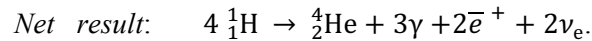


Chapter 13: Life and Death of Stars

Stars, like humans, have life cycles. They are born from contraction of clouds, and pass through various stages of life before they die. Although most of these stages last for millions or billions of years, depending on the mass of the star, the most massive stars end their lives suddenly and violently. This chapter tells the story of stars that astronomers have written based on a large collection of scientific data.

Nuclear Fusion in the Core of a Star

A newly formed star eventually “blows off” the remains of the gas and dust cloud out of which it formed through strong winds and luminous radiation that emanate from the star. Once the center of the star reaches a temperature exceeding about 10 million K, a new source of energy turns on in the core of the star: nuclear fusion (see Ch. 8). The basic process is the conversion of hydrogen nuclei — protons — into helium nuclei. This involves a chain of reactions, with the net result that four hydrogen nuclei are converted to a helium nucleus plus mass-energy in the form of photons, positrons, and neutrinos:



The neutrinos (ν_e) escape, since they do not interact strongly with matter (only through gravity and the weak interaction). The positrons (e^+), however, quickly annihilate with the electrons in the core of the star, producing photons. Because photons are a form of pure energy (since they have no mass), the effect of the reaction is to turn hydrogen to helium plus energy plus some “useless” neutrinos. The reaction converts mass to energy according to the formula $(m_0 - m_f)c^2$ because the mass of the resultant helium nucleus (m_f) is less than the combined mass of the 4 original hydrogen nuclei (m_0). The reaction occurs in several steps, since it is much more likely for a single hydrogen nucleus (a proton) to collide with another nucleus than for four hydrogen nuclei to fuse at the same instant.

Basic Properties of Stars

The vast majority of stars are stable, in a state of pressure equilibrium. The inward force of gravity is balanced by the pressure of the hot gas that composes the star, heated by the nuclear reactions that continuously occur in the core. The density of the star is highest in the core and lowest in the “corona” that surrounds the atmosphere.

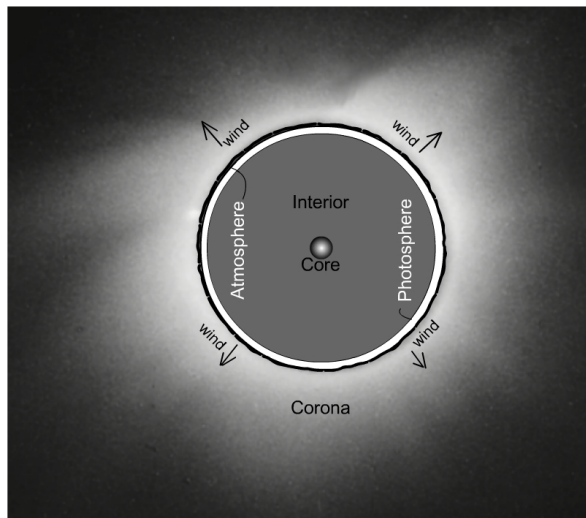


Figure 13-1. The basic structure of a star. What we see as the “surface” is the photosphere, inside of which the star is opaque. So the photosphere produces blackbody radiation. The atmosphere is usually cooler than the photosphere and so creates dark absorption lines in the spectrum of the star. The corona and wind are hot and transparent, and so produce emission lines, mostly at UV and X-ray wavelengths.

What we see when we look at a star at visible wavelengths is the “surface” of the star, called the **photosphere**. This is the greatest distance from the center at which the star is still opaque, meaning that most photons cannot escape without being absorbed by atoms. Note that the entire body of a normal star is composed of gas. This gas, however, is so dense that it is opaque beneath the photosphere, and the pressure is so high in the **interior** that a dense object would float if it did not evaporate from the heat. The light emitted by the photosphere has a blackbody spectrum, as for any opaque object (see Ch. 5). As that light propagates toward outer space, atoms in the cooler **atmosphere** absorb some of the wavelengths to form an absorption-line spectrum (see Ch. 8). Figure 13-1 shows the basic structure of a star.

The energy produced by nuclear fusion at the core of the star is transported outward by two processes: convection and radiative transport. **Convection** exchanges gas from the hot interior with gas in less-hot regions farther out; this is most important close to the surface. **Radiative transport** works as the name implies: energy moves outward in the form of photons. The original photons are generated in the fusion reactions in the core. They only travel a short distance before they are absorbed, exciting an atom in the process, but then the excited electron in the atom jumps back down to a lower energy level, which emits another photon. The directions of all these photons are random, but after many such episodes the net result is that the energy of the original photon is transported toward the surface of the star, where it eventually is radiated into space.

The **temperature of the photosphere** of a star can be determined in one of two ways. As described in Chapter 5, the star’s color — or, more precisely, the wavelength of the peak brightness of its blackbody spectrum — specifies the temperature. But this is difficult to apply if dust is in the way or if the absorption lines (formed by the atmosphere) are so numerous that they mask the underlying continuous spectrum. A more precise method is to use the **absorption line spectrum** (Fig. 13-2), since the excitation and ionization states of various elements depends on the temperature. This is what astronomers did originally. They then divided the stars into “spectral classes” and assigned each a letter. It was not until later that they connected spectral classes with temperature, so the letters of the spectral classes are mixed up. From hottest to least hot, the spectral classes are O, B, A, F, G, K, M, which generations of astronomy students have memorized with the line “Oh Be A Fine Girl/Guy, Kiss Me.” The spectra of O and B stars have few absorption lines — mostly those of hydrogen and helium — while those of the cooler G, K, and M stars have a multitude of dark lines from heavier elements.

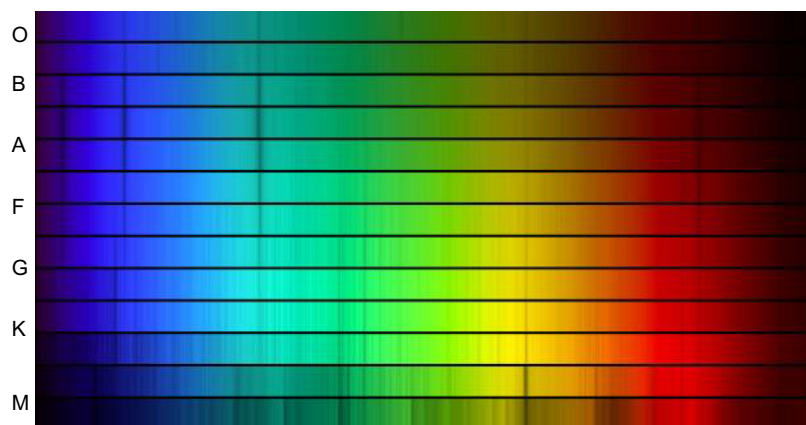


Figure 13-2. Absorption-line spectra of the different spectral classes of stars.
[Source: National Optical Astronomy Observatories]

As was mentioned in Chapter 4, the mass of a star can be determined by measuring the period and semi-major axis of an object that orbits it. For the Sun, those objects are the planets. For other stars, we can derive the mass if the star is in a binary system with another star, in which case they both orbit about the center of mass of the system. The masses of all types of stars can be determined this way. The masses are most conveniently measured in solar masses, given the symbol M_s , equal to 2×10^{30} kg.

As a star, the Sun is only a little above average in mass, temperature, and luminosity. The radius of the Sun is 700,000 km, almost twice as large as the Moon's orbit. Its mass is about 300,000 times more than that of Earth and almost 1000 times that of Jupiter, the most massive planet in the solar system. The temperature of the Sun's photosphere is 5800 K, while that of its core is about 15 million K. The Sun's luminosity is 3.9×10^{26} W, the same as about 4 trillion trillion 100 W light bulbs. The average density of the Sun is about 1.4 times that of liquid water, although in the core it is about 100 times greater than this.

The Evolution of Stars

Hydrogen Fusion Stage

As is the case for sources of energy on the Earth, the nuclear fusion reactions by which a star converts mass to energy use up its fuel, in this case hydrogen nuclei. Eventually, the hydrogen in the core of the star will become exhausted and the star must change. The time over which a star can fuse hydrogen depends on both how much mass in hydrogen it starts out with in its core and how fast it uses it up. The former is proportional to the mass of the star, while the latter is proportional to the luminosity of the star. The luminosity L of a star (measured in solar units, L_s) is roughly proportional to its mass M (in M_s) raised to the power of 3.5:

$$L \approx L_s (M/M_s)^{3.5} \quad (13-1)$$

L = luminosity (in watts, or W), L_s = luminosity of Sun = 3.9×10^{26} W, M = mass of the star,
 M_s = mass of the Sun = 2×10^{30} kg.

Although stars more massive than the Sun have more hydrogen “fuel,” they use up this fuel much more rapidly to maintain their high luminosities. Because of this, high-mass stars have shorter lives than do low-mass stars. The hydrogen fusing lifetime of the Sun is about 10 billion years, which makes the Sun (which is nearly 5 billion years old already) a truly “middle-aged” star. A handy formula for the hydrogen fusing lifetime of a star is

$$\text{H-lifetime} \approx 10[(M/M_s) / (L/L_s)] \text{ billion yr} \quad (13-2)$$

H-lifetime = time until hydrogen fuel in the core is consumed (in billions of years), M = mass of star,
 M_s = mass of Sun = 2×10^{30} kg, L = luminosity of star, L_s = luminosity of Sun = 3.9×10^{26} W.

We can combine equations (13-1) and (13-2) to express the lifetime in terms of only the mass:

$$\text{H-lifetime} \approx 10 / (M/M_s)^{2.5} \text{ billion yr.} \quad (13-3)$$

A star 10 times as massive as the Sun will therefore only live about 100 million years before the hydrogen fuel in its core is exhausted. The star, with luminosity about 1000 times that of the Sun, will live a bright, but brief life. Here, “brief” is relative: since the universe is about 14 billion years old, any time shorter than about a billion years is considered “brief” in cosmic terms.

Red Giant Stage and Helium Fusion

After the hydrogen fuel is used up, the core can no longer provide the pressure needed to balance gravity. Hence, the core collapses to a much smaller size — about the size of the Earth. In the process, its density and temperature increase (since contracting gases heat up). The release of energy from the contraction

heats a shell near the outer edge of the core so that the rate of its fusion of hydrogen to helium there increases.¹

This process releases an enormous amount of energy, which heats the interior of the star to a higher temperature. The higher pressure that this generates causes the entire star outside the core to expand greatly, out to distances as large as the sizes of the orbits of the inner planets in our solar system (100 million to 1 billion km). Since expanding gases cool, the temperature of the photosphere drops to about 3000 K. A star whose photosphere has this temperature has a red color, so a star in this stage of its evolution is called a red giant (see Fig. 13-3).

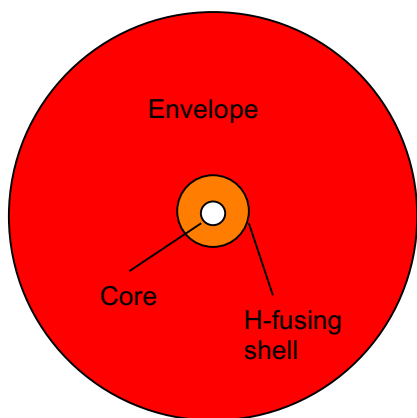
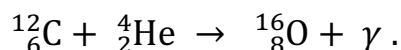


Figure 13-3. The basic structure of a red giant. Not drawn to scale: the core shrinks down to a size not much larger than the Earth, while the envelope extends out to a distance comparable to the orbits of the inner planets of our solar system. The core at first contains He with little fusion, then contracts further and fuses helium to produce carbon and oxygen.

As more hydrogen is used up, the core continues to contract. Once the temperature reaches about 100 million K, another, more powerful fusion reaction occurs: nuclear fusion of helium into carbon. The two-step reaction has the net result:



The fusion of helium goes through a few stages, some of which are very rapid or lead to an instability that causes the radius and luminosity of the red giant to change. A layer of hydrogen that has yet to be used up, and is still fusing to form helium, surrounds the core of a red giant. The interior of the star outside of this layer is composed mostly of hydrogen and helium that is not involved in any fusion at this stage. As the core contracts further, carbon can fuse with remaining helium nuclei to make oxygen nuclei:



The H-R (Hertzsprung-Russell) Diagram

In 1910, two astronomers found that a plot called an H-R diagram of luminosity vs. temperature (or spectral class) of stars produces a pattern rather than just a scatter of data points. This is illustrated in Figure 13-4, which displays an H-R diagram of all types of stars and another with only the closest stars. Most stars lie on a band across the H-R diagram called the main sequence. **These stars are in their hydrogen fusing stage, the longest phase of a star's life.** Notice that the Sun is near the middle of the main sequence. On the main sequence, stars to the left (higher temperature) are more massive than stars on the right. (*Note: this is not generally true for non-main-sequence stars.*) Since the luminosity of a

¹The density decreases from the center outward, so the hydrogen fuel runs out first at the center while a shell remains that still fuses hydrogen to helium.

blackbody is proportional to the fourth power of the temperature and the square of the radius (see eq. 5-5), at any given temperature, **stars on the upper part of the diagram have larger radii than those on the lower part**. Above the right-hand portion of the main sequence is the population of red giant stars

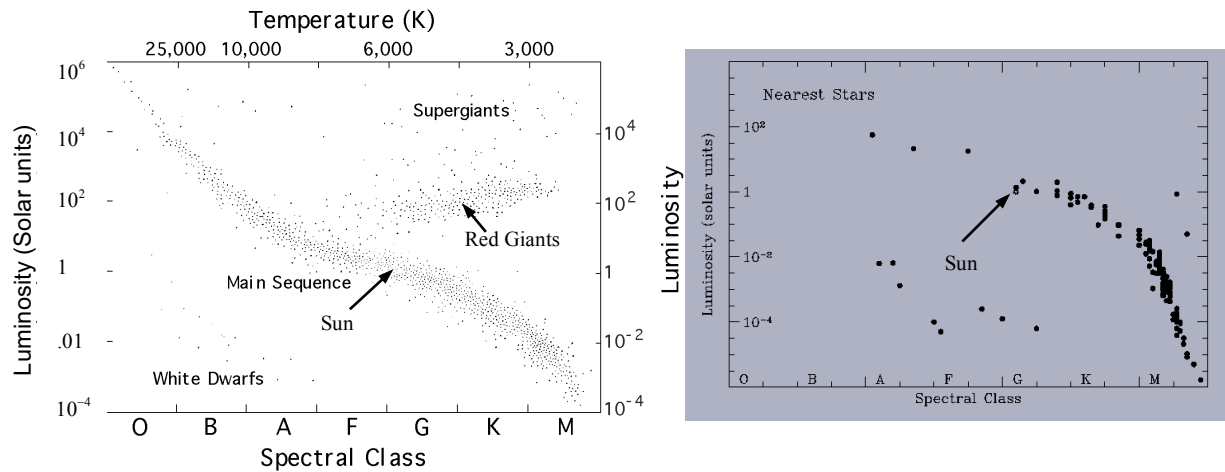


Figure 13-4. Hertzprung-Russell (H-R) diagrams. *Left*: Drawn with essentially all types of stars represented. *Right*: 100 nearest stars. No stars more luminous than about 100 solar luminosities appear, since these are rare compared with low-luminosity stars.

described above. Above these are even larger red supergiants at the same temperature. Stars on the far right-hand side of the main sequence (lower right corner on the diagram) are called “red dwarfs.” Below the middle of the main sequence is a distinct population of stars called white dwarfs. This class of stars is discussed in more detail below.

The lowest mass that an object can have and still be a true star (*i.e.*, convert mass to energy via nuclear fusion in its core) is about 8% the mass of the Sun. Objects with masses between about 1% and 8% the mass of the Sun are called brown dwarfs. These do not actually appear brown, but rather shine mostly at infrared wavelengths because they are too cool to emit much visible light. They lie off the H-R diagram, below the lower right corner.) Below about 1% the mass of the Sun, an object would correspond to a planet. It is unknown whether planet-sized objects not associated with stars are common, since they would be almost impossible to detect with current telescopes.

As is discussed above, red giants are at a later stage of evolution than main sequence stars. Below, we will see that white dwarfs represent an even later stage in the lives of lower-mass stars (*i.e.*, stars that start out less than several times as massive as the Sun). The H-R diagram is like a snapshot of a population of stars, each of which is at a particular stage in its life.² Consider as an analogy a photo of a busy highway. Very few cars will be seen where the cars can travel rapidly, since each car spends only a short time at such a section of the road. However, at toll booths and traffic jams, which take longer to traverse, the photo will show many vehicles. The heavily populated portions of the H-R diagram therefore correspond to stages in which stars spend a sizable fraction of their lives.³ This means that all stages other than the main-sequence, red giant, and white dwarf phases must be relatively short-lived.

²A star on the main sequence stays in about the same place on the H-R diagram until it uses up the hydrogen in its core.

³This is true if the diagram includes all stars within a given volume of space, as in the right-hand panel of Fig. 13-4 if it included many more stars from a larger volume.

It is particularly enlightening to look at the H-R diagram of a cluster of stars, since the stars in a cluster were all formed at roughly the same time, so they all have similar ages. This is shown in Figure 13-5 for three clusters of different ages. The age of the cluster can be determined by the high-temperature point at which its main sequence ends and “turns off” toward the red giant area of the diagram. This is because the stars on the left-hand side of the main sequence are more massive and therefore evolve more rapidly. The cores of the stars on the main sequence to the right of the turn-off are still in their hydrogen fusing stage.

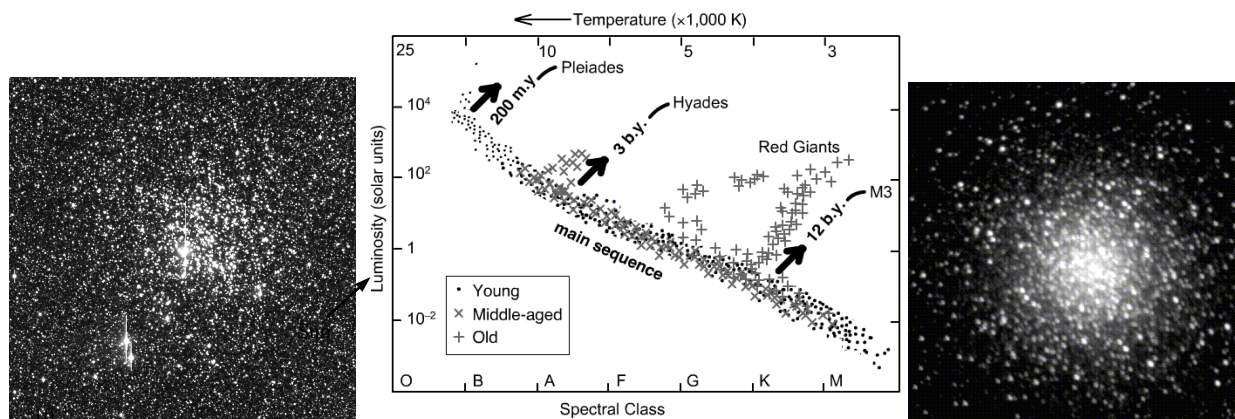


Figure 13-5. *Middle:* H-R diagram of star clusters (examples of which are shown in the images on the left and right) of different ages. The stars within any given cluster all formed at about the same time. In the youngest cluster (200 million yr old), only the hottest (O and some B) stars have moved off the main sequence to become red giants. In a cluster of intermediate age (3 billion yr in the diagram), all of the O and B stars are missing from the main sequence, having already become red giants and then exploded as supernovae. In an old cluster (12 billion yr in the diagram) such as the one in the image on the right, even the G stars have left the main sequence. The hottest stars remaining on the H-R diagram of a cluster therefore indicate the age of the stars in the cluster. [Source of images: W. Keel]

The End State of a Low- to Medium-Mass Star: A White Dwarf

In stars less massive than roughly 7 times the mass of the Sun, the fusion reactions in the core will eventually cease. This is because, after the helium fuel is exhausted, further collapse and heating of the core is prevented by the pressure of the electrons. (The electrons resist being squeezed so tightly that they would occupy the same quantum states; see the discussion of the Pauli exclusion principle in Ch. 8). The composition of the core is mainly carbon from fusion of helium and oxygen from fusion of carbon and helium. Winds eventually blow away the entire outer part of the star — the “envelope,” which can hold a few times more matter than the mass of the core — into space, forming a gas cloud called a planetary nebula.⁴ This exposes the core of the star, which is only about the size of the Earth.

At first, the star (*i.e.*, the former core) is very hot and appears blue, but quickly — relative to the time spent in the red giant stage — cools to about 10,000 K to become a white dwarf. After this, it cools more slowly and eventually fades to a low luminosity and redder color after billions of years. **This will be the fate of the Sun after about 5 billion years from now.** The planetary nebula eventually escapes into space, carrying with it some of the carbon and oxygen nuclei that were created by nuclear fusion in the core. The evolution of a low-mass star along the H-R diagram is shown in Figure 13-6, along with a photo of a planetary nebula and a white dwarf.

⁴This is a misnomer: The only similarity to planets is that the cloud surrounds a star.

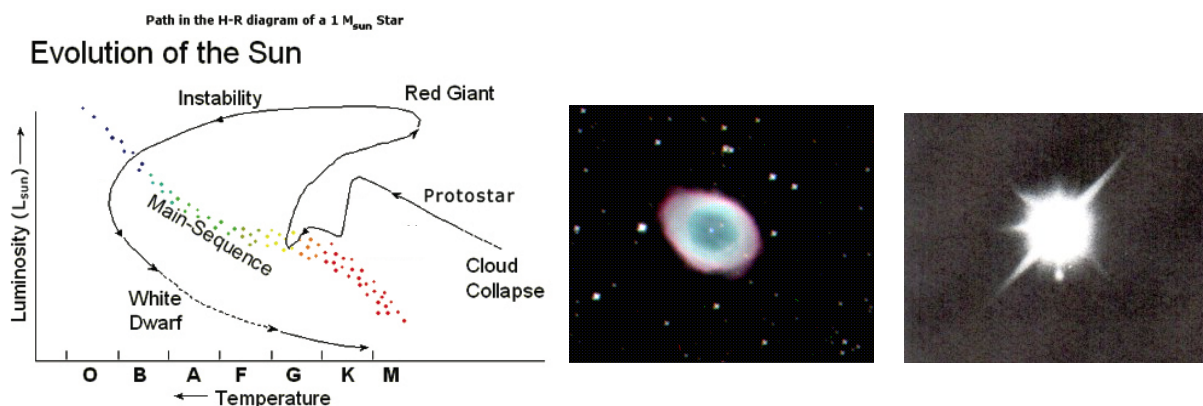


Figure 13-6. *Left:* Evolutionary path on the H-R diagram of a star that starts out with a mass similar to the mass of the Sun. Most of the star's lifetime is spent on the main sequence, the position on which is determined by the star's mass. *Center:* Example of a planetary nebula (the Ring Nebula) surrounding the newly exposed core of the star, which is at the center of the cloud. *Right:* The white dwarf Sirius B is part of a binary system with the brightest night-time star, Sirius A. (Sirius A is the bright, over-exposed star with spikes that are artifacts of diffraction in the telescope, while Sirius B is the little dot below it.) Sirius A is still on the main sequence, spectral class A. Although the mass of the white dwarf is now only $1.1M_{\text{sun}}$, the original star must have been greater than $3M_{\text{sun}}$ in order to have evolved more rapidly than its companion. [Sources: T. Herter (diagram), W. Keel (images)]

The Death of a Massive Star: Supernova and Neutron Star

Stars more massive than about $7M_{\odot}$ cannot end up as white dwarfs because the inward force of gravity in their cores is too great for the pressure of the electrons to overcome. Instead, the core continues to fuse heavier elements: oxygen and helium to form neon, neon and helium to form magnesium, and so on. Each time two protons and two neutrons are added to the nuclei. As the temperature increases, fusion of heavier elements with each other (e.g., carbon with carbon) also take place. The more massive elements require higher temperatures for fusion to occur because the collisions must take place at higher speeds to overcome the greater electromagnetic repulsion of the protons in the nuclei until the short-ranged strong force can take over. These higher temperatures are achieved by further contraction of the core.

The star contains many layers of nuclear fusion, with the core making the heaviest nuclei and successive surrounding shells producing lighter nuclei. Eventually, however, after iron nuclei are formed in the core, fusion can no longer produce energy (see Ch. 8). After this point, there is no longer the energy needed to maintain enough pressure to support the central part of the star against the inward force of gravity. The core then collapses *very* quickly (over a time span of seconds) until the quarks resist further contraction. It is thought that nuclear reactions then occur very rapidly throughout the core, converting a high fraction of the rest mass into energetic neutrinos. Even though neutrinos need to pass through a lot of matter to interact with it, the density is so high in the collapsed core of the star that the neutrinos are momentarily bottled up inside the core. The enormous pressure of the neutrinos pushes outward with an extremely powerful force. This force literally explodes the entire outer part of the star into space. This phenomenon, called a **supernova**, is extremely luminous. As was discussed in Chapter 6, exploding stars can be observed by telescopes rather easily even in remote galaxies. (The Hubble diagram shown in Fig. 11-8 was made using a particular type of supernova.) When a typical supernova occurs in our section of the Milky Way galaxy, it can even be seen in the daytime sky! An example of a supernova that exploded in another galaxy is shown in Figure 13-7, along with a photo of the remnant of a supernova that exploded in the Milky Way galaxy several thousand years ago and was observed at the Earth in the year 1054 by Chinese astronomers.

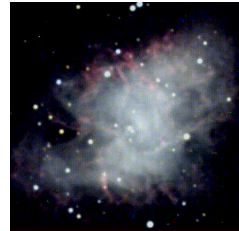
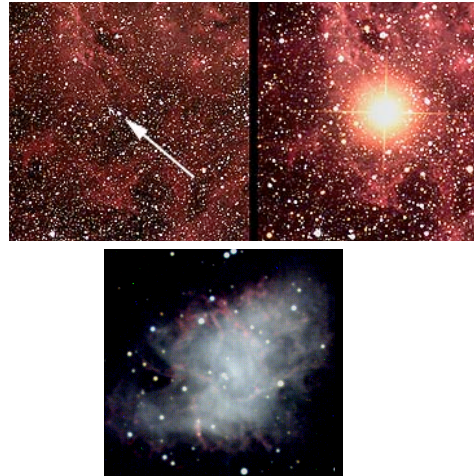
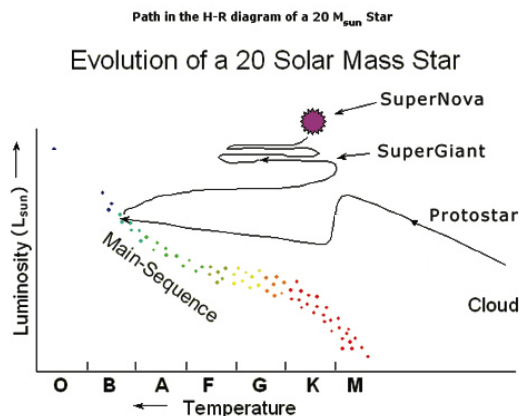


Figure 13-7. *Left*: Evolutionary path on the H-R diagram of a star that starts out with a mass much greater than that of the Sun. [Source: T. Herter] *Center top*: Star that exploded in the Large Magellanic Cloud, observed in 1987. *Left*: Before the explosion; *right*: during the explosion. (The spikes are artifacts from diffraction inside the telescope.) [Source: David Malin] *Bottom right*: The Crab Nebula, the remnant of a supernova observed in the year 1054. The cloud of gas and high-energy particles is expanding at a speed of about 1500 km/s. A neutron star seen as a pulsar lies at the center.

Most of the remains of the supernova escape into space. This gas contains all of the elements and isotopes that occur in nature. These were fused in the core and surrounding fusing layers before or during the explosion. The reactions that occur most readily create elements such as oxygen and silicon that are relatively abundant in stars and on the Earth. The energy from the explosion also allows many reactions to occur that use up rather than release energy. These less common reactions produce the rarer elements and isotopes. Some of the nuclei thus created are radioactive and decay into lighter elements after the envelope is ejected into space. **Nearly all the nuclei of atoms heavier than helium in the universe were created in massive stars and dispersed into interstellar space through supernova explosions.**

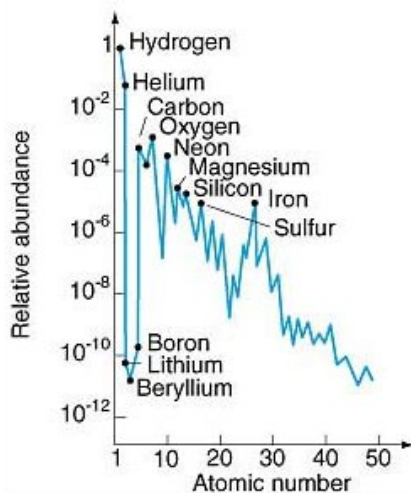


Figure 13-8. Relative abundances of various elements in the cosmos. Note that the vertical scale is in multiples of 0.01. Besides hydrogen and helium, the most abundant elements are those that are formed by fusing lighter nuclei with He nuclei in massive stars. The elements and isotopes with low abundances form mainly during supernova explosions. [Source: www.phy.olemiss.edu/~luca/astr/Topics-Extrasolar/Images/CosmicAbundances_252x292.jpg]

The material from supernova remnants eventually mixes with other gas clouds, some of which later form stars and planets. Each generation of stars is therefore richer in heavier elements than the preceding generation. The implications of this are rather amazing: except for the hydrogen and some of the carbon and oxygen atoms in your body, **you are composed of atoms that were created in massive stars that exploded!** In fact, an iron atom in your blood has passed through an average of five stars before becoming part of you.

At least some supernovae leave behind their core, which remains intact after the rest of the star has exploded outward. The core by this time has been crushed to the density of atomic nuclei and is supported by the resistance of the quarks in the nuclei from being squeezed together so tightly that they would share the same quantum state (see Ch. 8). In the past, before quarks were discovered, it was thought that the neutrons supply this resistance, so the core is called a neutron star. It has a mass between about 1 and 3 times the mass of the Sun, but shrunk down to the tiny (for a star) radius of only 10 km (roughly the size of a city). Conservation of angular momentum (see Ch. 12) causes the contracted neutron star to spin very rapidly, at hundreds of rotations per second at the beginning. In addition, the magnetic field is compressed to a very high value. This rapidly spinning magnetic field creates beams of radio — and, for young neutron stars, infrared, visible, and X-ray — emission. As the neutron star rotates, these beams pass into and out of a distant observer's line of sight, giving a lighthouse effect of flashing on and off. When a neutron star is observed to do this, it is called a pulsar. The first pulsar was discovered by Jocelyn Bell and Anthony Hewish in 1967. Their first task was to verify that the pulses of radio waves were natural rather than made by aliens from another star system trying to communicate with other intelligent life!

Black Holes as Remnants of the Most Massive Stars

If the core of the star is more massive than about $3M_s$, then even the quarks cannot overcome the inward pull of gravity. The original mass of a star with such a core was probably more than 30 times M_s . Nothing known can stop the gravitational collapse after nuclear fusion ceases in such a massive core. The core continues to collapse to a radius less than the Schwarzschild radius (see Ch. 12, eq. 12-1). The core then becomes a black hole. Both observational and theoretical studies indicate that the outer part of the star still explodes, but with even more energy than do supernovae that leave behind neutron stars. This class of supernova is termed a hypernova.

Exactly what happens during a hypernova explosion is controversial. But they have been linked observationally to a spectacular cosmic event called a gamma-ray burst. As the name implies, this phenomenon is a sudden flash of γ -ray photons. Usually, gamma-ray bursts last for only a minute or two, but during that time they are more luminous than a quasar and so can be seen out to great cosmic distances. The properties of gamma-ray bursts have led astronomers to understand that they come from beams of particles that are moving toward us at very close to light speed. A model for explaining this borrows from our description of quasars (see Ch. 12). For a very short time, the black hole created at the center of the star draws matter from just outside the star's core. This gas forms a disk around the black hole as it falls in, and magnetic fields swirling around in the disk drive a pair of high-speed jets of particles out along the poles. A shock wave in one of the jets produces the flash of γ rays (and, a bit later, X-rays and visible light) if the jet happens to point in our direction. Within seconds, the matter from the star either falls into the black hole or is expelled outward in the hypernova explosion, and the gamma-ray burst ends.

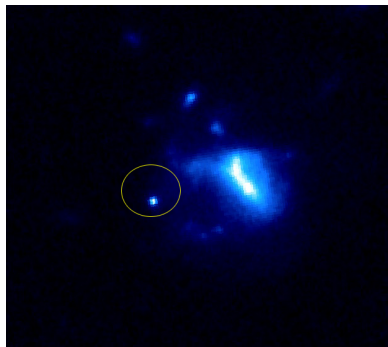


Figure 13-9. *Left:* Hubble Space Telescope image of the visible light following a gamma-ray burst (circled) in the outskirts of a galaxy. [Source: NASA/STScI/Penn State/D.Fox, image at chandra.harvard.edu] *Right:* Artist's rendition of an event in a hypernova that causes a gamma-ray burst. [Source: science.nasa.gov]

As mentioned in Chapter 12, black holes can be detected by X-rays, UV, and visible light that hot gas radiates while falling toward it, or by the light across the electromagnetic spectrum produced by the jets. There are about 20 confirmed or suspected such black holes in the Milky Way Galaxy. But if little or no matter is currently falling into a black hole, it can only be detected by its gravitational influence on other bodies that are nearby. So how many black holes are there in our Galaxy that we cannot detect because they are solitary? We can estimate by multiplying (1) the number of stars in the Galaxy (about 100 billion) by (2) the fraction of stars that form with masses greater than about $30M_{\odot}$ (of order 0.05%), since their cores eventually become black holes. This leads us to the conclusion that there are roughly 100 million black holes lurking in our Galaxy! Is this cause to worry? The answer is “no.” Space is so vast that collisions between stars — which are much more numerous than black holes and have the same gravitational pull from a distance greater than the size of Earth’s orbit — are extremely rare, occurring about once every few hundred million years in our Galaxy. A collision between a star or planet and a stellar-mass black hole happens less than once every 100 billion years in our region of the Milky Way.

Gravitational Waves from Colliding Black Holes and Neutron Stars

In some binary systems containing very massive stars, the cores of both stars eventually become black holes. The black holes slow down in their orbits by losing energy to the emission of gravitational waves (see Chapter 9). This occurs gradually at first, but eventually the orbits become so small that the black holes merge. The final stage is the emission of a burst of gravitational waves over a time span of less than 1 second. Three such events were observed between 2015 and 2017 by gravitational wave detectors on the Earth, with the changing pattern of the amplitude and frequency of the waves matching theoretical predictions. The most massive of the merging black holes each has a mass of roughly 30 solar masses.

A second type of gamma-ray burst that lasts for only a few seconds has properties that match theoretical models of colliding neutron stars in a binary system. In August 2017, gravitational waves, γ rays, X-rays, and visible light were detected from one such event. The optical spectrum fit the spectrum predicted if the neutron-rich material from the neutron stars combined to form a number of heavy elements (such as gold) that are more abundant in nature than can be explained by current models of supernovae.

Summary

A star produces energy from nuclear fusion reactions in its core. For most of the star’s lifetime, it does this by converting hydrogen to helium. After the hydrogen in the core becomes exhausted — a process that occurs more rapidly in more massive stars — the core collapses and heats up further. This intensifies the fusion of hydrogen surrounding the core and at some point causes helium nuclei to fuse to form carbon in the core. The extra energy release causes the outer part of the star to expand to a very large size, cooling as it does, to form a red giant. Eventually, in a relatively low to medium-mass star (*e.g.*, the Sun), the outer envelope of the red giant blows away into space, exposing a core called a white dwarf that is as small as the Earth but has a mass similar to that of the Sun. The Sun is middle-aged, about 4.6 billion years old, with another 5 billion years remaining until it uses up the hydrogen fuel in its core and becomes first a red giant and then a white dwarf.

The H-R diagram, on which stars are placed according to their luminosities (as determined from brightness and distance) and temperatures (as determined from their spectra or, more crudely, colors), contains a curved band called the main sequence. Stars on the main sequence are in their hydrogen-fusion stage. Stars in the red giant phase lie above the main sequence, while white dwarfs lie below it. For clusters of stars, in which the stars all have about the same age, the high-temperature/high luminosity end of the main sequence is missing; these stars have already gone on to later stages. A band of stars connects the main sequence stars in clusters with the red giants; stars in this band are in transition between the two

stages. The age of the cluster can be determined by the position of this “turn-off” from the main sequence, with the turn-offs in older clusters lying farther down and to the right on the H-R diagram.

A star more massive than about 7 solar masses eventually explodes as a supernova, spewing most of the material — by then enriched in heavy elements — into interstellar space where it can mix with other gas that will later form new stars. The core becomes a neutron star or, for the most massive stars, a black hole. The newly formed black hole can produce a spectacular gamma-ray burst as gas from just outside the core falls toward the black hole and ultra-high-speed jets of high-energy particles shoot out along the poles. For a few seconds or minutes, a gamma-ray burst can be even more luminous than a quasar. Pairs of black holes or two neutron stars in a binary system will eventually merge, emitting bursts of gravitational waves. Such events have been detected from three black hole binaries and one pair of neutron stars, with the latter also causing a short gamma-ray burst as well as luminous X-ray and visible light.

Glossary

Gravitational collapse: Process by which the attraction of the mass of different regions causes them all to fall toward the center of the mass distribution.

Nuclear fusion: Process by which “light” nuclei of atoms combine to form more complex nuclei. (See also Chapter 8.) Mass is converted to energy. Main source of energy in a normal star.

Fusion: See nuclear fusion.

Atmosphere of a star: Transparent layer of gas in the outer regions.

Photosphere: Visible surface of a star, beneath which the star is opaque. The photosphere emits a blackbody spectrum.

Core of a star: Central region where most nuclear fusion reactions take place.

Interior of a star: The region between the core and the photosphere.

Convection: Process of heat exchange in which cells of hot gas (or liquid) are exchanged with cells of less-hot gas through mass motions. Example: boiling water.

Radiative transport: Outward movement of energy in the form of photons from the core of a star. Photons are repeatedly absorbed and emitted by atoms as the energy diffuses toward the surface.

Absorption-Line Spectrum: Dark lines that are superposed on a continuous spectrum, when the light of a hot, opaque object shines through a cooler gas cloud.

Spectral class: System of categorizing stars according to their absorption-line spectra. Ranging from hottest to least hot, the main spectral classes are O, B, A, F, G, K, and M.

Luminosity: Energy emitted per unit time in the form of electromagnetic waves (light). Measured in watts (W).

Red giant star: A star that has used up its hydrogen fuel in its inner core, which has collapsed to a dense, hot state. The outer “envelope” has expanded greatly and cooled such that its color is red.

H-R (Hertzsprung-Russell) diagram: Plot of luminosity vs. spectral class or temperature of a population of stars. See Fig. 13-4.

Main sequence: Band on an H-R diagram where most stars are located. This represents the stage when stars are converting hydrogen to helium in their cores.

White dwarf: Former core of a red giant star that has lost its envelope. The radius is small, roughly equal to the radius of the Earth. The star is supported against gravity by resistance of electrons against occupying the same quantum state.

Brown dwarf: An object with mass between that of a planet and the lowest-mass stars.

Planetary nebula: Cloud of hot gas surrounding an exposed core of a star. The cloud was formerly part of the interior of the star. The star will evolve into a white dwarf.

Supernova: The explosion of a star. The star, except for the central core, is ejected into space. The luminosity of the expanding remnant is extremely high during the first several weeks after the explosion.

Neutron star: The remaining core of a star that explodes as a supernova. The star is supported against gravity by resistance of quarks against occupying the same quantum state. Can be observed as pulsars.

Pulsar: Source of radio waves and in some cases optical light and X-rays that turn on and off with a regular period that can range from milliseconds to a few seconds. Explained as a rapidly spinning neutron star with a strong magnetic field that acts as a lighthouse with a rotating beam of electromagnetic waves.

Hypernova: A particularly energetic supernova caused by the collapse of the core of a very massive star. A black hole is thought to form at the center while the outer part of the star explodes apart.

Black hole: Object that has shrunk to a radius smaller than the Schwarzschild radius corresponding to its mass (see eq. 12-1). Matter or energy that falls into a black hole cannot escape.

Schwarzschild radius (symbol: R_s): See black hole. Also see eq. 12-1.

Pole (or Rotational Axis): Imaginary line about which an object revolves or rotates. It is perpendicular to the equatorial plane.

Gamma-ray Burst: An extraordinarily luminous flash of γ rays, usually lasting only a few seconds. At least some gamma-ray bursts are associated with hypernovae. Current models explain the bursts with newly formed black holes either during a hypernova explosion or when two neutrons stars spiral into each other and coalesce to form a black hole.

Quasar: The center of a galaxy that produces extremely energetic phenomena. Thought to be powered by matter falling into a black hole, which converts gravitational potential energy to thermal and kinetic energy.

Questions for Discussion

A. Explain why the Sun must eventually change dramatically to become a different type of star. What stages will it go through? Roughly how many years from now will this occur?

- B. If humans are still alive when the Sun becomes a red giant, what could they do to survive?
- C. If a star is powered by nuclear fusion reactions in its core, why does it shine steadily rather than explode as a big hydrogen bomb?
- D. A supernova explosion would destroy the star and the environment of any planet that was orbiting around it, probably causing it to hurtle into interstellar space. Yet, new star systems will eventually form from the heavy-element enriched material ejected by the supernova. Compare this process with the life cycle of living organisms on the Earth.
- E. What would happen to the Earth if the Sun were to shrink suddenly down to a radius less than 3 km? (*Note:* We are sure that this will not happen!) You should keep in mind that, at distances much greater than the Schwarzschild radius, the force of gravity of even a black hole is accurately represented by Newton's Law of Universal Gravitation (eq. 4-6).
- F. Imagine that there are two stars (A and B) in a binary system. One star has a mass 40 times that of the Sun, while the other has a mass 2 times that of the Sun. Each star is initially in a circular orbit about the center of mass of the system. (This is an imaginary point that is closer to the more massive star.) Describe what you think would be the evolution of this star system, starting with the main-sequence phase. Do this in steps, with each step corresponding to a new stage of one of the stars.

Examples of How to Solve Problems on Stars

1. A main-sequence star's mass is 2 times that of the Sun, $2M_s$.
 - a. Calculate the luminosity (in solar units, L_s) of the star.
 - b. If the main-sequence lifetime of the Sun is about 10 billion years, what is the main-sequence lifetime of the star?

Answer:

- a. Eq. (13-1) gives $L \approx (M/M_s)^{3.5} L_s$. We are given that $M = 2M_s$.
So, $L \approx 2^{3.5} L_s = 11 L_s$.

- b. Eq. (13-3) gives lifetime = $10 / [M/M_s]^{2.5}$ billion yr. We use $M = 2M_s$ to get
H-lifetime = $10/2^{2.5} = 10/5.7 = 1.8$ billion yr.

Homework Problems

1. A main-sequence star has a mass of $0.8 M_s$.
 - a. Calculate the luminosity (in solar units, L_s) of the star.
 - b. What is the hydrogen fusing lifetime of the star?
2. A main-sequence star has a mass 40 times that of the Sun, $40M_s$.
 - a. Calculate the luminosity (in solar units, L_s) of the star.
 - b. What is the hydrogen fusing lifetime of the star?
 - c. If the core of this star has a mass of 15 solar masses, to what radius must the core shrink to become a black hole? [The relevant equation is 12-1 and a sample problem of this type is included in Chapter 12.]

3. Sketch the H-R diagram expected for a cluster of stars that is 5 billion years old. Use the same scale as in Fig. 13-5, which you should use as a guide to the appearance of your diagram.

4. The net result of nuclear fusion reactions is the conversion of a number of light nuclei into a heavy nucleus plus energy. (Here we will neglect the mass-energy of the neutrinos that are produced as a by-product.)

a. In hydrogen fusion in the core of a main-sequence star, 4 H nuclei with a combined mass of 6.6943×10^{-27} kg are converted into a He nucleus with a mass of 6.6466×10^{-27} kg. Energy is conserved (see Ch. 4) in the reaction. How much energy does the reaction produce? [Hint: Use Einstein's famous formula $E = mc^2$ to convert from rest-mass to energy. Your answer will automatically be in joules (J) if you use kg for m and $c = 3.00 \times 10^8$ m/s for the speed of light.]

b. In helium fusion in the core of a red giant, 3 He nuclei with a combined mass of 1.9940×10^{-26} kg are converted into a carbon nucleus with a mass of 1.9926×10^{-26} kg. How much energy does the reaction produce? Compare this with the energy of 3 hydrogen fusion net reactions, i.e., the energy from three occurrences of the reaction $4\text{H} \rightarrow \text{He} + \text{energy}$, using your result from part (a).

c. The luminosity of a red giant star is about 100 times higher than that of a main-sequence star similar to the Sun. Given the results of parts (a) and (b), compare with a ratio the reaction rate (number of reactions per second) of helium fusion required in the red giant star with the reaction rate of hydrogen fusion in a main-sequence star. [Hint: If less energy is produced by each reaction, the reaction rate must be correspondingly higher to produce a given luminosity. Use this logic to figure out how to proceed and to check your answer.]

d. What factors could cause the reaction rates to be so different? [Hint: What conditions could cause collisions among particles to become more frequent and at a higher speed in the core of a star?]

5. A binary system is a bright source of X-rays. A giant star is orbiting around a black point in space and no companion star is visible. Astronomers conclude that the unseen object is a black hole containing a mass of $12M_{\odot}$.

a. What is the Schwarzschild radius in meters? [The relevant equation is 12-1 and a sample problem of this type is included in Chapter 12.]

b. Use equation (4-10) to calculate the period P of the orbit of gas in a circular orbit with radius $A = 3$ times the Schwarzschild radius that you calculated in part (a).

c. X-rays are often observed to pulse with a period of about 0.01 s in such binary systems. Comment on whether the period P of the orbit of gas at a distance of 3 Schwarzschild radii from the black hole might be related to the period of pulsation. [Hint: if the ratio of the periods is between about 0.5 and 2, then they could be related.]