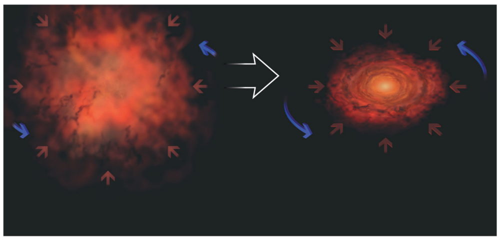
## Heading



- Conservation of energy
  - Gravitational potential → kinetic → thermal

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As gravity causes the cloud to contract, it heats up.

PLAY Collapse of the Solar Nebula

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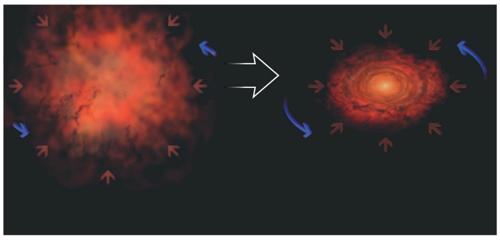
## Spinning



- Conservation of angular momentum
  - The rotational speed of the cloud increased as the cloud contracted.

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Collisions between gas particles in a cloud gradually reduce random motions.

PLAY Formation of Circular Orbits

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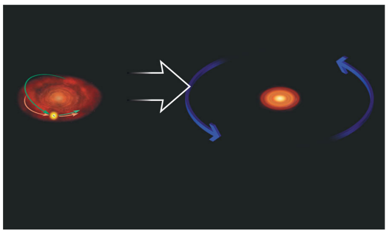
## Flattening



- Collisions between particles caused it to flatten into a disk.
  - Clumps collide and merge with average velocity
  - Collisions between highly elliptical orbits reduce eccentricities
  - Thus, random motions become more orderly

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Collisions between gas particles also reduce up and down motions.

PLAY Why Does the Disk Flatten?

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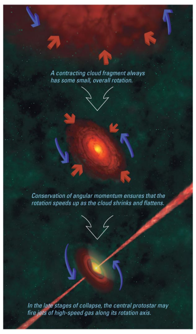
## Formation of Jets



Rotation also causes jets of matter to shoot out along the rotation axis.

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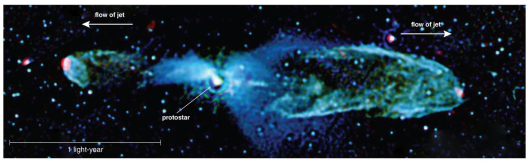

**a** This photograph shows two jets of material being shot in opposite directions by a protostar. The structures to the left and right of the protostar are formed as the jet material rams into surrounding interstellar gas.

Jets are observed coming from the centers of disks around protostars.

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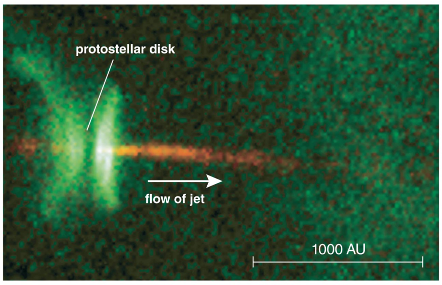

**b** This photograph shows a close-up view of a jet (red) and a disk of gas (green) around a protostar. We are seeing the disk nearly edge-on. The top and bottom surfaces of the disk are glowing, but we cannot see the darker middle layers of the disk.

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## Protostar to Main Sequence

- A protostar contracts and heats until the core temperature is sufficient for hydrogen fusion.
- Contraction ends when energy released by hydrogen fusion balances energy radiated from the surface.
- It takes 30 million years for a star like the Sun (less time for more massive stars).

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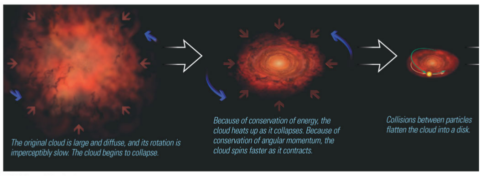
## *Summary of Star Birth*

1. Gravity causes gas cloud to shrink and fragment.
2. Core of shrinking cloud heats up.
3. When core gets hot enough, fusion begins and stops the shrinking.
4. New star achieves long-lasting state of balance



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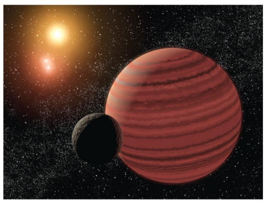
## •How massive are newborn stars?



**a** Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

**b** An infrared image showing brown dwarfs (circled) in the constellation Orion. They are easier to spot in star-forming regions like this one than elsewhere in our galaxy, because young brown dwarfs still have much of the thermal energy left by the process of gravitational contraction. They therefore emit measurable amounts of infrared light.

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A cluster of many stars can form out of a single cloud.

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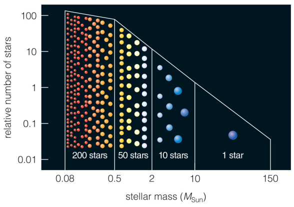

- Very massive stars are rare.
- Low-mass stars are common.

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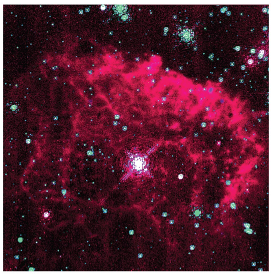
## Upper Limit on a Star's Mass



- Photons exert a slight amount of pressure when they strike matter.
- Very massive stars are so luminous that the collective pressure of photons drives their matter into space.

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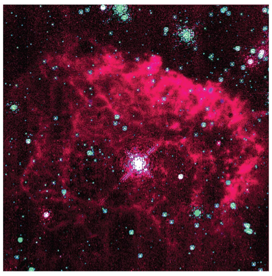
## Upper Limit on a Star's Mass



- Models of stars suggest that radiation pressure limits how massive a star can be without blowing itself apart.
- Observations have not found stars more massive than about $300M_{Sun}$.

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## Lower Limit on a Star's Mass

- Fusion will not begin in a contracting cloud if some sort of force stops contraction before the core temperature rises above $10^7$ K.
- Thermal pressure cannot stop contraction because the star is constantly losing thermal energy from its surface through radiation.
- Is there another form of pressure that can stop contraction?

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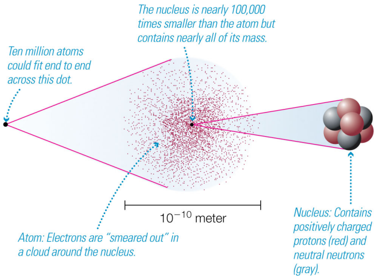

**Degeneracy Pressure:**

Laws of quantum mechanics prohibit two electrons from occupying the same state in the same place.

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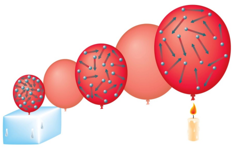

**Thermal Pressure:**

Depends on heat content

The main form of pressure in most stars

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**a** When there are many more available places (chairs) than particles (people), a particle is unlikely to try to occupy the same place as another particle. The only pressure comes from the temperature-related motion of the particles.

**b** When the number of particles (people) approaches the number of available places (chairs), finding an available place requires that the particles move faster than they would otherwise. The extra motion creates degeneracy pressure.

**Degeneracy Pressure:**

Particles can't be in same state in same place

Doesn't depend on heat content

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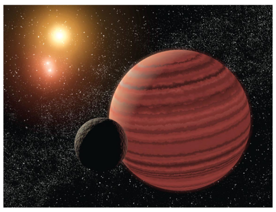
## Brown Dwarfs



**a** Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

- Degeneracy pressure halts the contraction of objects with <0.08$M_{\text{Sun}}$ before the core temperature becomes hot enough for fusion.
- Starlike objects not massive enough to start fusion are **brown dwarfs**.

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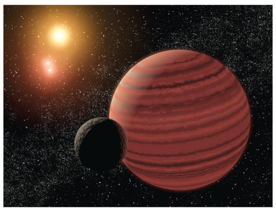
## Brown Dwarfs



**a** Artist's conception of a brown dwarf, orbited by a planet (to its left) in a system with multiple stars. The reddish color approximates how a brown dwarf would appear to human eyes. The bands are shown because we expect brown dwarfs to look more like giant jovian planets than stars.

- A brown dwarf emits infrared light because of heat left over from contraction.
- Its luminosity gradually declines with time as it loses thermal energy.

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## Brown Dwarfs in Orion

**b** An infrared image showing brown dwarfs (circled) in the constellation Orion. They are easier to spot in star-forming regions like this one than elsewhere in our galaxy, because young brown dwarfs still have much of the thermal energy left by the process of gravitational contraction. They therefore emit measurable amounts of infrared light.

- Infrared observations can reveal recently formed brown dwarfs because they are still relatively warm and luminous.

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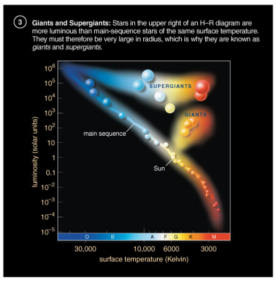

③ **Giants and Supergiants:** Stars in the upper right of an H–R diagram are more luminous than main-sequence stars of the same surface temperature. They must therefore be very large in radius, which is why they are known as *giants* and *supergiants*.

- Stars more massive than 300$M_{\text{Sun}}$ would blow apart.
- Stars less massive than 0.08$M_{\text{Sun}}$ can't sustain fusion.

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## What have we learned?

- How do stars form?
  - Stars are born in cold, relatively dense molecular clouds.
  - As a cloud fragment collapses under gravity, it becomes a protostar surrounded by a spinning disk of gas.
  - The protostar may also fire jets of matter outward along its poles.

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## What have we learned?

- How massive are newborn stars?
  - Stars greater than about $300M_{\text{Sun}}$ would be so luminous that radiation pressure would blow them apart.
  - Degeneracy pressure stops the contraction of objects $<0.08M_{\text{Sun}}$ before fusion starts.

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## 13.2 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?

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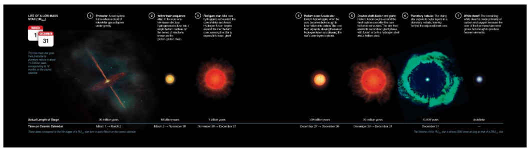
## •What are the life stages of a low-mass star?



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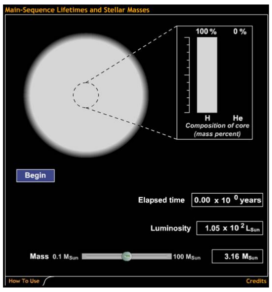

- A star remains on the main sequence as long as it can fuse hydrogen into helium in its core.

PLAY Main-Sequence Lifetimes and Stellar Masses

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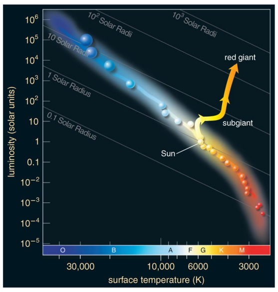
## Life Track After Main Sequence



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

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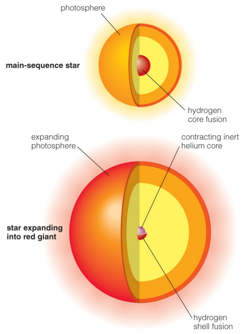
## Broken Thermostat



- 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.

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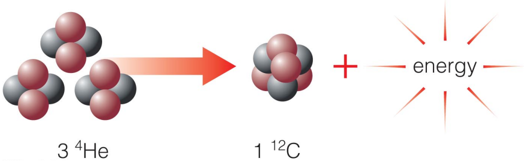

- Helium fusion does not begin right away because it requires higher temperatures than hydrogen fusion—larger charge leads to greater repulsion.
- The fusion of two helium nuclei doesn't work, so helium fusion must combine three He nuclei to make carbon.

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## Helium Flash

- The thermostat is broken in a low-mass red giant because degeneracy pressure supports the core.
- The core temperature rises rapidly when helium fusion begins.
- The helium fusion rate skyrockets until thermal pressure takes over and expands the core again.

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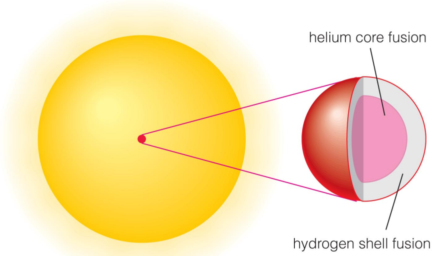

Helium core-fusion stars neither shrink nor grow because the core thermostat is temporarily fixed.

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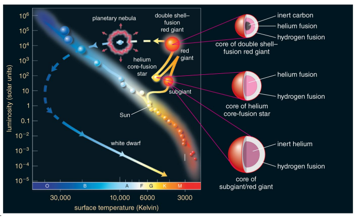
## Life Track After Helium Flash

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



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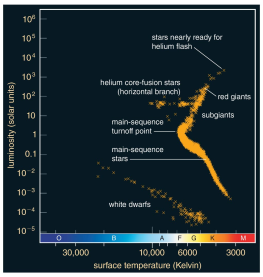
## Life Track After Helium Flash



- Observations of star clusters agree with these models.
- Helium core-fusion stars are found in a *horizontal branch* on the H-R diagram.

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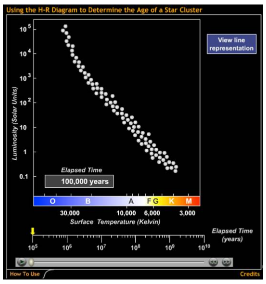

- Combining models of stars of similar age but different mass helps us to age-date star clusters.

PLAY Using the H-R Diagram to Determine the Age of a Star Cluster

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## •How does a low-mass star die?

a Helix Nebula. The central white dot is the hot white dwarf.

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## Double Shell Fusion

- 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–fusion stage never reaches equilibrium—the fusion rate periodically spikes upward in a series of *thermal pulses*.
- With each spike, convection dredges carbon up from the core and transports it to the surface.

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## Planetary Nebulae

b Butterfly Nebula. The hot white dwarf is hidden in the dark ring of dust at the center.

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

a Helix Nebula. The central white dot is the hot white dwarf.

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## 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.

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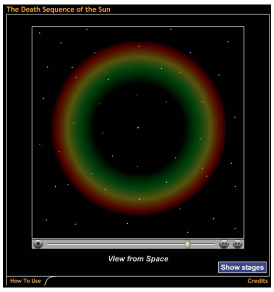

- Life stages of a low-mass star such as the Sun

PLAY The Death Sequence of the Sun

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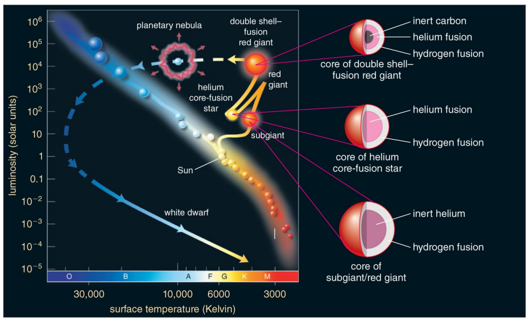
## Life Track of a Sun-Like Star



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## 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–fusion (red giant)
- How does a low-mass star die?
  - Ejection of H and He in a planetary nebula leaves behind an inert white dwarf.

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## 13.3 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?

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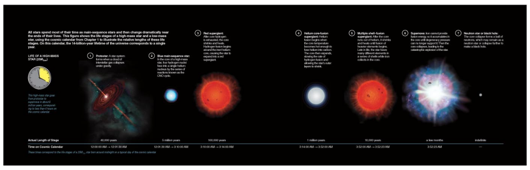
## •What are the life stages of a high-mass star?



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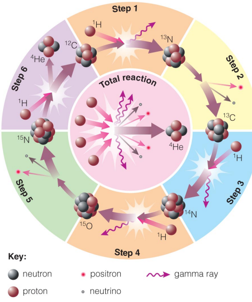
## CNO Cycle



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

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## 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 fusion (supergiant)
  - Helium core fusion (supergiant)

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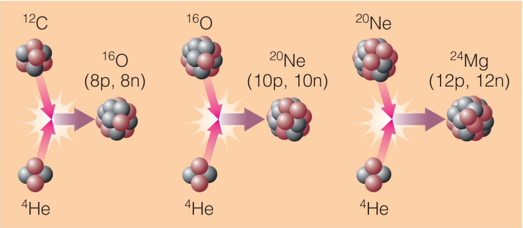
## How do high-mass stars make the elements necessary for life?



**a** Helium-capture reactions.

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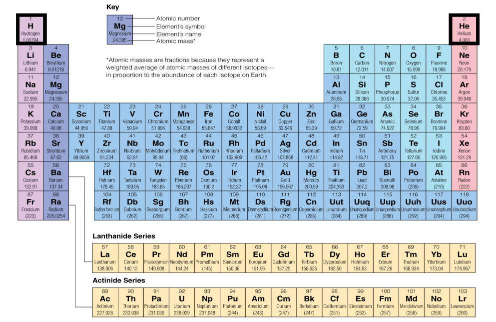

Big Bang made 75% H, 25% He—stars make everything else.

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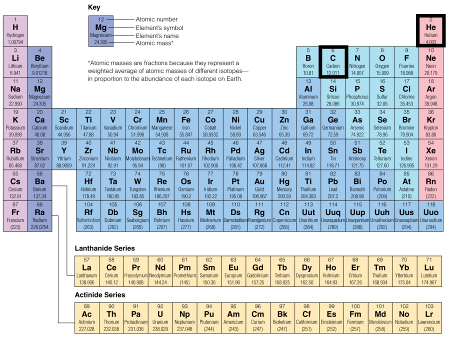

Helium fusion can make carbon in low-mass stars.

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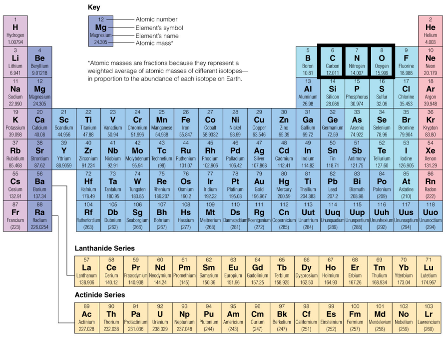

The CNO cycle can change C into N and O

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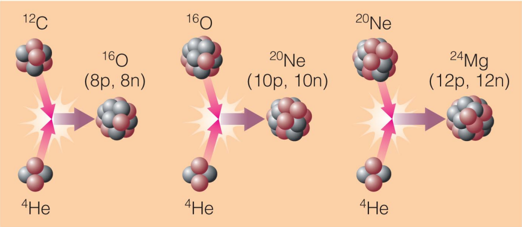
## Helium Capture



**a** Helium-capture reactions.

- High core temperatures allow helium to fuse with heavier elements.

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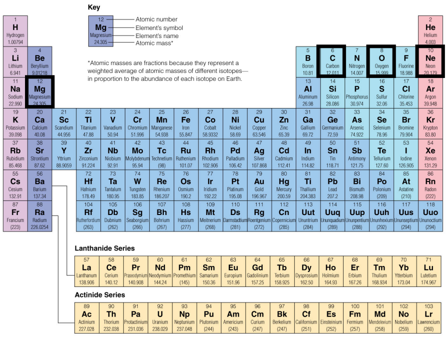

Helium capture builds C into O, Ne, Mg …

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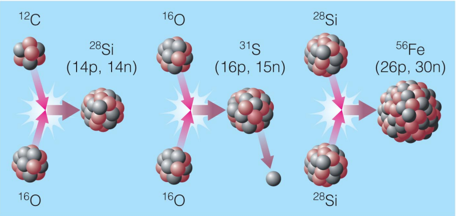
## Advanced Nuclear Burning



**b** Other reactions. (Note: Fusion of two silicon nuclei first produces nickel-56, which decays rapidly to cobalt-56 and then to iron-56.)

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

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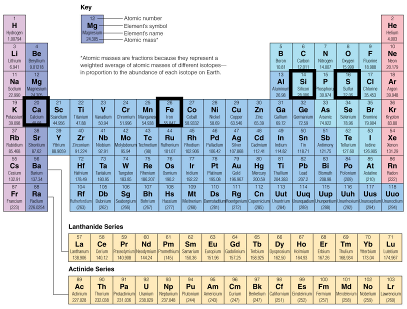

Advanced reactions in stars make elements such as Si, S, Ca, and Fe.

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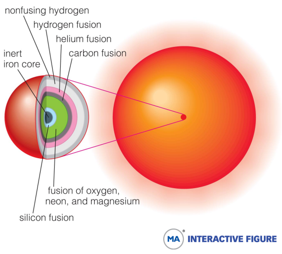
## Multiple Shell Burning



- Advanced nuclear burning proceeds in a series of nested shells.

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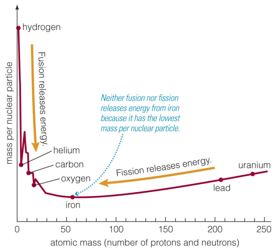

Iron is a dead end for fusion because nuclear reactions involving iron do not release energy.

(Fe has lowest mass per nuclear particle.)

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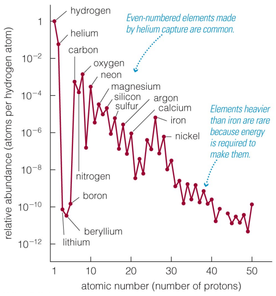

Evidence for helium capture:

Higher abundances of elements with even numbers of protons

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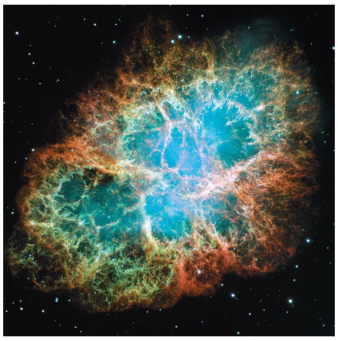
## •How does a high-mass star die?



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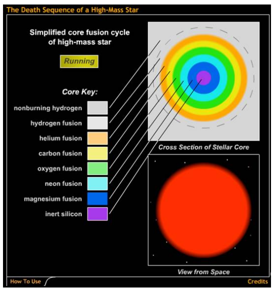

- Iron builds up in the core until degeneracy pressure can no longer resist gravity.
- The core then suddenly collapses, creating a supernova explosion.

PLAY The Death Sequence of a High-Mass Star

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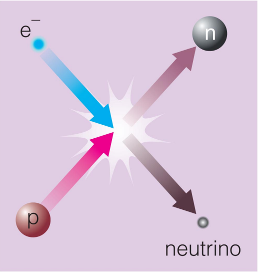
## Supernova Explosion



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

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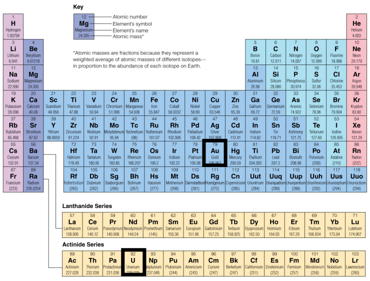

Energy and neutrons released in a supernova explosion enable elements heavier than iron to form, including Au and U.

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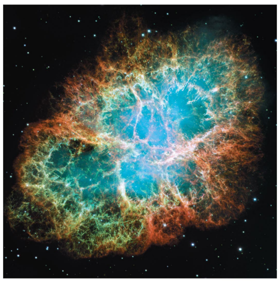
## Supernova Remnant



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

MA INTERACTIVE FIGURE

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## Supernova 1987A

**Before.** The arrow points to the star observed to explode in 1987.

**After.** The supernova actually appeared as a bright point of light. It appears larger than a point in this photograph only because of overexposure.

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

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## Summary - Role of Mass

- A star's mass determines its entire life story because it determines its core temperature.
- High-mass stars have short lives, eventually becoming hot enough to make iron, and end in supernova explosions.
- Low-mass stars have long lives, never become hot enough to fuse carbon nuclei, and end as white dwarfs.

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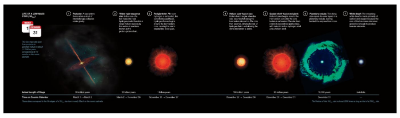
## Summary - Life Stages of Low-Mass Star

1. Main Sequence: H fuses to He in core
2. Red Giant: H fuses to He in shell around He core
3. Helium Core Fusion:  
   He fuses to C in core while H fuses to He in shell
4. Double Shell Fusion:  
   H and He both fuse in shells
5. Planetary Nebula: leaves white dwarf behind



***Not to scale!***

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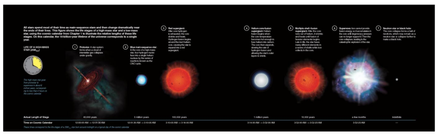
## Summary - Reasons for Life Stages

- 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.



***Not to scale!***

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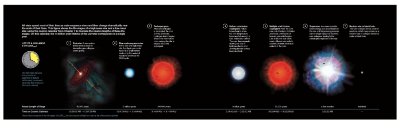
## Summary - Life Stages of High-Mass Star

1. Main Sequence: H fuses to He in core
2. Red Supergiant: H fuses to He in shell around He core
3. Helium Core Fusion:
   He fuses to C in core while H fuses to He in shell
4. Multiple Shell Fusion:
   many elements fuse in shells
5. Supernova leaves neutron star behind



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## 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?
  - The iron core collapses, leading to a supernova.

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## 13.4 Stars in Close Binaries

Our goals for learning:

- How are the lives of stars with close companions different?

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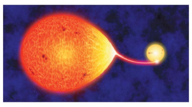
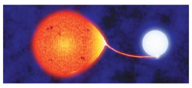
## •How are the lives of stars with close companions different?

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).



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.



Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

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## 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?

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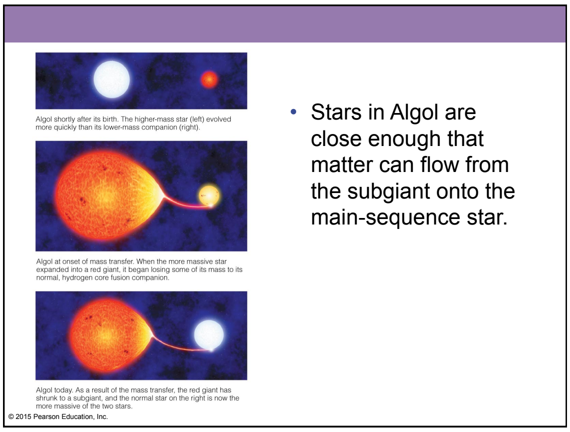

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).

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.

Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

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

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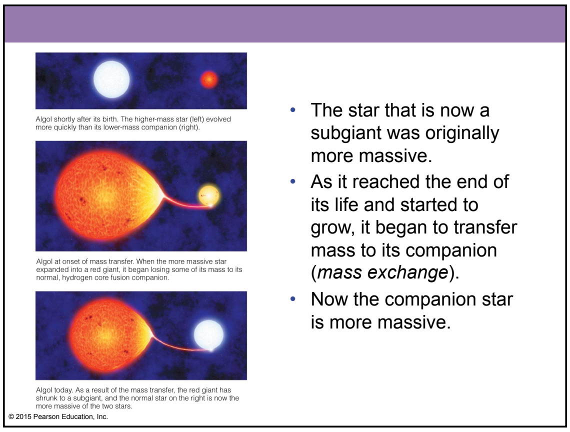

Algol shortly after its birth. The higher-mass star (left) evolved more quickly than its lower-mass companion (right).

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.

Algol today. As a result of the mass transfer, the red giant has shrunk to a subgiant, and the normal star on the right is now the more massive of the two stars.

- 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.

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## What have we learned?

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

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