ASTRONOMY

Chapter 22 STARS FROM ADOLESCENCE TO OLD AGE

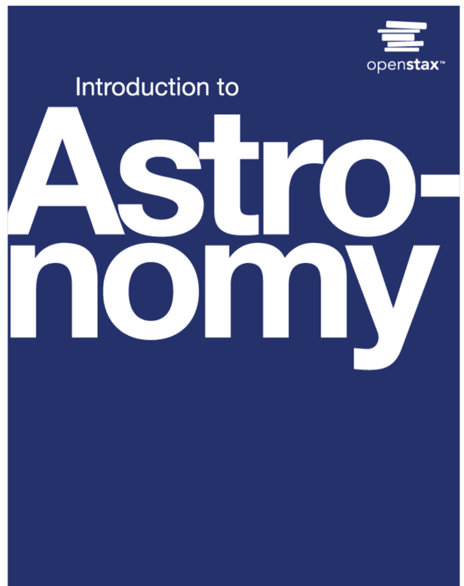

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FIGURE 22.1

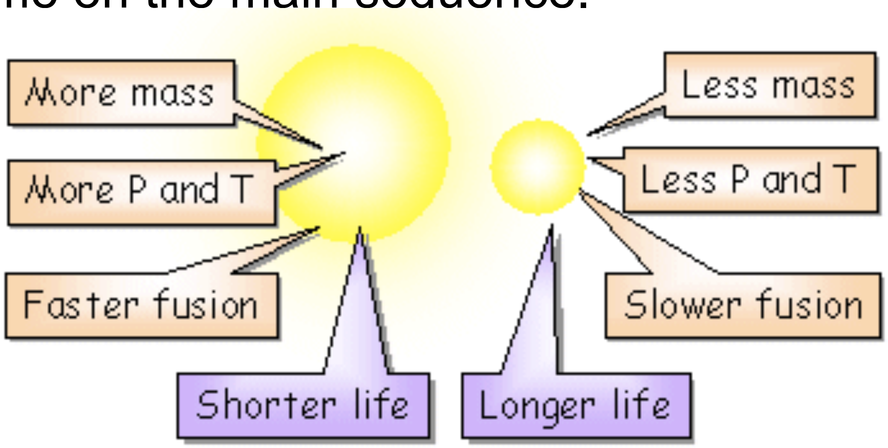
Ant Nebula. During the later phases of stellar evolution, stars expel some of their mass, which returns to the interstellar medium to form new stars. This Hubble Space Telescope image shows a star losing mass. Known as Menzel 3, or the Ant Nebula, this beautiful region of expelled gas is about 3000 light-years away from the Sun. We see a central star that has ejected mass preferentially in two opposite directions. The object is about 1.6 light-years long. The image is color coded—red corresponds to an emission line of sulfur, green to nitrogen, blue to hydrogen, and blue/violet to oxygen. (credit: modification of work by NASA, ESA and The Hubble Heritage Team (STScI/AURA))

THE RING NEBULA

MAIN SEQUENCE LIFETIME

Massive stars need higher central temperatures and pressures to support themselves against gravitational collapse, and for this reason, fusion reactions in these stars proceed at a faster rate than in lower mass stars.

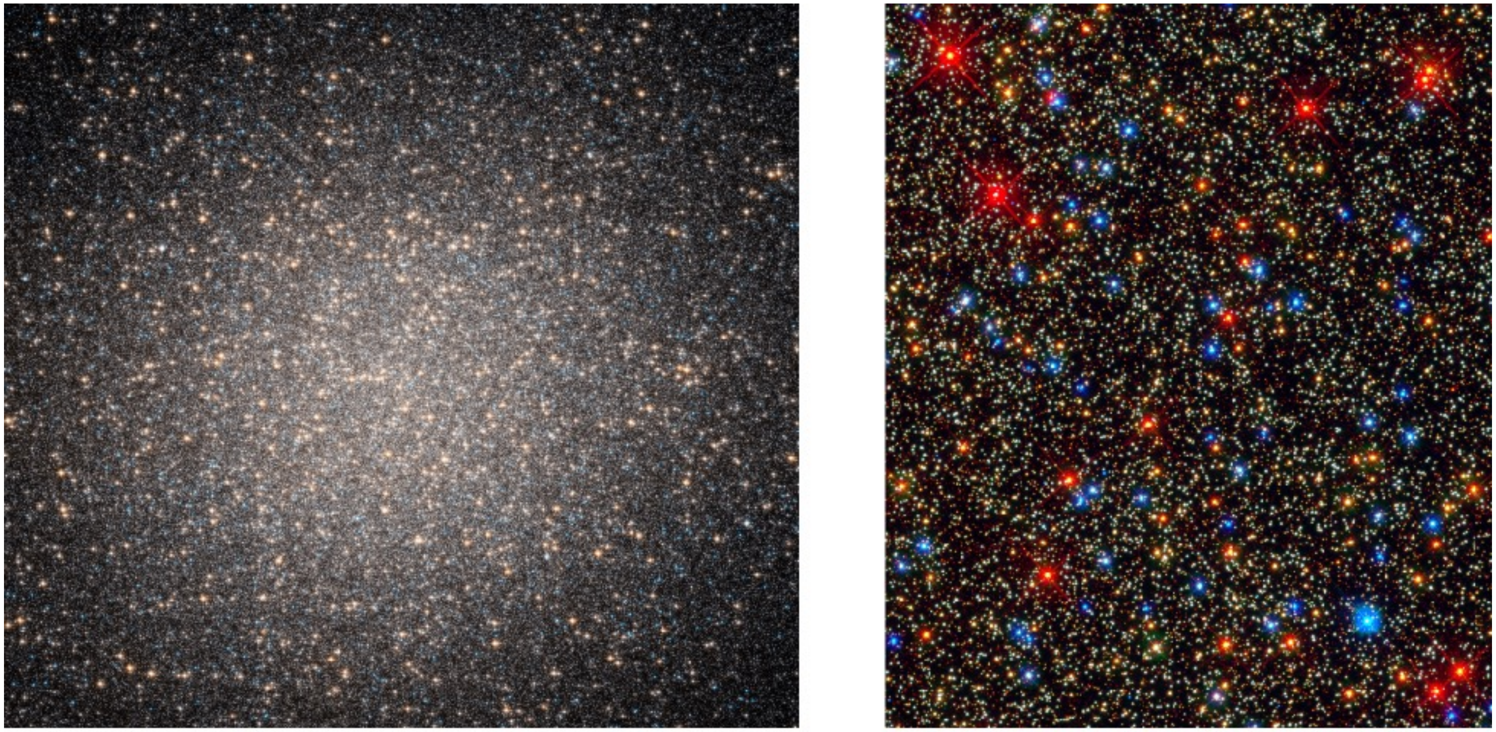
The result is that massive stars use up their core hydrogen fuel rapidly and spend less time on the main sequence.



In the above image, T refers to the temperature of the star, and P refers to the **pressure**.

http://astronomy.swin.edu.au/cosmos/M/Main+Sequence+Lifetime

FIGURE 22.6



(a) (b)

Omega Centauri.

(a) Located at about 16,000 light-years away, Omega Centauri is the most massive globular cluster in our Galaxy. It contains several million stars.

(b) This image, taken with the Hubble Space Telescope, zooms in near the center of Omega Centauri. The image is about 6.3 light-years wide. The most numerous stars in the image, which are yellow-white in color, are main-sequence stars similar to our Sun. The brightest stars are red giants that have begun to exhaust their hydrogen fuel and have expanded to about 100 times the diameter of our Sun. The blue stars have started helium fusion. (credit a: modification of work by NASA, ESA and the Hubble Heritage Team (STScI/AURA); credit b: modification of work by NASA, ESA, and the Hubble SM4 ERO Team)

FIGURE 22.8

Young Cluster H–R Diagram. We see an H–R diagram for a hypothetical young cluster with an age of 3 million years. Note that the high-mass (high-luminosity) stars have already arrived at the main-sequence stage of their lives, while the lower-mass (lower-luminosity) stars are still contracting toward the zero-age main sequence (the red line) and are not yet hot enough to derive all of their energy from the fusion of hydrogen.

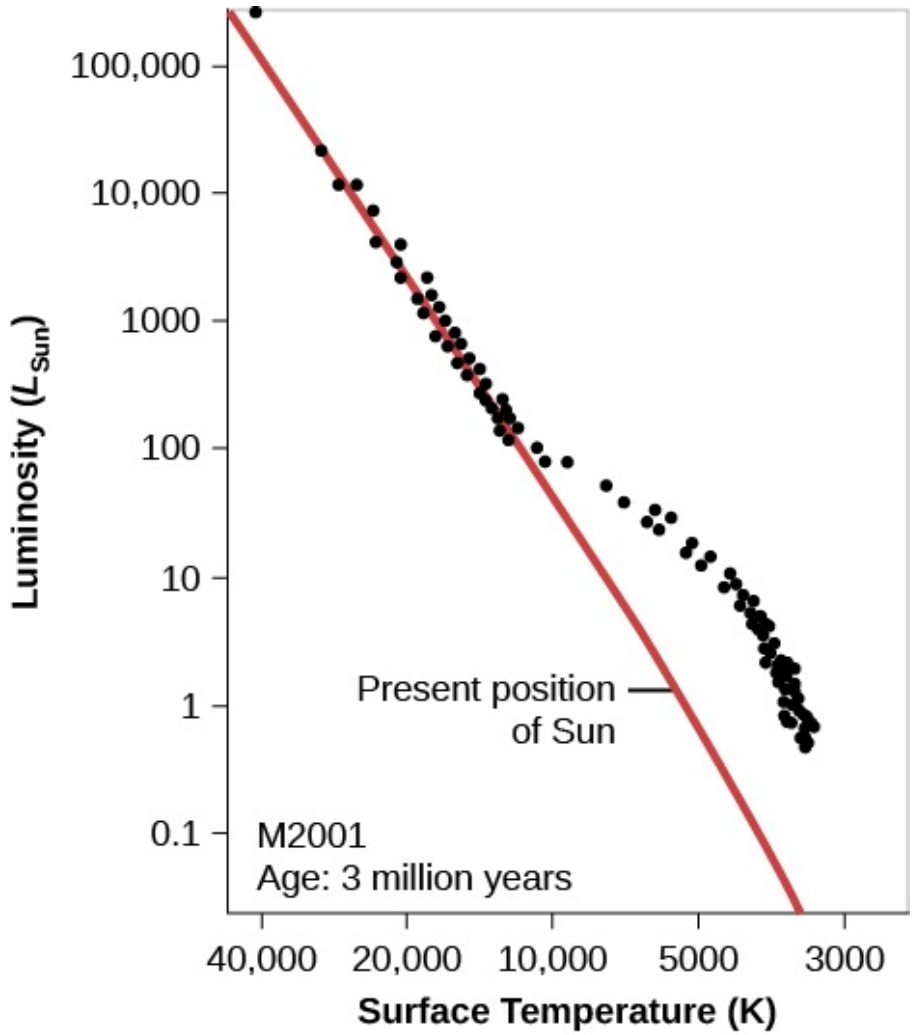
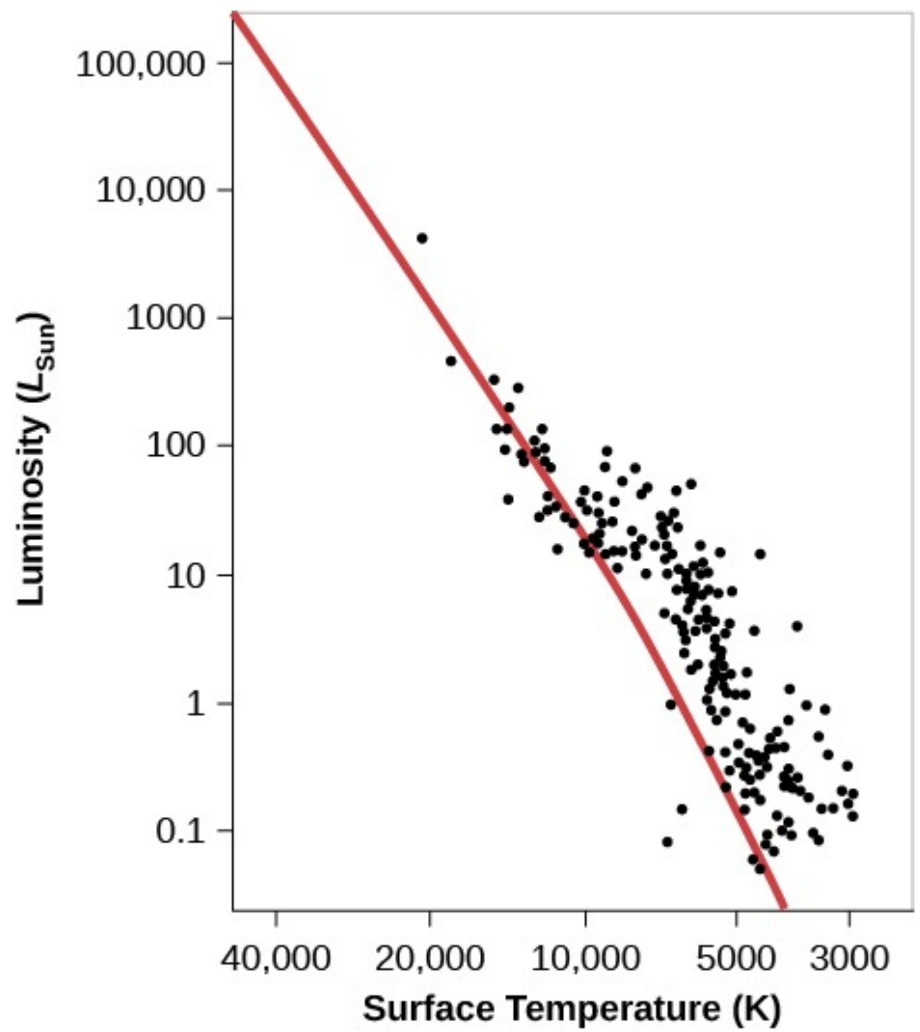


FIGURE 22.9

Young Cluster NGC 2264. Located about 2600 light-years from us, this region of newly formed stars, known as the Christmas Tree Cluster, is a complex mixture of hydrogen gas (which is ionized by hot embedded stars and shown in red), dark obscuring dust lanes, and brilliant young stars. The image shows a scene about 30 light-years across. (credit: ESO)

FIGURE 22.10

NGC 2264 H–R Diagram. Compare this H–R diagram to that in **Figure 22.8**; although the points scatter a bit more here, the theoretical and observational diagrams are remarkably, and satisfyingly, similar.



THE END OF THE MAIN SEQUENCE PHASE

The main sequence, hydrogen burning, stage for a star with the same mass as the Sun lasts for about 10^{10} years.

Main sequence stage is finished when supply of Hydrogen in the inner 10% of the Sun runs out.

At the end of this phase we have an inner core of Helium surrounded by Hydrogen.

The temperature at the core is only about 15 million Kelvin, which is hot enough for Hydrogen fusion to occur, but too cool for Helium fusion.

The temperature outside of the core is cooler and is not hot enough for Hydrogen fusion.

Not possible for any nuclear reactions to occur!!

No source of energy to create outward pressure to balance gravity.

The core of the star will begin to slowly collapse.

The collapse of the core will cause it to heat up.

http://www.ualberta.ca/~pogosyan/teaching/ASTRO_122/lect17/lecture17.html

THE RED GIANT STAGE

As the contracting core heats up, a shell of hydrogen around the inert Helium core will heat up to 15 million K and begin to fuse.

This begins the phase of shell-Hydrogen burning.

The burning of Hydrogen in the shell actually produces more energy than in the main sequence phase (due to the higher T).

However, the inert Hydrogen outside of the shell hinders the movement of the photons.

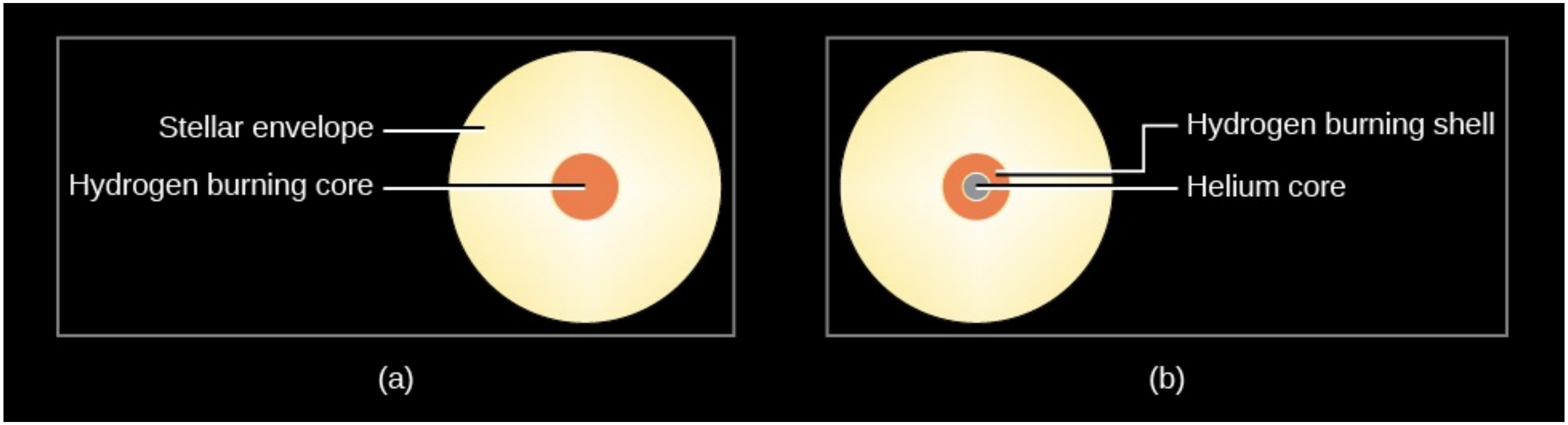
When photons have trouble moving through a medium, they end up pushing outwards on the matter.

This is called radiation pressure.

The extra photons produced in the shell of hydrogen push outwards on the outer layers of the star.

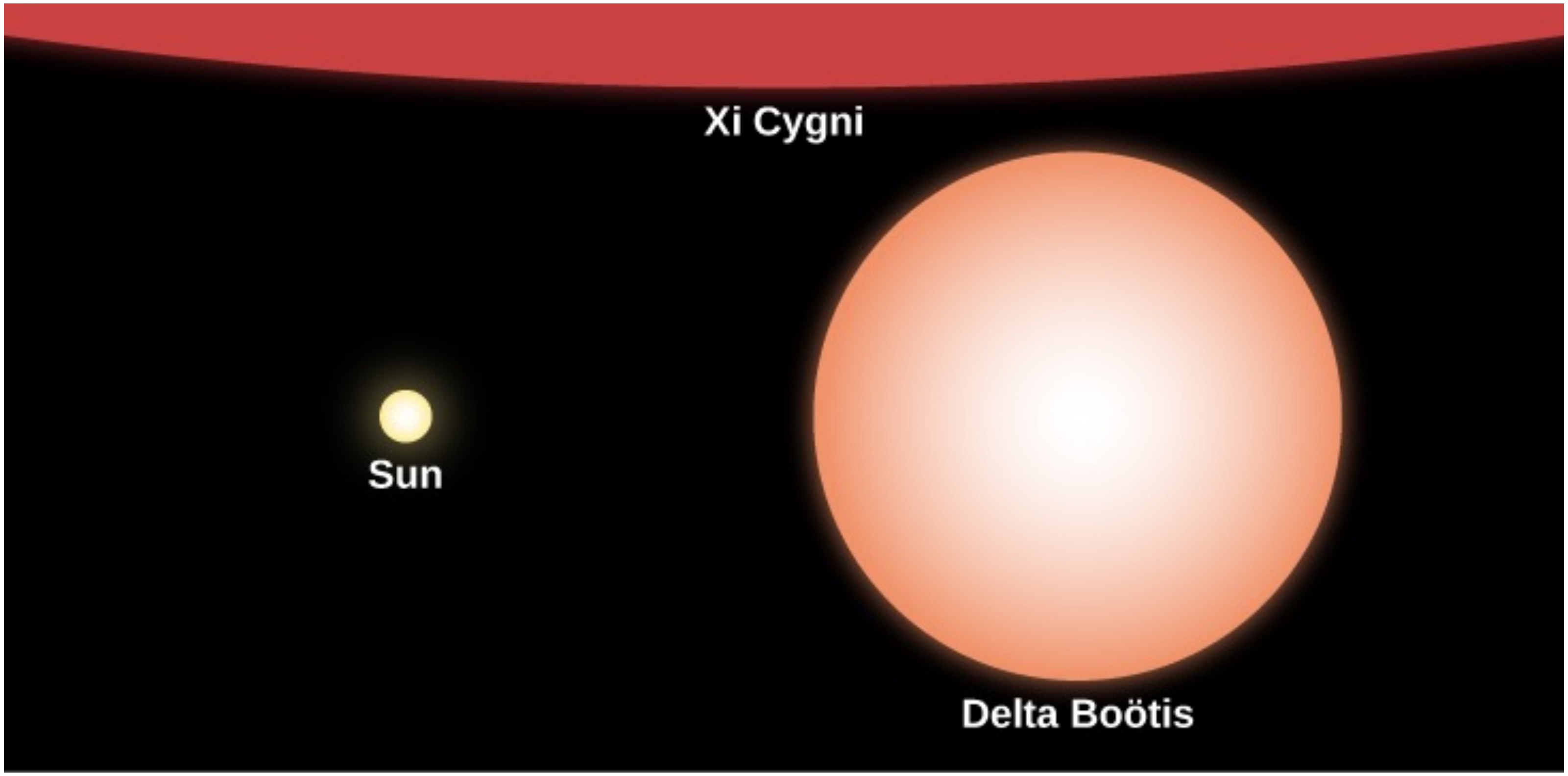
The expansion of the outer layers causes them to cool down.

FIGURE 22.2



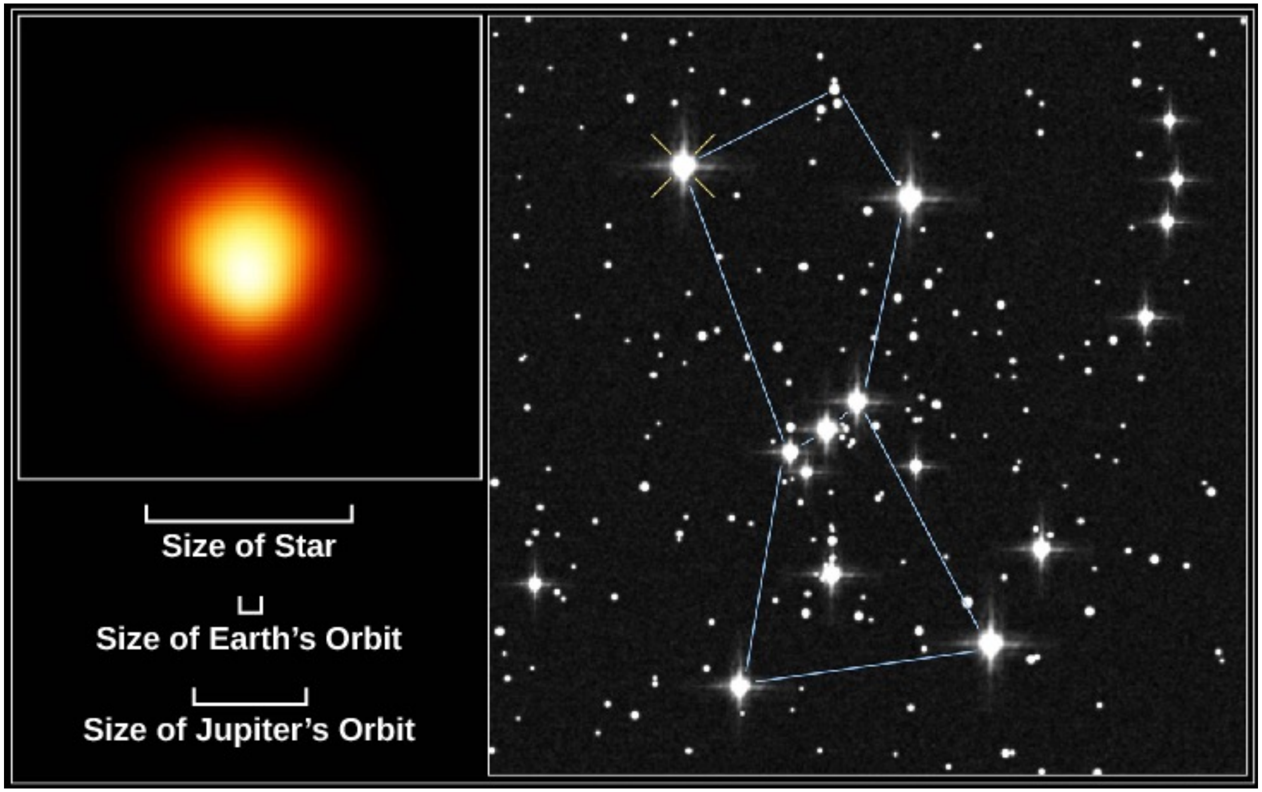
Star Layers during and after the Main Sequence. (a) During the main sequence, a star has a core where fusion takes place and a much larger envelope that is too cold for fusion. (b) When the hydrogen in the core is exhausted (made of helium, not hydrogen), the core is compressed by gravity and heats up. The additional heat starts hydrogen fusion in a layer just outside the core. Note that these parts of the Sun are not drawn to scale.

FIGURE 22.3



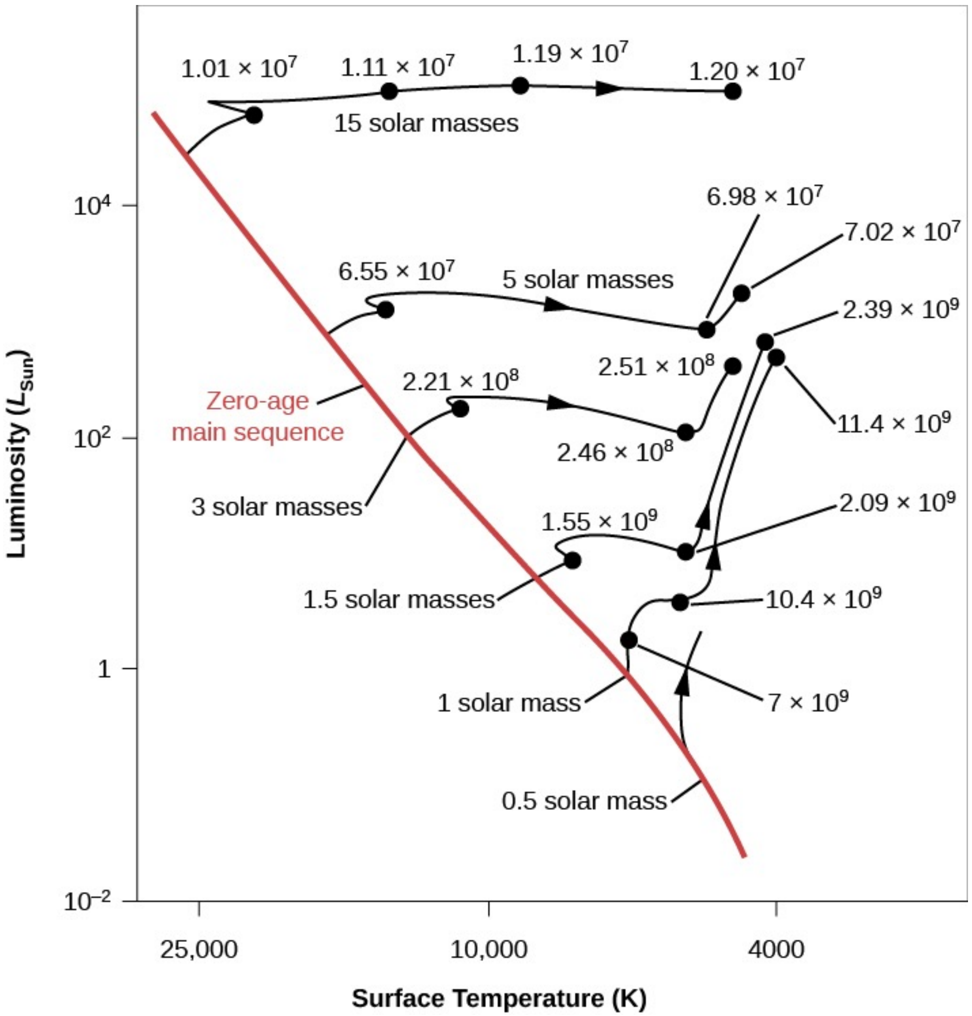
Relative Sizes of Stars. This image compares the size of the Sun to that of Delta Boötis, a giant star, and Xi Cygni, a supergiant. Note that Xi Cygni is so large in comparison to the other two stars that only a small portion of it is visible at the top of the frame.

FIGURE 22.4



Betelgeuse. Betelgeuse is in the constellation Orion, the hunter; in the right image, it is marked with a yellow "X" near the top left. In the left image, we see it in ultraviolet with the Hubble Space Telescope, in the first direct image ever made of the surface of another star. As shown by the scale at the bottom, Betelgeuse has an extended atmosphere so large that, if it were at the center of our solar system, it would stretch past the orbit of Jupiter. (credit: Modification of work by Andrea Dupree (Harvard-Smithsonian CfA), Ronald Gilliland (STScI), NASA and ESA)

FIGURE 22.5

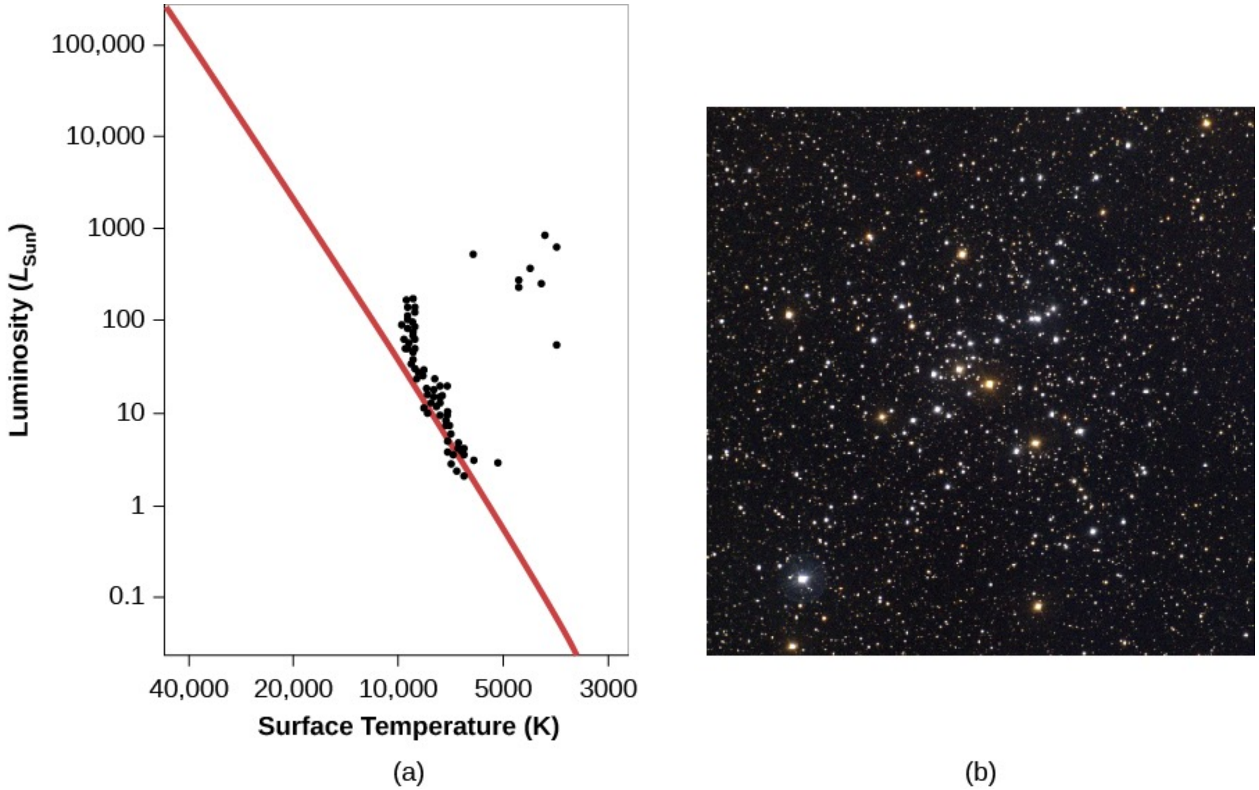


Evolutionary Tracks of Stars of Different Masses. The solid black lines show the predicted evolution from the main sequence through the red giant or supergiant stage on the H–R diagram. Each track is labeled with the mass of the star it is describing. The numbers show how many years each star takes to become a giant after leaving the main sequence. The red line is the zero-age main sequence.

FIGURE 22.11

NGC 3293. All the stars in an open star cluster like NGC 3293 form at about the same time. The most massive stars, however, exhaust their nuclear fuel more rapidly and hence evolve more quickly than stars of low mass. As stars evolve, they become redder. The bright orange star in NGC 3293 is the member of the cluster that has evolved most rapidly. (credit: ESO/G. Beccari)

FIGURE 22.12



Cluster M41.

(a) Cluster M41 is older than NGC 2264 (see **Figure 22.10**) and contains several red giants. Some of its more massive stars are no longer close to the zero-age main sequence (red line).

(b) This ground-based photograph shows the open cluster M41. Note that it contains several orange-color stars. These are stars that have exhausted hydrogen in their centers, and have swelled up to become red giants. (credit b: modification of work by NOAO/AURA/NSF)

FIGURE 22.14

Cluster 47 Tucanae. This H–R diagram is for the globular cluster 47. Note that the scale of luminosity differs from that of the other H–R diagrams in this chapter. We are only focusing on the lower portion of the main sequence, the only part where stars still remain in this old cluster.

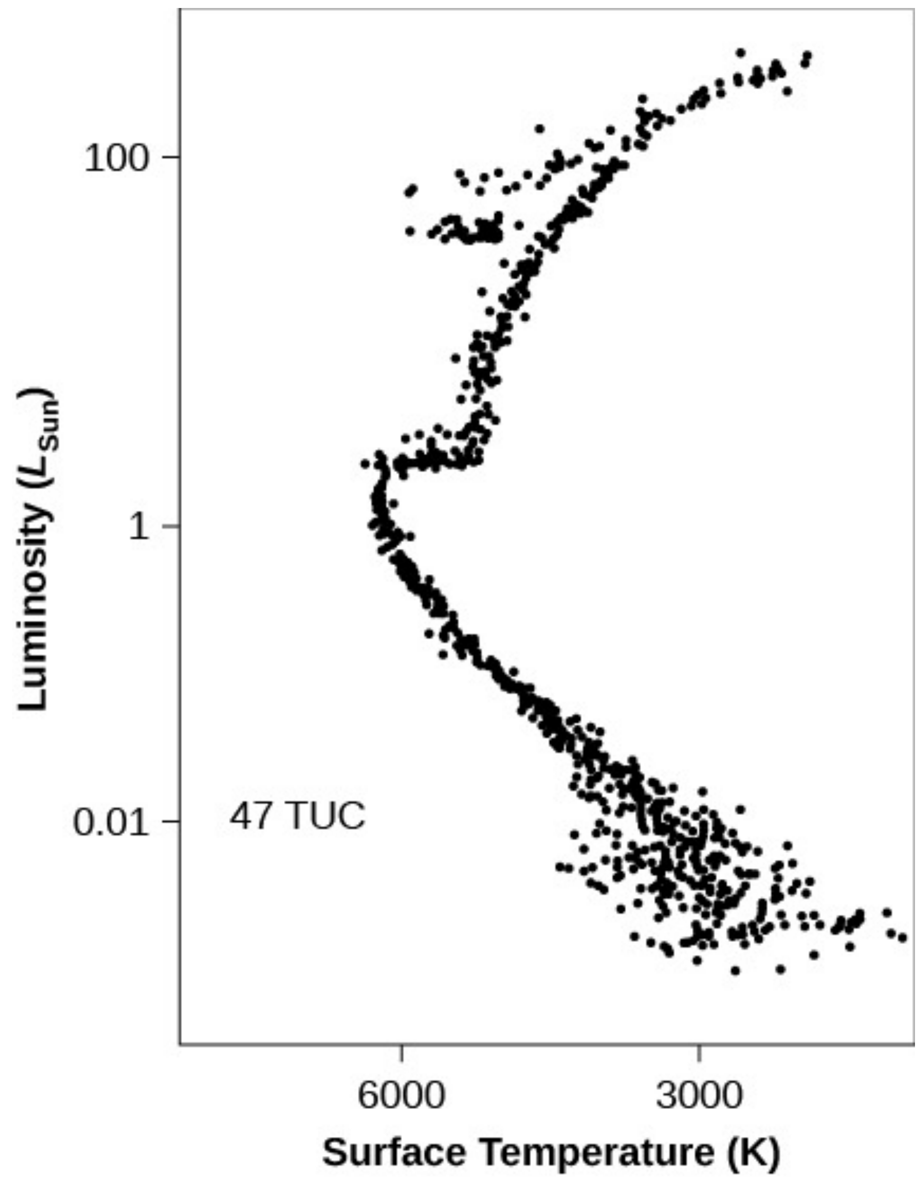
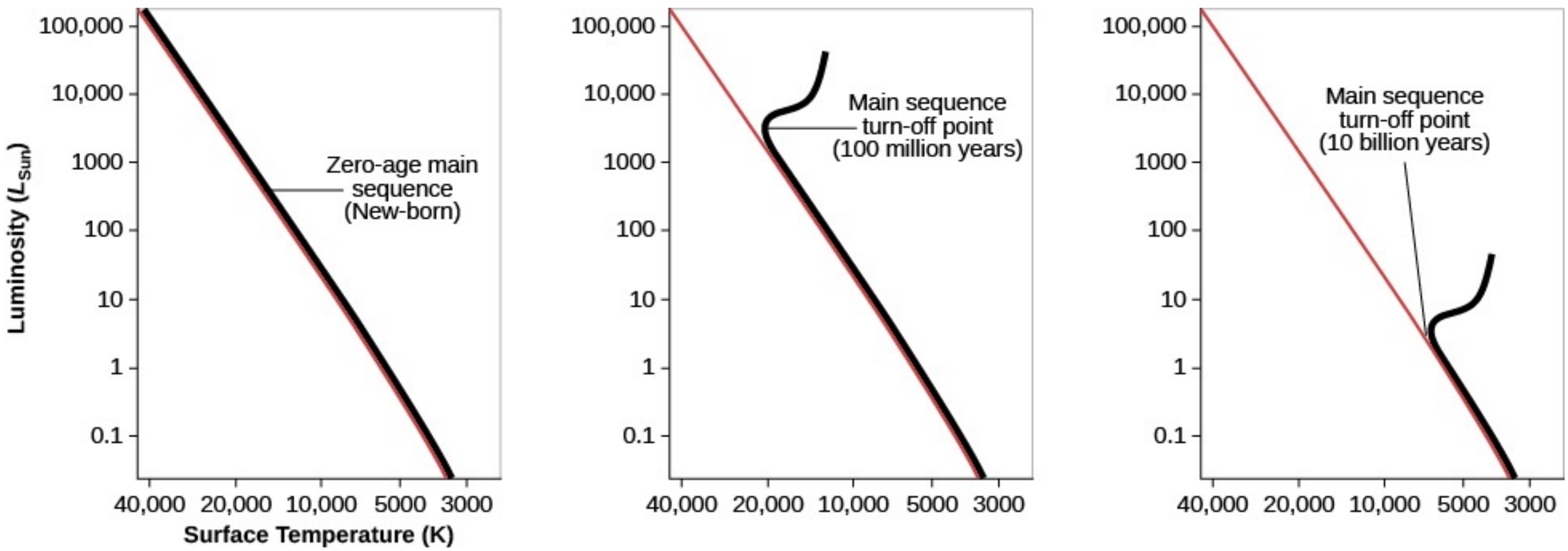


FIGURE 22.15



H–R Diagrams for Clusters of Different Ages. This sketch shows how the turn-off point from the main sequence gets lower as we make H–R diagrams for clusters that are older and older.

GENERAL PICTURE IN RED GIANT PHASE:

Helium core contracts and heats up.

Hydrogen shell around the core contracts, heats up and ignites.

Outer Hydrogen expands and cools off.

Since the star's surface temperature is lower, it will look redder than during the main sequence phase.

The radius of the star increases by a large factor and becomes a giant.

- Final radius is 10 to 100 times the original size of the star.
- Final surface temperature is about 1/2 the original surface temperature.
- Luminosity from larger surface area increases.

This stage lasts for about 2 billion years for a Sun-like star.

THE TRIPLE ALPHA PROCESS

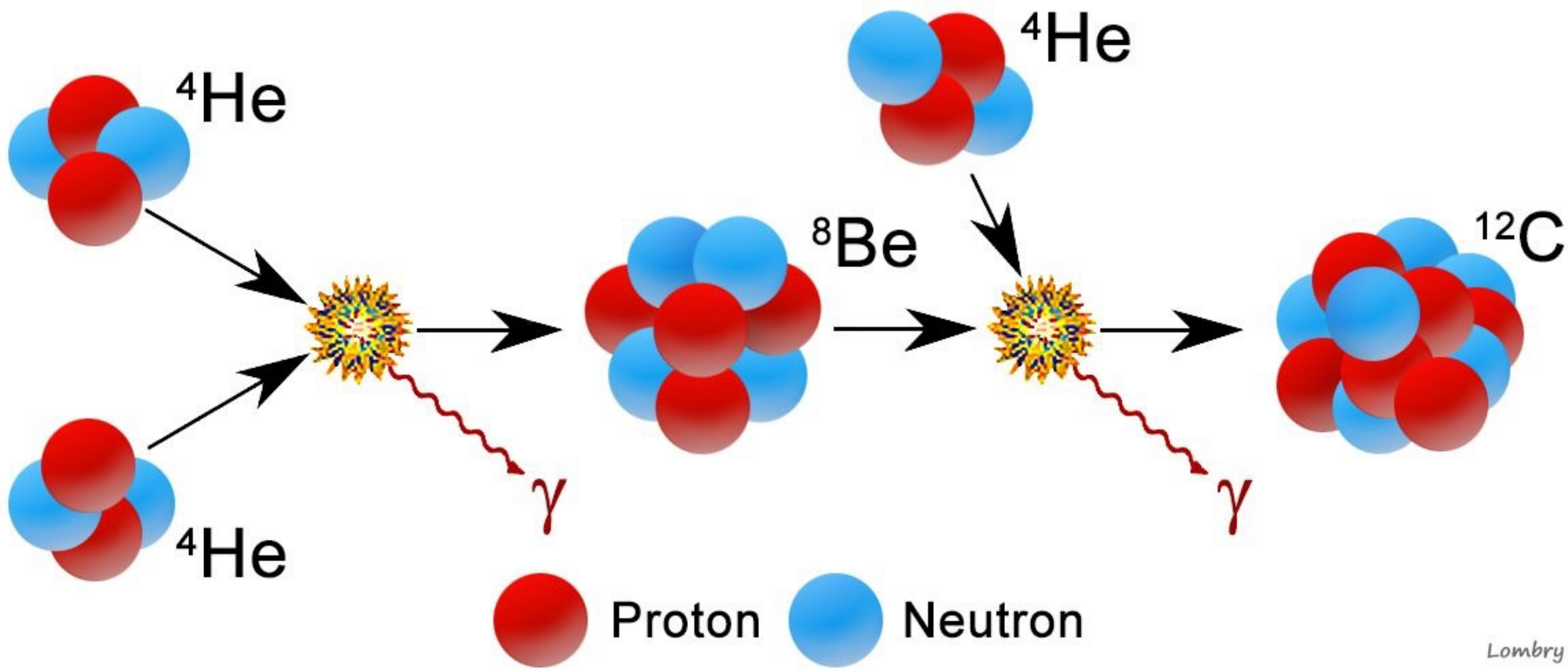
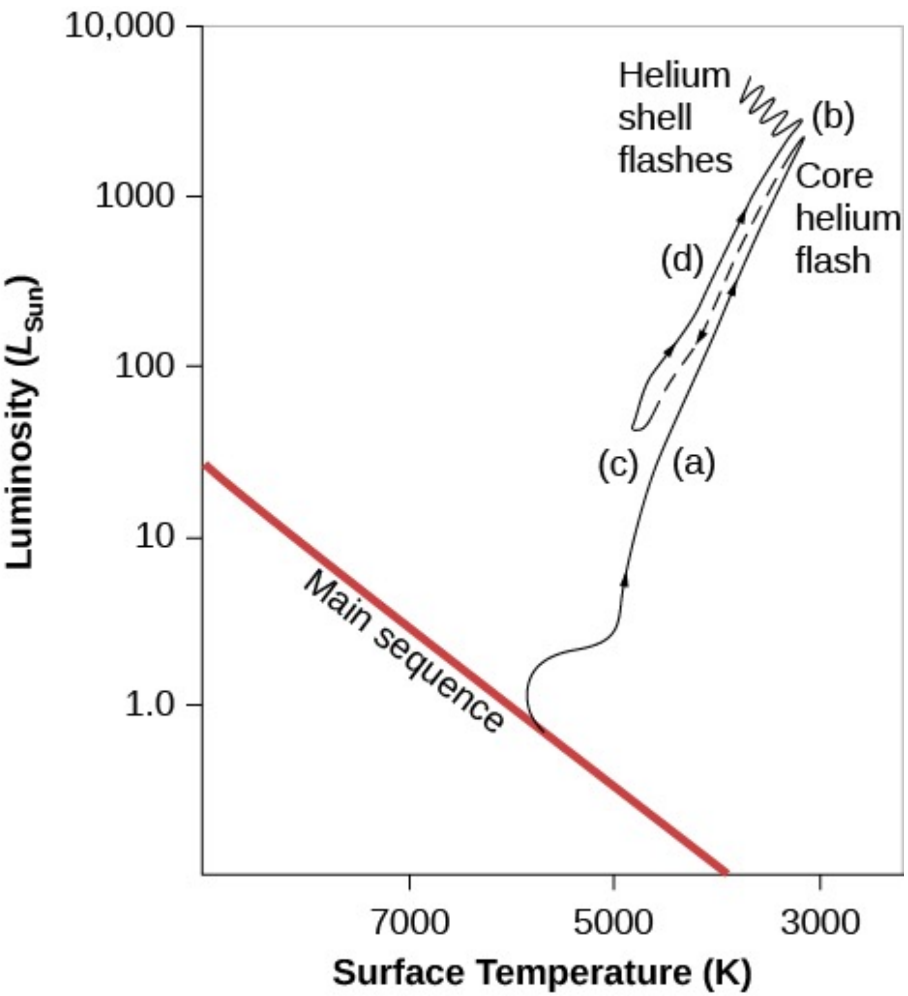
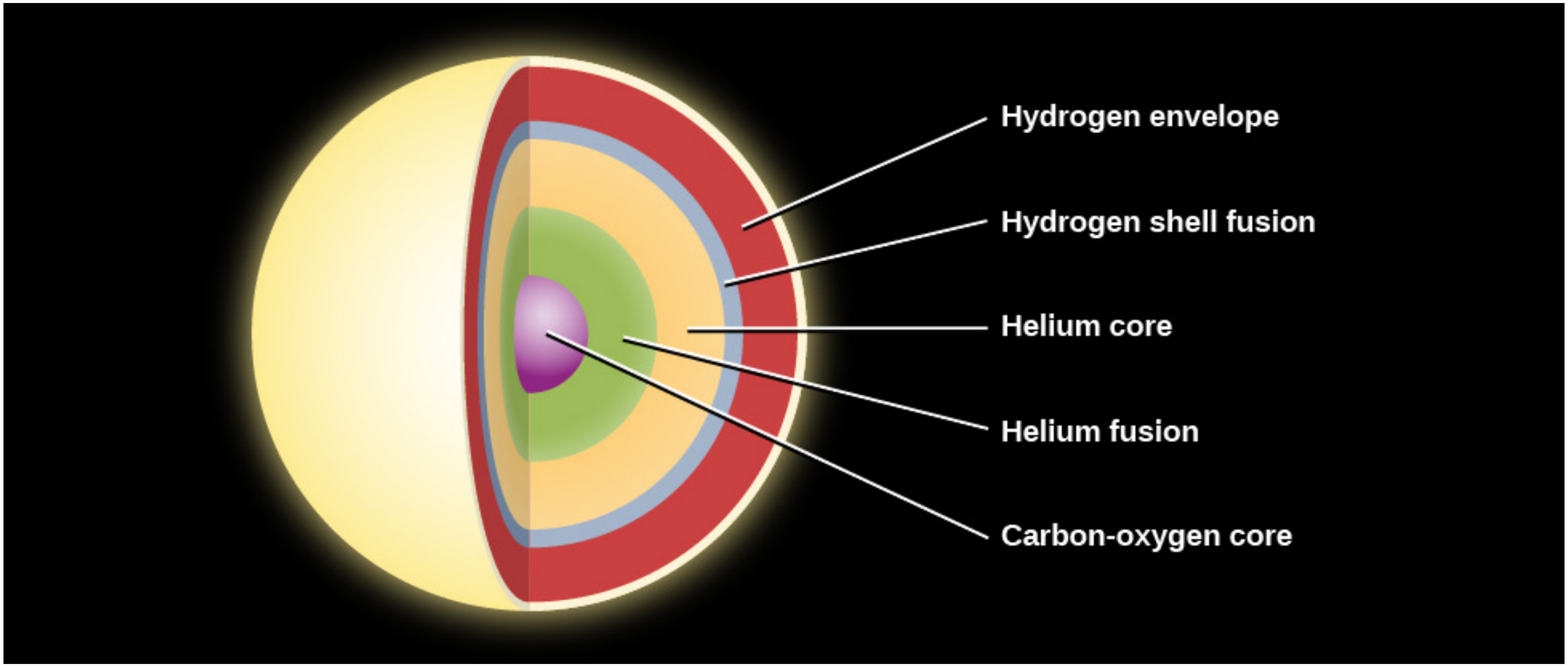


FIGURE 22.16



Evolution of a Star Like the Sun on an H–R Diagram. Each stage in the star's life is labeled. (a) The star evolves from the main sequence to be a red giant, decreasing in surface temperature and increasing in luminosity. (b) A helium flash occurs, leading to a readjustment of the star's internal structure and to (c) a brief period of stability during which helium is fused to carbon and oxygen in the core (in the process the star becomes hotter and less luminous than it was as a red giant). (d) After the central helium is exhausted, the star becomes a giant again and moves to higher luminosity and lower temperature. By this time, however, the star has exhausted its inner resources and will soon begin to die. Where the evolutionary track becomes a dashed line, the changes are so rapid that they are difficult to model.

FIGURE 22.17



Layers inside a Low-Mass Star before Death. Here we see the layers inside a star with an initial mass that is less than twice the mass of the Sun. These include, from the center outward, the carbon-oxygen core, a layer of helium hot enough to fuse, a layer of cooler helium, a layer of hydrogen hot enough to fuse, and then cooler hydrogen beyond.

THE END OF THE RED GIANT PHASE

We already know that medium mass stars, like our Sun, become red giants. But what happens after that?

Our red giant Sun will still be eating up helium and cranking out carbon.

But when it's finished its helium, it isn't quite hot enough to be able to burn the carbon it created. What now?

AFTER THE HELIUM IS GONE

Since our Sun won't be hot enough to ignite the carbon it its core, it will succumb to gravity again.

When the core of the star contracts, it will cause a release of energy that makes the envelope of the star expand.

Now the star has become an even bigger giant than before! Our Sun's radius will become larger than Earth's orbit.

MASS LOSS

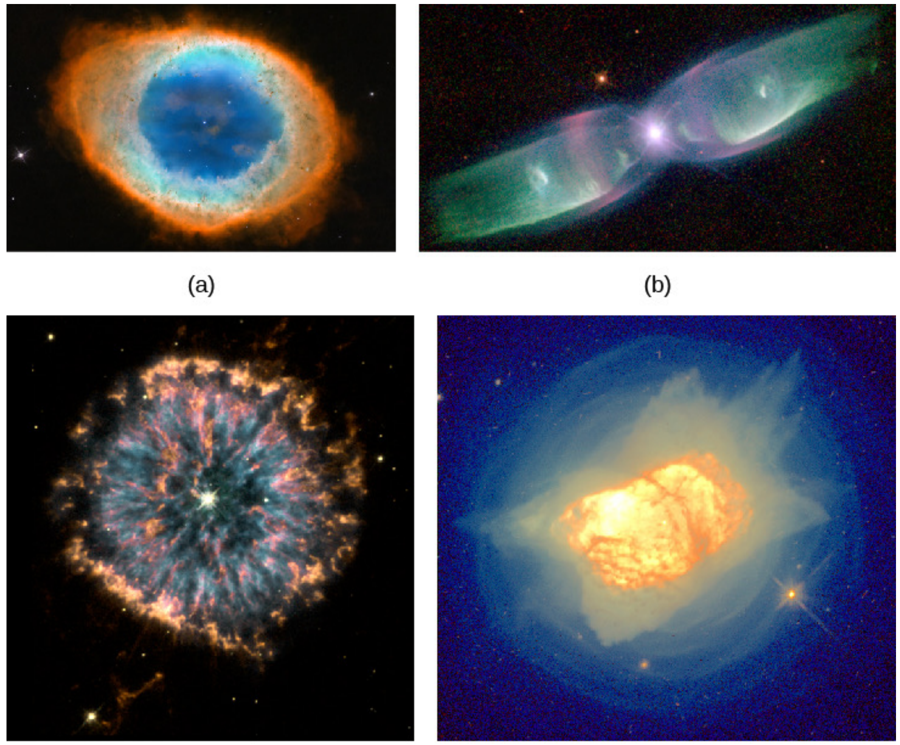
The Sun will not be very stable at this point and will lose mass.

This continues until the star finally blows its outer layers off.

The core of the star, however, remains intact, and becomes a white dwarf.

The white dwarf will be surrounded by an expanding shell of gas in an object known as a **planetary nebula.**

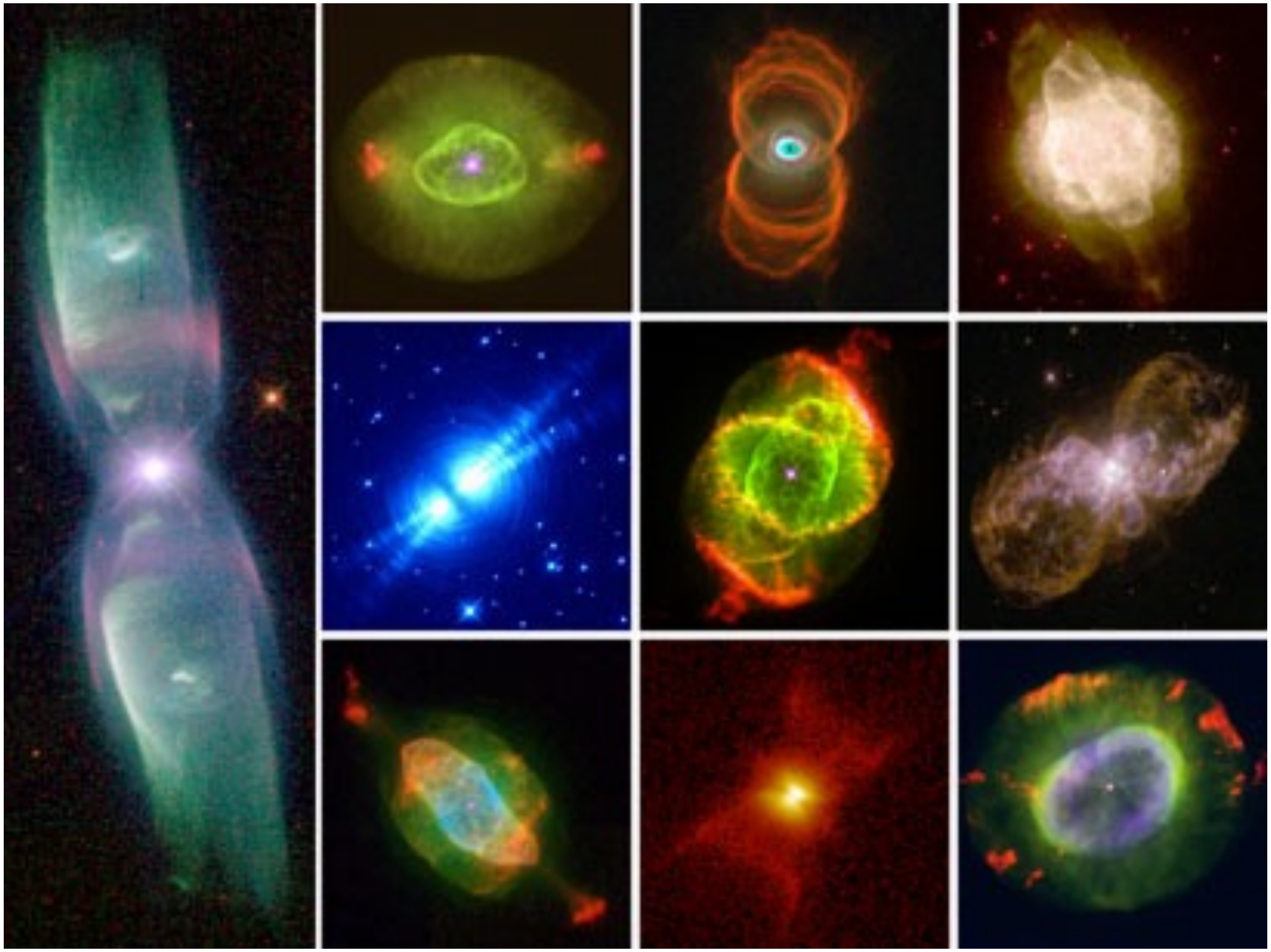
FIGURE 22.18



(a) (b) (c) (d)

Gallery of Planetary Nebulae. This series of beautiful images depicting some intriguing planetary nebulae highlights the capabilities of the Hubble Space Telescope. (a) Perhaps the best known planetary nebula is the Ring Nebula (M57), located about 2000 light-years away in the constellation of Lyra. The ring is about 1 light-year in diameter, and the central star has a temperature of about 120,000 °C. Careful study of this image has shown scientists that, instead of looking at a spherical shell around this dying star, we may be looking down the barrel of a tube or cone. The blue region shows emission from very hot helium, which is located very close to the star; the red region isolates emission from ionized nitrogen, which is radiated by the coolest gas farthest from the star; and the green region represents oxygen emission, which is produced at intermediate temperatures and is at an intermediate distance from the star. (b) This planetary nebula, M2-9, is an example of a butterfly nebula. The central star (which is part of a binary system) has ejected mass preferentially in two opposite directions. In other images, a disk, perpendicular to the two long streams of gas, can be seen around the two stars in the middle. The stellar outburst that resulted in the expulsion of matter occurred about 1200 years ago. Neutral oxygen is shown in red, once-ionized nitrogen in green, and twice-ionized oxygen in blue. The planetary nebula is about 2100 light-years away in the constellation of Ophiuchus. (c) In this image of the planetary nebula NGC 6751, the blue regions mark the hottest gas, which forms a ring around the central star. The orange and red regions show the locations of cooler gas. The origin of these cool streamers is not known, but their shapes indicate that they are affected by radiation and stellar winds from the hot star at the center. The temperature of the star is about 140,000 °C. The diameter of the nebula is about 600 times larger than the diameter of our solar system. The nebula is about 6500 light-years away in the constellation of Aquila. (d) This image of the planetary nebula NGC 7027 shows several stages of mass loss. The faint blue concentric shells surrounding the central region identify the mass that was shed slowly from the surface of the star when it became a red giant. Somewhat later, the remaining outer layers were ejected but not in a spherically symmetric way. The dense clouds formed by this late ejection produce the bright inner regions. The hot central star can be seen faintly near the center of the nebulosity. NGC 7027 is about 3000 light-years away in the direction of the constellation of Cygnus. (credit a: modification of work by NASA, ESA, and the Hubble Heritage (STScI/AURA)-ESA/Hubble Collaboration; credit b: modification of work by Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA; credit c: modification of work by NASA, The Hubble Heritage Team (STScI/AURA); credit d: modification of work by H. Bond (STScI) and NASA)

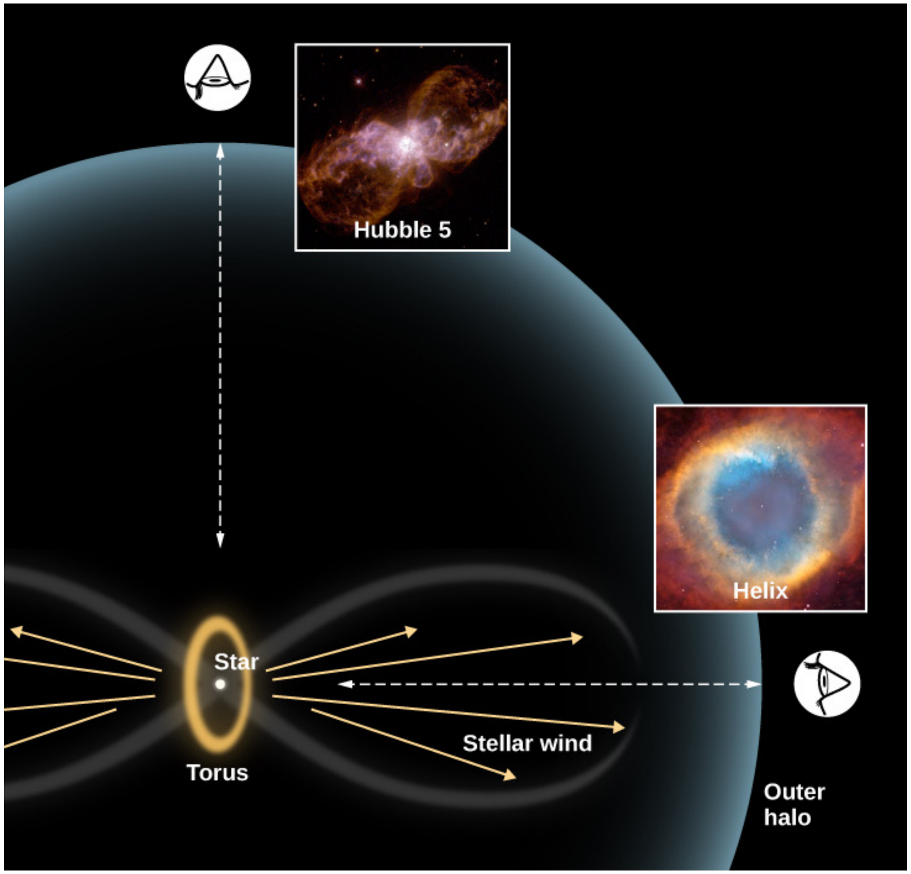
PLANETARY NEBULAE



http://www.astro.washington.edu/users/balick/WFPC2/

FIGURE 22.19

Model to Explain the Different Shapes of Planetary Nebulae. The range of different shapes that we see among planetary nebulae may, in many cases, arise from the same geometric shape, but seen from a variety of viewing directions. The basic shape is a hot central star surrounded by a thick torus (or doughnut-shaped disk) of gas. The star's wind cannot flow out into space very easily in the direction of the torus, but can escape more freely in the two directions perpendicular to it. If we view the nebula along the direction of the flow (Helix Nebula), it will appear nearly circular (like looking directly down into an empty ice-cream cone). If we look along the equator of the torus, we see both outflows and a very elongated shape (Hubble 5). Current research on planetary nebulae focuses on the reasons for having a torus around the star in the first place. Many astronomers suggest that the basic cause may be that many of the central stars are actually close binary stars, rather than single stars. (credit "Hubble 5": modification of work by Bruce Balick (University of Washington), Vincent Icke (Leiden University, The Netherlands), Garrelt Mellema (Stockholm University), and NASA/ESA; credit "Helix": modification of work by NASA, ESA, C.R. O'Dell (Vanderbilt University), and M. Meixner, P. McCullough)



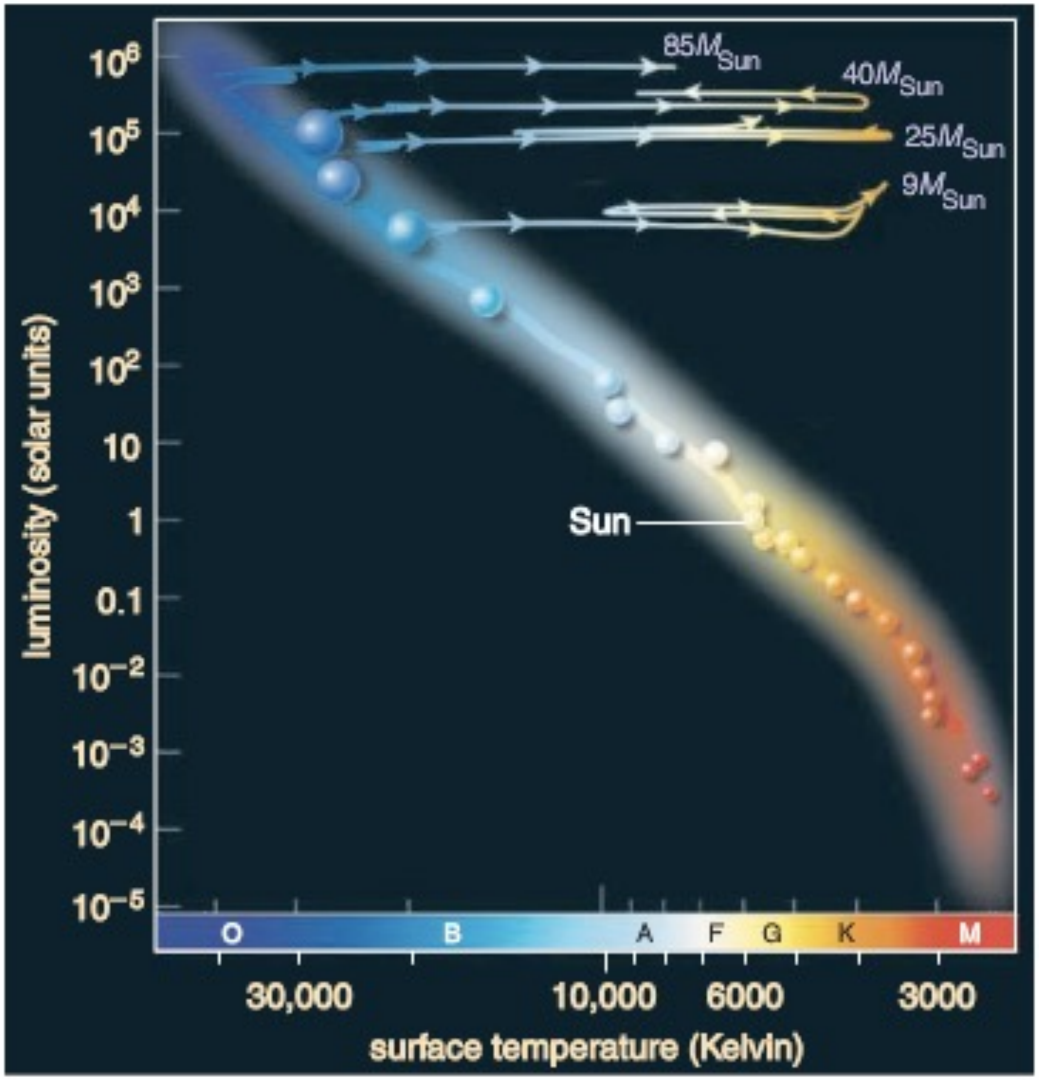


Figure 9.12 | Life tracks on the H-R diagram from main-sequence star to red supergiant for selected high-mass stars. Labels on the tracks give the star's mass at the beginning of its main-sequence life. Because of the strong wind from such a star, its mass can be considerably smaller when it leaves the main sequence. (Based on models from A. Maeder and G. Meynet.)

FOR EXAMPLE, A 25-SOLAR-MASS STAR

At first, these end stages are very similar to those of a low-mass star like the Sun, except they proceed much more rapidly.

Lasts only a few million years as a hydrogen-burning main-sequence star before it goes out of balance.

As its core hydrogen runs out, a hydrogen-burning shell forms around a shrinking helium core, generating so much energy that the star’s outer layers expand outward until the star becomes a supergiant.

25-SOLAR-MASS STAR (CONTINUED)

Gravitational contraction of the helium core continues until it becomes hot enough to fuse helium into carbon.

The high-mass star fuses helium into carbon so rapidly that it is left with an inert carbon core after no more than a few hundred thousand years.

25-SOLAR-MASS STAR (CONTINUED)

After that, the life stages of this 25-solar-mass star become quite different from those of the Sun.

Gravitational contraction simply continues after carbon fusion ends, the inert carbon core shrinks, and the core pressure, temperature, and density all rise.

The shrinking core gets hotter and hotter, and it soon becomes hot enough for carbon fusion.

25-SOLAR-MASS STAR (CONTINUED)

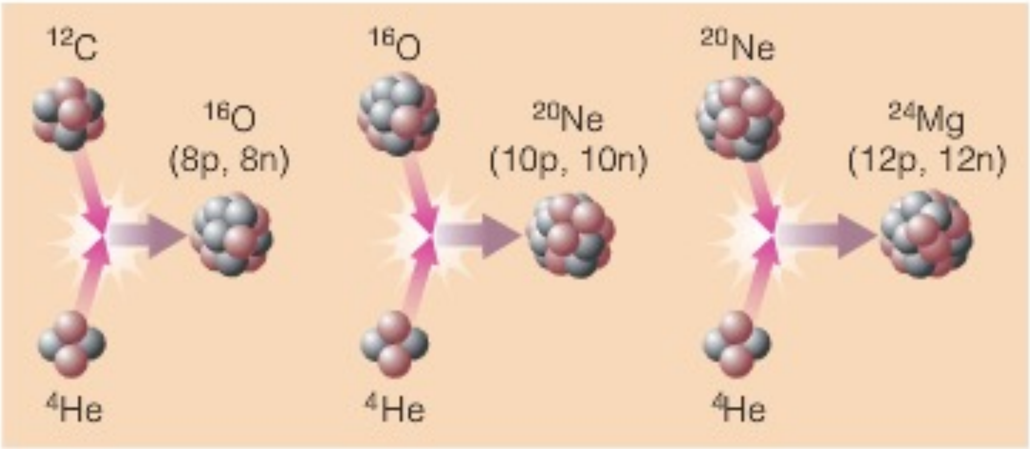
The core and shells go through several more phases of fusion of increasingly heavy elements—producing the “star stuff” that makes our lives possible—while the star’s outer layers continue to swell in size.

Despite the dramatic events taking place in its interior, the high-mass star’s outer appearance changes slowly. As each stage of core fusion ceases, the surrounding shell burning intensifies and further inflates the star’s outer layers.

Each time the core flares up, the outer layers contract somewhat, but the star’s overall luminosity remains about the same. The result is that the star’s life track zigzags across the top of the H-R diagram.

FUSION PRODUCES HEAVY ELEMENTS

Helium capture



a Many reactions proceed through *helium capture*, in which fusion joins a helium nucleus to some other nucleus.

Figure 9.13. Page 152. ***The Cosmic Perspective Fundamentals*.**
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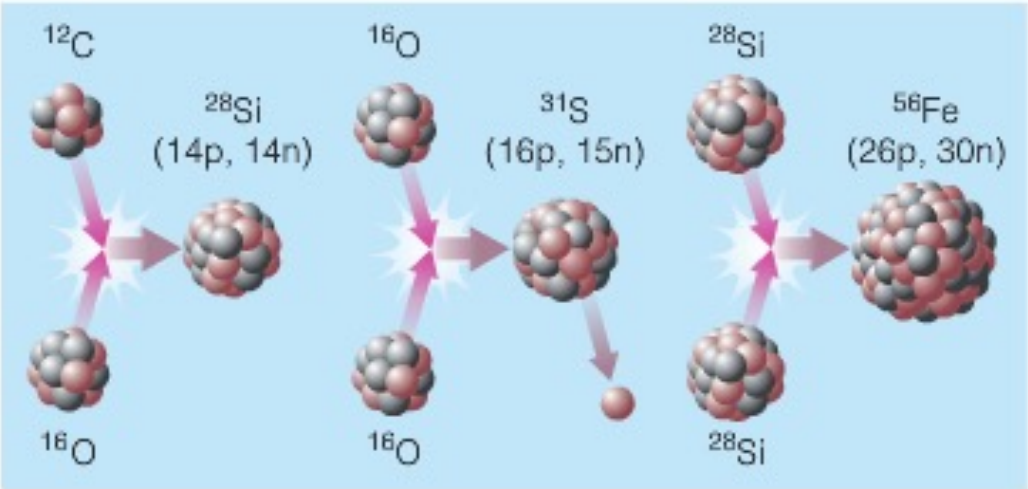
FUSION PRODUCES HEAVY ELEMENTS

And at even higher temperatures



b At extremely high temperatures, fusion of even heavier nuclei can occur.

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ADVANCED NUCLEAR BURNING

A high-mass star like Betelgeuse can make elements heavier than carbon because degeneracy pressure is never able to halt the contraction of its core.

The crush of gravity within the star is simply too strong.

Each time the core exhausts one source of fuel for fusion, it contracts and heats up until it can fuse even larger nuclei, while fusion of lighter elements continues in multiple shells around the core.

The complete set of nuclear reactions in a high-mass star's final stages of life is quite complex, and many different reactions may take place simultaneously, making elements like oxygen, silicon, and sulfur.

LIKE LAYERS OF AN ONION

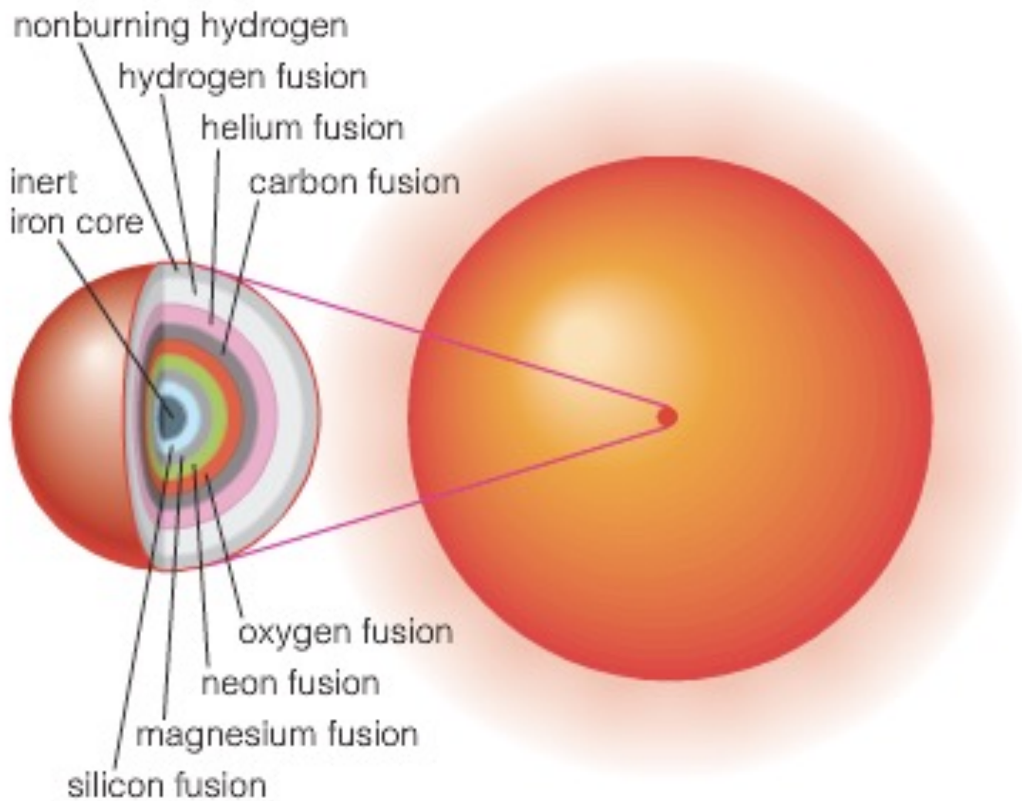

Figure 9.14. Page 153. ***The Cosmic Perspective Fundamentals*.**
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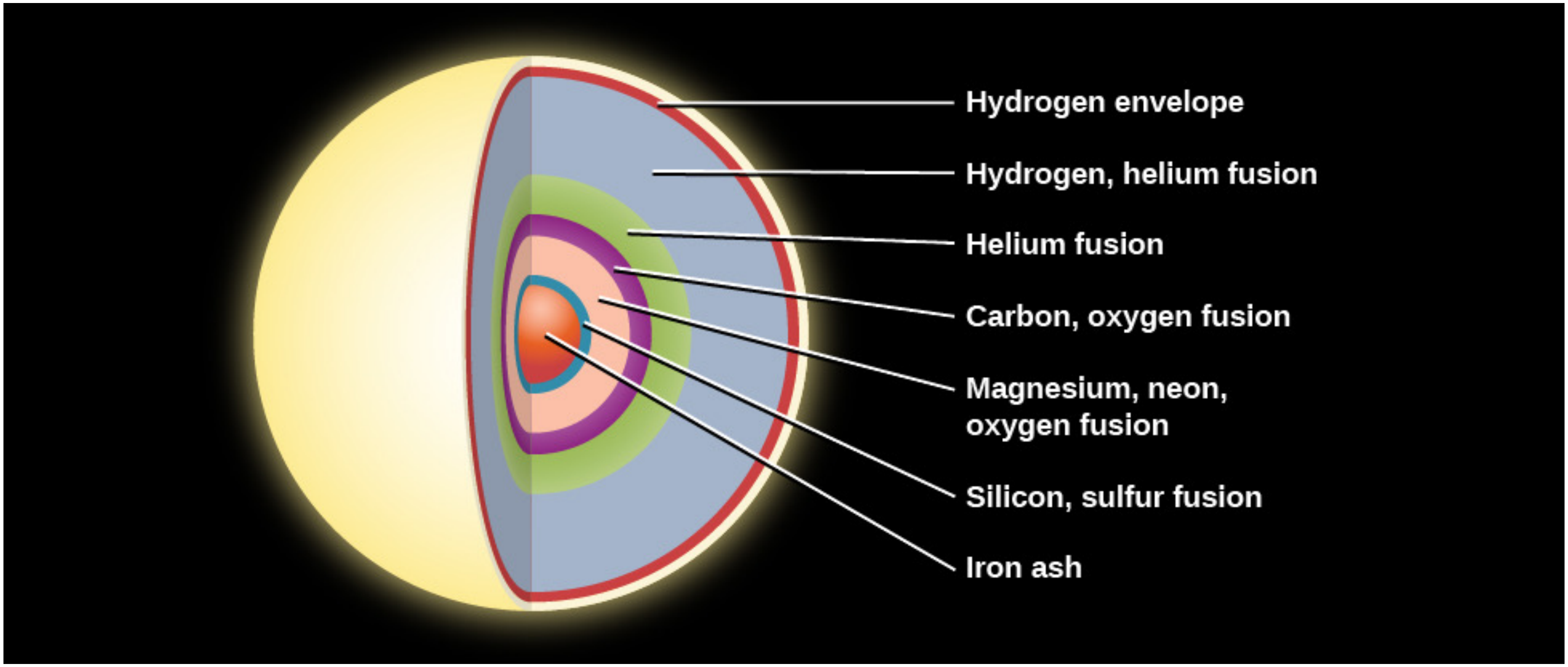
FIGURE 22.21



Interior Structure of a Massive Star Just before It Exhausts Its Nuclear Fuel. High-mass stars can fuse elements heavier than carbon. As a massive star nears the end of its evolution, its interior resembles an onion. Hydrogen fusion is taking place in an outer shell, and progressively heavier elements are undergoing fusion in the higher-temperature layers closer to the center. All of these fusion reactions generate energy and enable the star to continue shining. Iron is different. The fusion of iron requires energy, and when iron is finally created in the core, the star has only minutes to live.

THE MASS PER NUCLEAR PARTICLE

The mass per nuclear particle tends to decrease as we go from light elements to iron, which means that fusion of light nuclei into heavier nuclei generates energy.

This trend reverses beyond iron:

The mass per nuclear particle tends to increase as we look to still heavier elements.

As a result, elements heavier than iron can generate nuclear energy only through fission into lighter elements.

Iron has the lowest mass per nuclear particle of all nuclei and therefore cannot release energy by either fusion or fission.

IRON

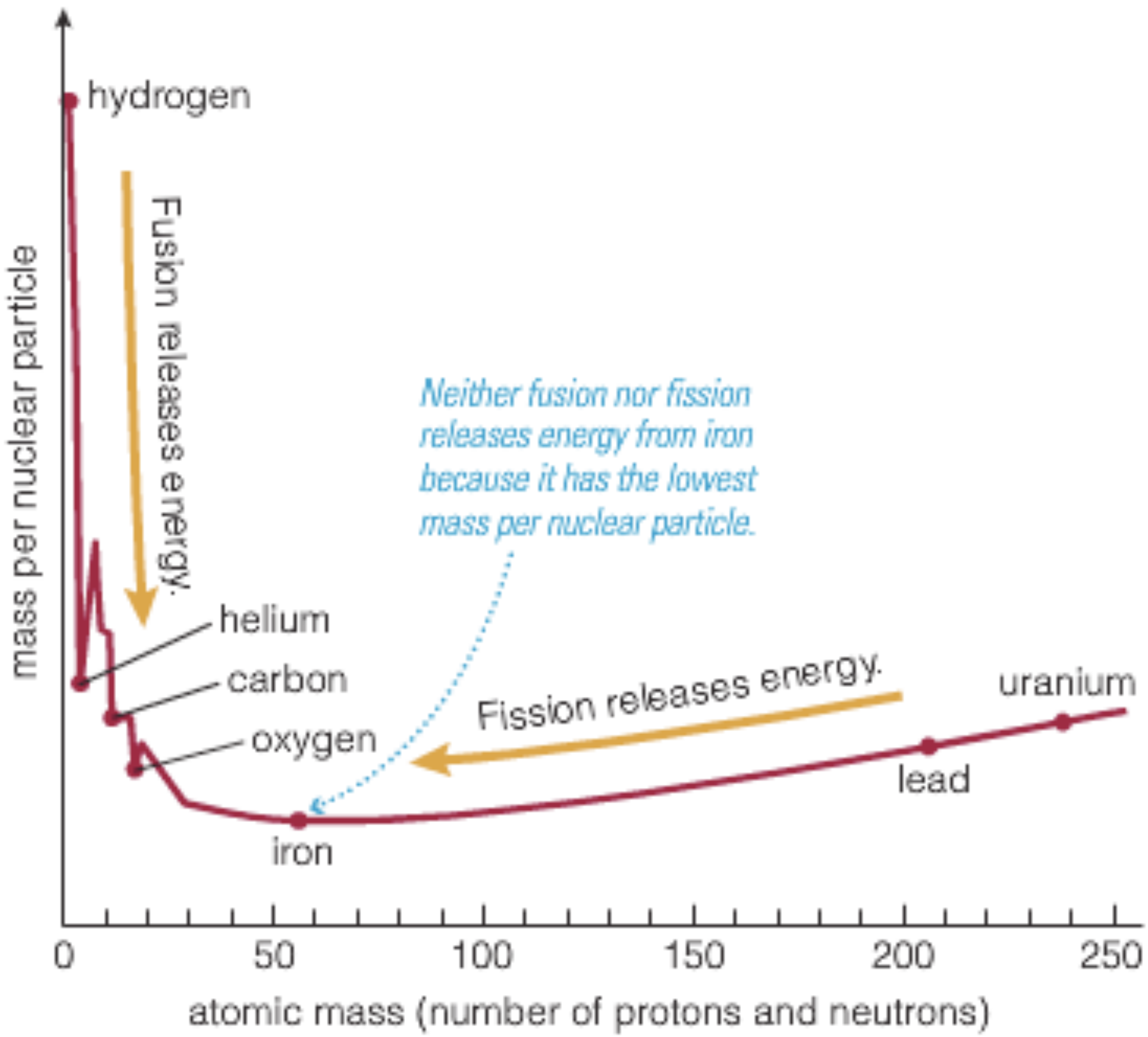


Figure 9.15. Page 153. ***The Cosmic Perspective Fundamentals*****.**
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THE SUPERNOVA EXPLOSION

Degeneracy pressure cannot support the inert iron core because the immense gravity of a high-mass star pushes electrons past their quantum mechanical limit.

Once they get too close together, they can no longer exist freely.

In an instant, the electrons disappear by combining with protons to form neutrons, releasing the tiny subatomic particles known as neutrinos in the process.

THE SUPERNOVA EXPLOSION

With the degeneracy pressure gone, gravity has free rein.

In a fraction of a second, an iron core with a mass comparable to that of our Sun and a size larger than that of Earth collapses into a ball of neutrons just a few kilometers across, making the type of stellar corpse that we call a neutron star.

THE SUPERNOVA EXPLOSION

The collapse halts only because the neutrons have a degeneracy pressure of their own. In some cases, the remaining core may be massive enough that gravity also overcomes the degeneracy pressure of the neutrons, in which case the core continues to collapse until it becomes a black hole.

THE SUPERNOVA EXPLOSION

The gravitational collapse of the core releases an enormous amount of energy—more than a hundred times what the Sun will radiate over its entire 10-billion-year lifetime.

This energy drives the outer layers of the star off into space in a titanic explosion called a supernova.

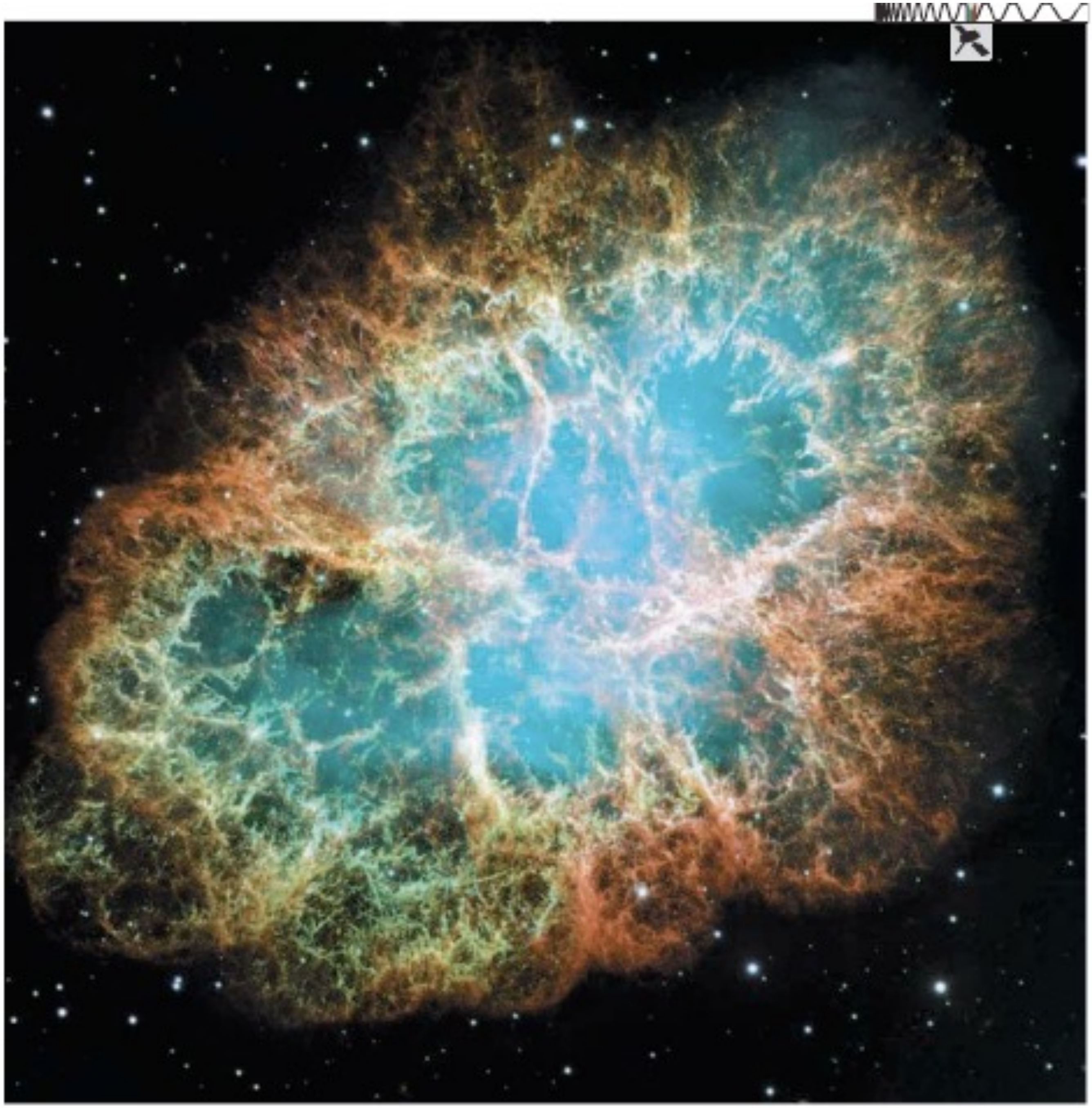

Figure 9.17. Page 154. ***The Cosmic Perspective Fundamentals.***
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STAR STUFF

The high-mass star has died, but the variety of elements produced in the star's nuclear furnace are now scattered throughout the gas clouds of interstellar space.

Millions or billions of years later, a new round of star formation may incorporate this supernova debris into a new generation of stars.

Some of the heavy elements that came from this supernova will become the building blocks of new planets—and perhaps even new life forms—around those newborn stars.

The building blocks of Earth and of our bodies came from supernovae in the distant past.

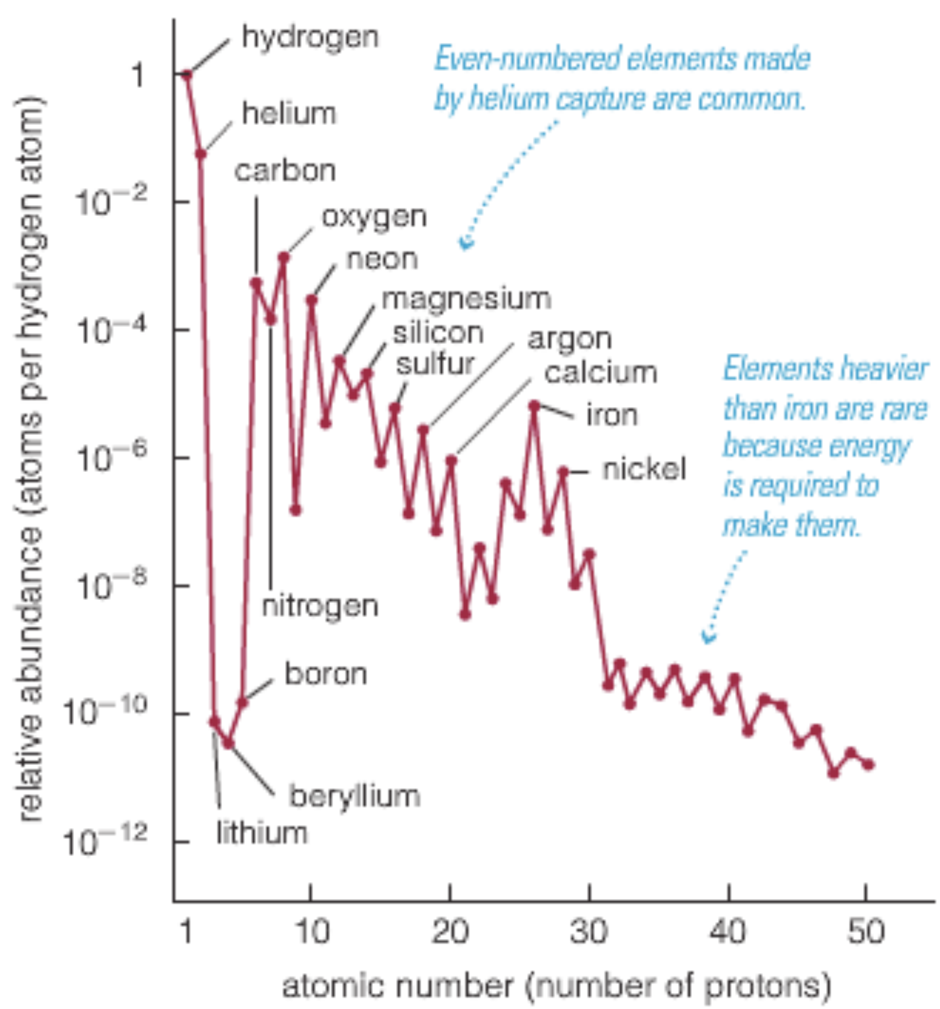

Figure 9.18. Page 155. ***The Cosmic Perspective Fundamentals*****.**
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SUMMARY

- What is happening inside the star when it is on the main sequence
- What is happening inside the star to cause it to become a red giant
- The different evolutionary stages for solar-like stars (protostar, main-sequence, red giant, helium-core burning, planetary nebula, white dwarf)
- How long the different stages last for a solar-mass star and an O or B star
- What helium nuclear burning produces
- What happens to the star's core when the outer layers are ejected in a planetary nebula.
- Low mass vs. high mass stars: how their evolution differs, and why
- Which element has the lowest energy per nucleon, and therefore is the end of the line for stellar fusion.