23

The Death of Stars

Figure 23.1 Stellar Life Cycle. This remarkable picture of NGC 3603, a nebula in the Milky Way Galaxy, was taken with the Hubble Space Telescope. This image illustrates the life cycle of stars. In the bottom half of the image, we see clouds of dust and gas, where it is likely that star formation will take place in the near future. Near the center, there is a cluster of massive, hot young stars that are only a few million years old. Above and to the right of the cluster, there is an isolated star surrounded by a ring of gas. Perpendicular to the ring and on either side of it, there are two bluish blobs of gas. The ring and the blobs were ejected by the star, which is nearing the end of its life. (credit: modification of work by NASA, Wolfgang Brandner (JPL/IPAC), Eva K. Grebel (University of Washington), You-Hua Chu (University of Illinois Urbana-Champaign))

Chapter Outline

Thinking Ahead

Do stars die with a bang or a whimper? In the preceding two chapters, we followed the life story of stars, from the process of birth to the brink of death. Now we are ready to explore the ways that stars end their lives. Sooner or later, each star exhausts its store of nuclear energy. Without a source of internal pressure to balance the weight of the overlying layers, every star eventually gives way to the inexorable pull of gravity and collapses under its own weight.

Following the rough distinction made in the last chapter, we will discuss the end-of-life evolution of stars of lower and higher mass separately. What determines the outcome—bang or whimper—is the mass of the star *when it is ready to die*, not the mass it was born with. As we noted in the last chapter, stars can lose a significant amount of mass in their middle and old age.

23.1 The Death of Low-Mass Stars

Learning Objectives

By the end of this section, you will be able to:

- Describe the physical characteristics of degenerate matter and explain how the mass and radius of degenerate stars are related
- Plot the future evolution of a white dwarf and show how its observable features will change over time
- Distinguish which stars will become white dwarfs

Let's begin with those stars whose final mass just before death is less than about 1.4 times the mass of the Sun (M_{Sun}). (We will explain why this mass is the crucial dividing line in a moment.) Note that most stars in the universe fall into this category. The number of stars decreases as mass increases; really massive stars are rare (see The Stars: A Celestial Census). This is similar to the music business where only a few musicians ever become superstars. Furthermore, many stars with an initial mass much greater than 1.4 M_{Sun} will be reduced to that level by the time they die. For example, we now know that stars that start out with masses of at least 8.0 M_{Sun} (and possibly as much as 10 M_{Sun}) manage to lose enough mass during their lives to fit into this category (an accomplishment anyone who has ever attempted to lose weight would surely envy).

A Star in Crisis

In the last chapter, we left the life story of a star with a mass like the Sun's just after it had climbed up to the red-giant region of the H–R diagram for a second time and had shed some of its outer layers to form a planetary nebula. Recall that during this time, the *core* of the star was undergoing an "energy crisis." Earlier in its life, during a brief stable period, helium in the core had gotten hot enough to fuse into carbon (and oxygen). But after this helium was exhausted, the star's core had once more found itself without a source of pressure to balance gravity and so had begun to contract.

This collapse is the final event in the life of the core. Because the star's mass is relatively low, it cannot push its core temperature high enough to begin another round of fusion (in the same way larger-mass stars can). The core continues to shrink until it reaches a density equal to nearly a million times the density of water! That is 200,000 times greater than the average density of Earth. At this extreme density, a new and different way for matter to behave kicks in and helps the star achieve a final state of equilibrium. In the process, what remains of the star becomes one of the strange *white dwarfs* that we met in The Stars: A Celestial Census.

Degenerate Stars

Because white dwarfs are far denser than any substance on Earth, the matter inside them behaves in a very unusual way—unlike anything we know from everyday experience. At this high density, gravity is incredibly strong and tries to shrink the star still further, but all the *electrons* resist being pushed closer together and set up a powerful pressure inside the core. This pressure is the result of the fundamental rules that govern the behavior of electrons (the quantum physics you were introduced to in The Sun: A Nuclear Powerhouse). According to these rules (known to physicists as the Pauli exclusion principle), which have been verified in studies of atoms in the laboratory, no two electrons can be in the same place at the same time doing the same thing. We specify the *place* of an electron by its position in space, and we specify what it is doing by its motion and the way it is spinning.

The temperature in the interior of a star is always so high that the atoms are stripped of virtually all their electrons. For most of a star's life, the density of matter is also relatively low, and the electrons in the star are moving rapidly. This means that no two of them will be in the same place moving in exactly the same way at the same time. But this all changes when a star exhausts its store of nuclear energy and begins its final collapse.

As the star's core contracts, electrons are squeezed closer and closer together. Eventually, a star like the Sun becomes so dense that further contraction would in fact require two or more electrons to violate the rule against occupying the same place and moving in the same way. Such a dense gas is said to be degenerate (a term coined by physicists and not related to the electron's moral character). The electrons in a **degenerate gas** resist further crowding with tremendous pressure. (It's as if the electrons said, "You can press inward all you want, but there is simply no room for any other electrons to squeeze in here without violating the rules of our existence.")

The degenerate electrons do not require an input of heat to maintain the pressure they exert, and so a star with this kind of structure, if nothing disturbs it, can last essentially forever. (Note that the repulsive force between degenerate electrons is different from, and much stronger than, the normal electrical repulsion between charges that have the same sign.)

The electrons in a degenerate gas do move about, as do particles in any gas, but not with a lot of freedom. A particular electron cannot change position or momentum until another electron in an adjacent stage gets out of the way. The situation is much like that in the parking lot after a big football game. Vehicles are closely packed, and a given car cannot move until the one in front of it moves, leaving an empty space to be filled.

Of course, the dying star also has atomic nuclei in it, not just electrons, but it turns out that the nuclei must be squeezed to much higher densities before their quantum nature becomes apparent. As a result, in white dwarfs, the nuclei do not exhibit degeneracy pressure. Hence, in the white dwarf stage of stellar evolution, it is the degeneracy pressure of the electrons, and not of the nuclei, that halts the collapse of the core.

White Dwarfs

White dwarfs, then, are stable, compact objects with electron-degenerate cores that cannot contract any further. Calculations showing that white dwarfs are the likely end state of low-mass stars were first carried out by the Indian-American astrophysicist Subrahmanyan Chandrasekhar. He was able to show how much a star will shrink before the degenerate electrons halt its further contraction and hence what its final diameter will be (Figure 23.2).

When Chandrasekhar made his calculation about white dwarfs, he found something very surprising: the radius of a white dwarf shrinks as the mass in the star increases (the larger the mass, the more tightly packed the electrons can become, resulting in a smaller radius). According to the best theoretical models, a white dwarf with a mass of about 1.4 M_{Sun} or larger would have a radius of zero. What the calculations are telling us is that even the force of degenerate electrons cannot stop the collapse of a star with more mass than this. The maximum mass that a star can end its life with and still become a white dwarf—1.4 M_{Sun}—is called the **Chandrasekhar limit**. Stars with end-of-life masses that exceed this limit have a different kind of end in store—one that we will explore in the next section.

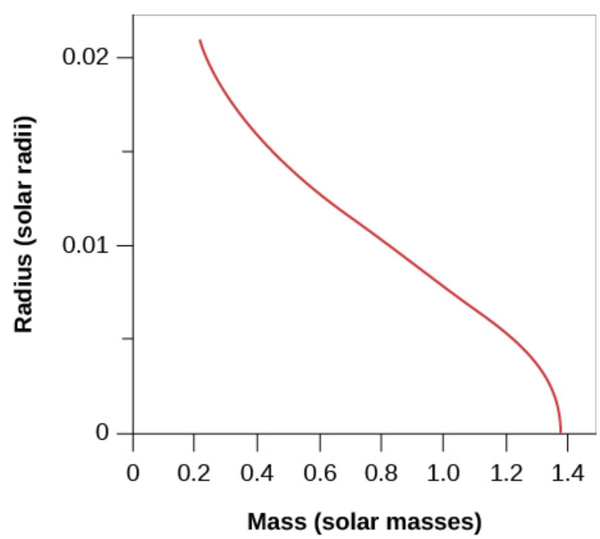


Figure 23.2 Relating Masses and Radii of White Dwarfs. Models of white-dwarf structure predict that as the mass of the star

increases (toward the right), its radius gets smaller and smaller.

VOYAGERS IN ASTRONOMY

Subrahmanyan Chandrasekhar

Born in 1910 in Lahore, India, Subrahmanyan Chandrasekhar (known as Chandra to his friends and colleagues) grew up in a home that encouraged scholarship and an interest in science (Figure 23.3). His uncle, C. V. Raman, was a physicist who won the 1930 Nobel Prize. A precocious student, Chandra tried to read as much as he could about the latest ideas in physics and astronomy, although obtaining technical books was not easy in India at the time. He finished college at age 19 and won a scholarship to study in England. It was during the long boat voyage to get to graduate school that he first began doing calculations about the structure of white dwarf stars.

Chandra developed his ideas during and after his studies as a graduate student, showing—as we have discussed—that white dwarfs with masses greater than 1.4 times the mass of the Sun cannot exist and that the theory predicts the existence of other kinds of stellar corpses. He wrote later that he felt very shy and lonely during this period, isolated from students, afraid to assert himself, and sometimes waiting for hours to speak with some of the famous professors he had read about in India. His calculations soon brought him into conflict with certain distinguished astronomers, including Sir Arthur Eddington, who publicly ridiculed Chandra’s ideas. At a number of meetings of astronomers, such leaders in the field as Henry Norris Russell refused to give Chandra the opportunity to defend his ideas, while allowing his more senior critics lots of time to criticize them.

Yet Chandra persevered, writing books and articles elucidating his theories, which turned out not only to be correct, but to lay the foundation for much of our modern understanding of the death of stars. In 1983, he received the Nobel Prize in physics for this early work.

In 1937, Chandra came to the United States and joined the faculty at the University of Chicago, where he remained for the rest of his life. There he devoted himself to research and teaching, making major contributions to many fields of astronomy, from our understanding of the motions of stars through the Galaxy to the behavior of the bizarre objects called black holes (see Black Holes and Curved Spacetime). In 1999, NASA named its sophisticated orbiting X-ray telescope (designed in part to explore such stellar corpses) the Chandra X-ray Observatory.

Figure 23.3 S. Chandrasekhar (1910–1995). Chandra's research provided the basis for much of what we now know about stellar corpses. (credit: modification of work by American Institute of Physics)

Chandra spent a great deal of time with his graduate students, supervising the research of more than 50 PhDs during his life. He took his teaching responsibilities very seriously: during the 1940s, while based at the Yerkes Observatory, he willingly drove the more than 100-mile trip to the university each week to teach a class of only a few students.

Chandra also had a deep devotion to music, art, and philosophy, writing articles and books about the relationship between the humanities and science. He once wrote that "one can learn science the way one enjoys music or art. . . . Heisenberg had a marvelous phrase 'shuddering before the beautiful'. . . that is the kind of feeling I have."

LINK TO LEARNING

Using the Hubble Space Telescope, astronomers were able to detect images (https://openstax.org/l/30hubimgwhidwa) of faint white dwarf stars and other "stellar corpses" in the M4 star cluster, located about 7200 light-years away.

The Ultimate Fate of White Dwarfs

If the birth of a main-sequence star is defined by the onset of fusion reactions, then we must consider the end of all fusion reactions to be the time of a star's death. As the core is stabilized by degeneracy pressure, a last shudder of fusion passes through the outside of the star, consuming the little hydrogen still remaining. Now the star is a true white dwarf: nuclear fusion in its interior has ceased. Figure 23.4 shows the path of a star like the Sun on the H–R diagram during its final stages.

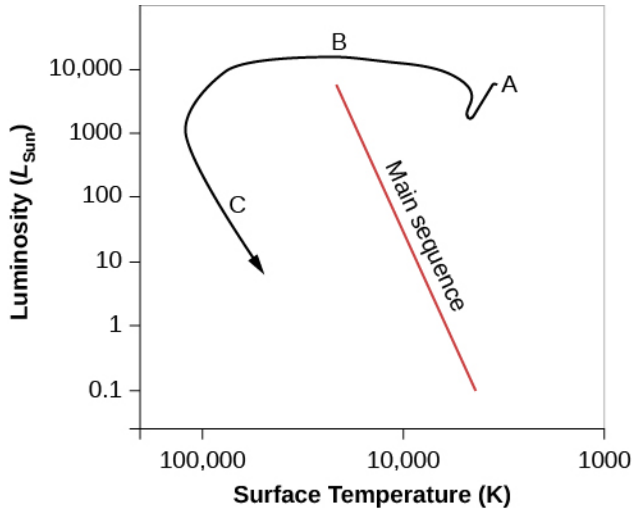
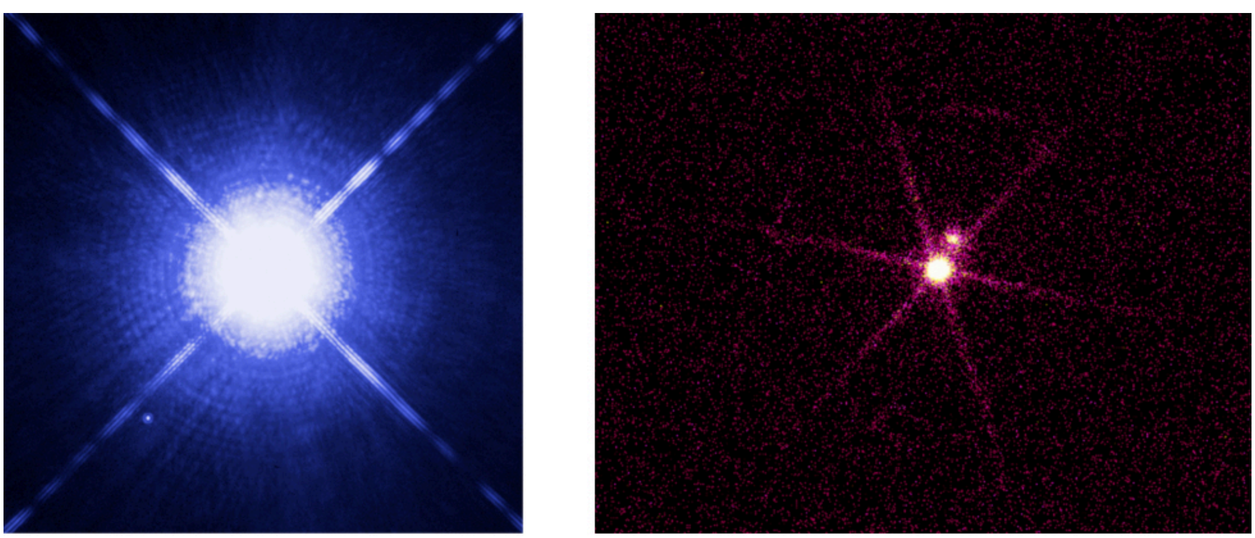


Figure 23.4 Evolutionary Track for a Star Like the Sun. This diagram shows the changes in luminosity and surface temperature for a star with a mass like the Sun's as it nears the end of its life. After the star becomes a giant again (point A on the diagram), it will lose more and more mass as its core begins to collapse. The mass loss will expose the hot inner core, which will appear at the center of a planetary nebula. In this stage, the star moves across the diagram to the left as it becomes hotter and hotter during its collapse (point B). At first, the luminosity remains nearly constant, but as the star begins to cool off, it becomes less and less bright (point C). It is now a white dwarf and will continue to cool slowly for billions of years until all of its remaining store of energy is radiated away. (This assumes the Sun will lose between 46–50% of its mass during the giant stages, based upon various theoretical models).

Since a stable white dwarf can no longer contract or produce energy through fusion, its only energy source is the heat represented by the motions of the atomic nuclei in its interior. The light it emits comes from this internal stored heat, which is substantial. Gradually, however, the white dwarf radiates away all its heat into space. After many billions of years, the nuclei will be moving much more slowly, and the white dwarf will no longer shine (Figure 23.5). It will then be a black dwarf—a cold stellar corpse with the mass of a star and the size of a planet. It will be composed mostly of carbon, oxygen, and neon, the products of the most advanced fusion reactions of which the star was capable.



(a) (b)

Figure 23.5 Visible Light and X-Ray Images of the Sirius Star System. (a) This image taken by the Hubble Space Telescope shows Sirius A (the large bright star), and its companion star, the white dwarf known as Sirius B (the tiny, faint star at the lower left). Sirius A and B are 8.6 light-years from Earth and are our fifth-closest star system. Note that the image has intentionally been overexposed to allow us to see Sirius B. (b) The same system is shown in X-ray taken with the Chandra Space Telescope. Note that Sirius A is fainter in X-rays than the hot white dwarf that is Sirius B. (credit a: modification of work by NASA, ESA, H. Bond, M. Barstow(University of Leicester); credit b: modification of work by NASA/SAO/CXC)

We have one final surprise as we leave our low-mass star in the stellar graveyard. Calculations show that as a degenerate star cools, the atoms inside it in essence "solidify" into a giant, highly compact lattice (organized rows of atoms, just like in a crystal). When carbon is compressed and crystallized in this way, it becomes a giant *diamond-like* star. A white dwarf star might make the most impressive engagement present you could ever see, although any attempt to mine the diamond-like material inside would crush an ardent lover instantly!

LINK TO LEARNING

Learn about a recent “diamond star” find, a cold, white dwarf star (https://openstax.org/l/30diamondstar) detected in 2014, which is considered the coldest and dimmest found to date, at the website of the National Radio Astronomy Observatory.

Evidence That Stars Can Shed a Lot of Mass as They Evolve

Whether or not a star will become a white dwarf depends on how much mass is lost in the red-giant and earlier phases of evolution. All stars that have masses below the Chandrasekhar limit when they run out of fuel will become white dwarfs, no matter what mass they were born with. But which stars shed enough mass to reach this limit?

One strategy for answering this question is to look in young, open clusters (which were discussed in Star Clusters). The basic idea is to search for young clusters that contain one or more white dwarf stars. Remember that more massive stars go through all stages of their evolution more rapidly than less massive ones. Suppose we find a cluster that has a white dwarf member and also contains stars on the main sequence that have 6 times the mass of the Sun. This means that only those stars with masses greater than 6 M_{Sun} have had time to exhaust their supply of nuclear energy and complete their evolution to the white dwarf stage. The star that turned into the white dwarf must therefore have had a main-sequence mass of more than 6 M_{Sun}, since stars with lower masses have not yet had time to use up their stores of nuclear energy. The star that became the white dwarf must, therefore, have gotten rid of at least 4.6 M_{Sun} so that its mass at the time nuclear energy generation ceased could be less than 1.4 M_{Sun}.

Astronomers continue to search for suitable clusters to make this test, and the evidence so far suggests that stars with masses up to about 8 M_{Sun} can shed enough mass to end their lives as white dwarfs. Stars like the Sun will probably lose about 45% of their initial mass and become white dwarfs with masses less than 1.4 M_{Sun}.

23.2 Evolution of Massive Stars: An Explosive Finish

Learning Objectives

By the end of this section, you will be able to:

- Describe the interior of a massive star before a supernova
- Explain the steps of a core collapse and explosion
- List the hazards associated with nearby supernovae

Thanks to mass loss, then, stars with starting masses of at least 8 M_{Sun} (and perhaps even more) probably end their lives as white dwarfs. But we know stars can have masses as large as 150 (or more) M_{Sun}. They have a different kind of death in store for them. As we will see, these stars die with a bang.

Nuclear Fusion of Heavy Elements

After the helium in its core is exhausted (see The Evolution of More Massive Stars), the evolution of a massive star takes a significantly different course from that of lower-mass stars. In a massive star, the weight of the outer layers is sufficient to force the carbon core to contract until it becomes hot enough to fuse carbon into oxygen, neon, and magnesium. This cycle of contraction, heating, and the ignition of another nuclear fuel repeats several more times. After each of the possible nuclear fuels is exhausted, the core contracts again until it reaches a new temperature high enough to fuse still-heavier nuclei. The products of carbon fusion can be further converted into silicon, sulfur, calcium, and argon. And these elements, when heated to a still-higher temperature, can combine to produce iron. Massive stars go through these stages very, very quickly. In really massive stars, some fusion stages toward the very end can take only months or even days! This is a far cry from the millions of years they spend in the main-sequence stage.

At this stage of its evolution, a massive star resembles an onion with an iron core. As we get farther from the center, we find shells of decreasing temperature in which nuclear reactions involve nuclei of progressively lower mass—silicon and sulfur, oxygen, neon, carbon, helium, and finally, hydrogen (Figure 23.6).

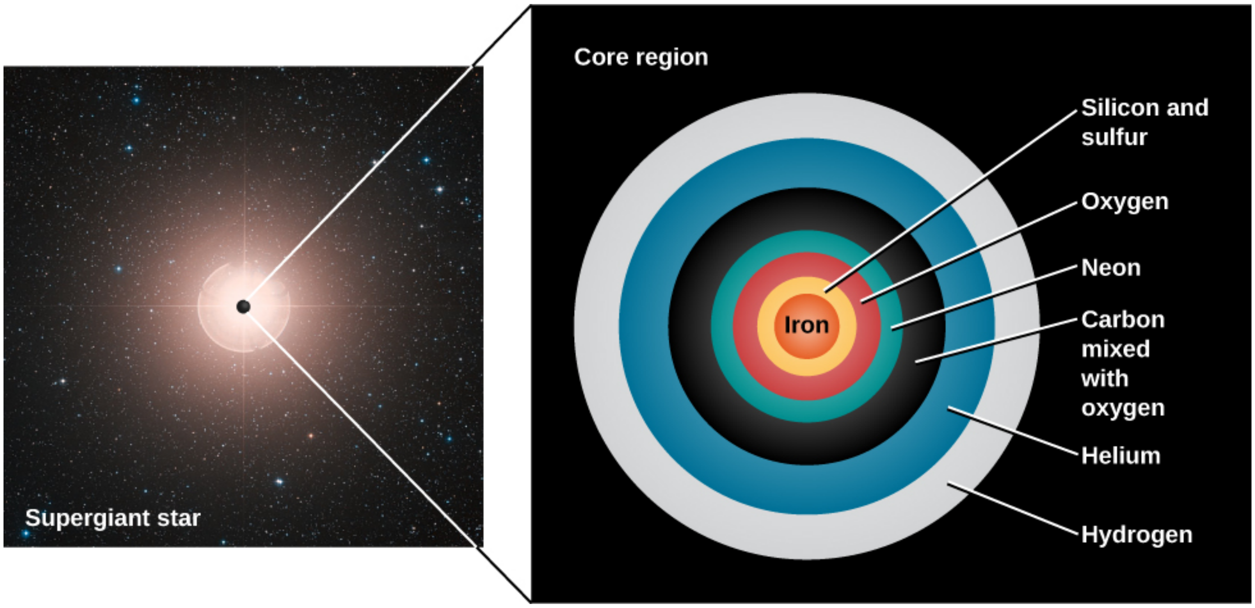


Figure 23.6 Structure of an Old Massive Star. Just before its final gravitational collapse, the core of a massive star resembles an onion. The iron core is surrounded by layers of silicon and sulfur, oxygen, neon, carbon mixed with some oxygen, helium, and finally hydrogen. Outside the core, the composition is mainly hydrogen and helium. (Note that this diagram is not precisely to scale but is just meant to convey the general idea of what such a star would be like.) (credit: modification of work by ESO, Digitized Sky Survey)

But there is a limit to how long this process of building up elements by fusion can go on. The fusion of silicon into iron turns out to be the last step in the sequence of nonexplosive element production. Up to this point, each fusion reaction has *produced* energy because the nucleus of each fusion product has been a bit more stable than the nuclei that formed it. As discussed in The Sun: A Nuclear Powerhouse, light nuclei give up some of their binding energy in the process of fusing into more tightly bound, heavier nuclei. It is this released energy that maintains the outward pressure in the core so that the star does not collapse. But of all the nuclei known, iron is the most tightly bound and thus the most stable.

You might think of the situation like this: all smaller nuclei want to “grow up” to be like iron, and they are willing to pay (*produce* energy) to move toward that goal. But iron is a mature nucleus with good self-esteem, perfectly content being iron; it requires payment (must *absorb* energy) to change its stable nuclear structure. This is the exact opposite of what has happened in each nuclear reaction so far: instead of *providing* energy to balance the inward pull of gravity, any nuclear reactions involving iron would *remove* some energy from the core of the star.

Unable to generate energy, the star now faces catastrophe.

Collapse into a Ball of Neutrons

When nuclear reactions stop, the core of a massive star is supported by degenerate electrons, just as a white dwarf is. For stars that begin their evolution with masses of at least 10 M_{Sun}, this core is likely made mainly of iron. (For stars with initial masses in the range 8 to 10 M_{Sun}, the core is likely made of oxygen, neon, and magnesium, because the star never gets hot enough to form elements as heavy as iron. The exact composition of the cores of stars in this mass range is very difficult to determine because of the complex physical characteristics in the cores, particularly at the very high densities and temperatures involved.) We will focus on the more massive iron cores in our discussion.

While no energy is being generated within the white dwarf core of the star, fusion still occurs in the shells that surround the core. As the shells finish their fusion reactions and stop producing energy, the ashes of the last reaction fall onto the white dwarf core, increasing its mass. As Figure 23.2 shows, a higher mass means a smaller core. The core can contract because even a degenerate gas is still mostly empty space. Electrons and atomic nuclei are, after all, extremely small. The electrons and nuclei in a stellar core may be crowded compared to the air in your room, but there is still lots of space between them.

The electrons at first resist being crowded closer together, and so the core shrinks only a small amount. Ultimately, however, the iron core reaches a mass so large that even degenerate electrons can no longer support it. When the density reaches 4×10^{11} g/cm^3 (400 billion times the density of water), some electrons are actually squeezed into the atomic nuclei, where they combine with protons to form neutrons and neutrinos. This transformation is not something that is familiar from everyday life, but becomes very important as such a massive star core collapses.

Some of the electrons are now gone, so the core can no longer resist the crushing mass of the star's overlying layers. The core begins to shrink rapidly. More and more electrons are now pushed into the atomic nuclei, which ultimately become so saturated with neutrons that they cannot hold onto them.

At this point, the neutrons are squeezed out of the nuclei and can exert a new force. As is true for electrons, it turns out that the neutrons strongly resist being in the same place and moving in the same way. The force that can be exerted by such *degenerate neutrons* is much greater than that produced by degenerate electrons, so unless the core is too massive, they can ultimately stop the collapse.

This means the collapsing core can reach a stable state as a crushed ball made mainly of neutrons, which astronomers call a **neutron star**. We don't have an exact number (a "Chandrasekhar limit") for the maximum mass of a neutron star, but calculations tell us that the upper mass limit of a body made of neutrons might only be about 3 M_{Sun}. So if the mass of the core were greater than this, then even neutron degeneracy would not be able to stop the core from collapsing further. The dying star must end up as something even more extremely compressed, which until recently was believed to be only one possible type of object—the state of ultimate compaction known as a black hole (which is the subject of our next chapter). This is because no force was believed to exist that could stop a collapse beyond the neutron star stage.

Collapse and Explosion

When the collapse of a high-mass star's core is stopped by degenerate neutrons, the core is saved from further destruction, but it turns out that the rest of the star is literally blown apart. Here's how it happens.

The collapse that takes place when electrons are absorbed into the nuclei is very rapid. In less than a second, a core with a mass of about 1 M_{Sun}, which originally was approximately the size of Earth, collapses to a diameter of less than 20 kilometers. The speed with which material falls inward reaches one-fourth the speed of light. The collapse halts only when the density of the core exceeds the density of an atomic nucleus (which is the densest form of matter we know). A typical neutron star is so compressed that to duplicate its density, we would have to squeeze all the people in the world into a single sugar cube! This would give us one sugar cube's worth (one cubic centimeter's worth) of a neutron star.

The neutron degenerate core strongly resists further compression, abruptly halting the collapse. The shock of the sudden jolt initiates a shock wave that starts to propagate outward. However, this shock alone is not enough to create a star explosion. The energy produced by the outflowing matter is quickly absorbed by atomic nuclei in the dense, overlying layers of gas, where it breaks up the nuclei into individual neutrons and protons.

Our understanding of nuclear processes indicates (as we mentioned above) that each time an electron and a proton in the star's core merge to make a neutron, the merger releases a *neutrino*. These ghostly subatomic particles, introduced in The Sun: A Nuclear Powerhouse, carry away some of the nuclear energy. It is their presence that launches the final disastrous explosion of the star. The total energy contained in the neutrinos is huge. In the initial second of the star's explosion, the power carried by the neutrinos (10^{46} watts) is greater than the power put out by all the stars in over a billion galaxies.

While neutrinos ordinarily do not interact very much with ordinary matter (we earlier accused them of being downright antisocial), matter near the center of a collapsing star is so dense that the neutrinos do interact with it to some degree. They deposit some of this energy in the layers of the star just outside the core. This huge, sudden input of energy reverses the infall of these layers and drives them explosively outward. Most of the mass of the star (apart from that which went into the neutron star in the core) is then ejected outward into space. As we saw earlier, such an explosion requires a star of at least 8 M_{Sun}, and the neutron star can have a mass of at most 3 $M_{Sun.}$ Consequently, at least five times the mass of our Sun is ejected into space in each such explosive event!

The resulting explosion is called a supernova (Figure 23.7). When these explosions happen close by, they can be among the most spectacular celestial events, as we will discuss in the next section. (Actually, there are at least two different types of supernova explosions: the kind we have been describing, which is the collapse of a massive star, is called, for historical reasons, a **type II supernova**. We will describe how the types differ later in this chapter).

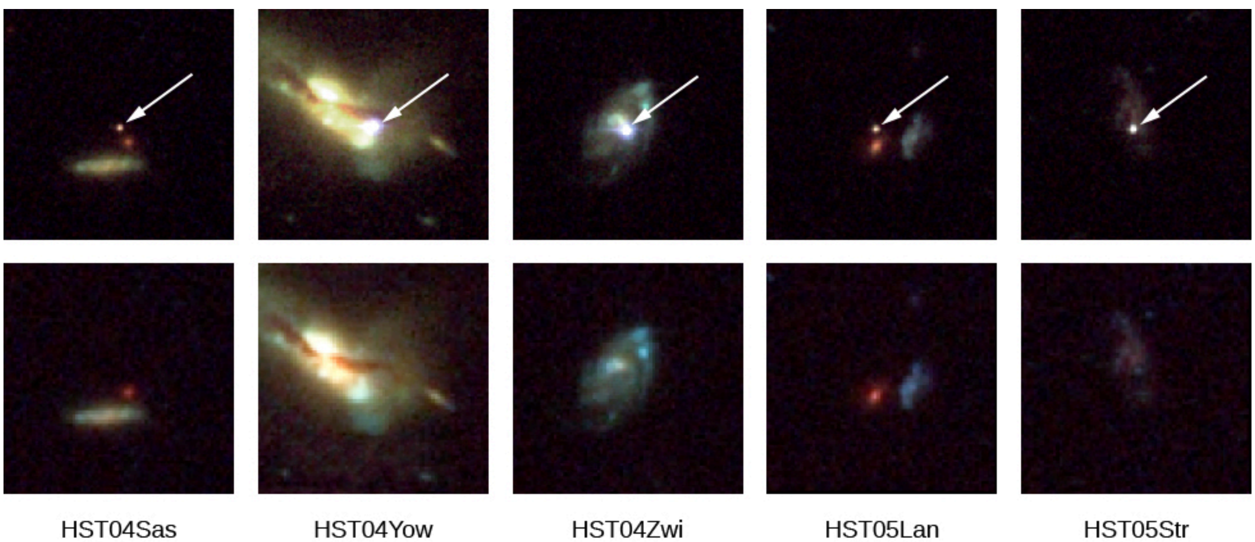


Figure 23.7 Five Supernova Explosions in Other Galaxies. The arrows in the top row of images point to the supernovae. The bottom row shows the host galaxies before or after the stars exploded. Each of these supernovae exploded between 3.5 and 10 billion years ago. Note that the supernovae when they first explode can be as bright as an entire galaxy. (credit: modification of work by NASA, ESA, and A. Riess (STScI))

Table 23.1 summarizes the discussion so far about what happens to stars and substellar objects of different initial masses at the ends of their lives. Like so much of our scientific understanding, this list represents a progress report: it is the best we can do with our present models and observations. The mass limits corresponding to various outcomes may change somewhat as models are improved. There is much we do not yet understand about the details of what happens when stars die.

The Ultimate Fate of Stars and Substellar Objects with Different Masses

Initial Mass (Mass of Sun = 1)[1]	Final State at the End of Its Life
< 0.01	Planet
0.01 to 0.08	Brown dwarf
0.08 to 0.25	White dwarf made mostly of helium
0.25 to 8	White dwarf made mostly of carbon and oxygen
8 to 10	White dwarf made of oxygen, neon, and magnesium
10 to 40	Supernova explosion that leaves a neutron star
> 40	Supernova explosion that leaves a black hole

Table 23.1

The Supernova Giveth and the Supernova Taketh Away

After the supernova explosion, the life of a massive star comes to an end. But the death of each massive star is an important event in the history of its galaxy. The elements built up by fusion during the star's life are now "recycled" into space by the explosion, making them available to enrich the gas and dust that form new stars and planets. Because these heavy elements ejected by supernovae are critical for the formation of planets and the origin of life, it's fair to say that without mass loss from supernovae and planetary nebulae, neither the authors nor the readers of this book would exist.[2]

But the supernova explosion has one more creative contribution to make, one we alluded to in Stars from Adolescence to Old Age when we asked where the atoms in your jewelry came from. The supernova explosion produces a flood of energetic neutrons that barrel through the expanding material. These neutrons can be absorbed by iron and other nuclei where they can turn into protons. Thus, they can build up elements that are more massive than iron, possibly including such terrestrial favorites as gold, silver and uranium. Supernovae (and, as we will shortly see, the explosive mergers of neutron stars) are the only candidates we have for places where such heavier atoms can be made. Next time you wear some gold jewelry (or give some to your sweetheart), bear in mind that those gold atoms were forged long ago in these kinds of celestial explosions!

When supernovae explode, these elements (as well as the ones the star made during more stable times) are ejected into the existing gas between the stars and mixed with it. Thus, supernovae play a crucial role in enriching their galaxy with heavier elements, allowing, among other things, the chemical elements that make up earthlike planets and the building blocks of life to become more common as time goes on (Figure 23.8).

1 Stars in the mass ranges 0.25–8 and 8–10 may later produce a type of supernova different from the one we have discussed so far. These are discussed in The Evolution of Binary Star Systems.

2 To tell the full story, there is another way to make and recycle these heavier elements which we will discuss in The Milky Way Galaxy. That is the merger of two neutron stars, which also causes a huge explosion.

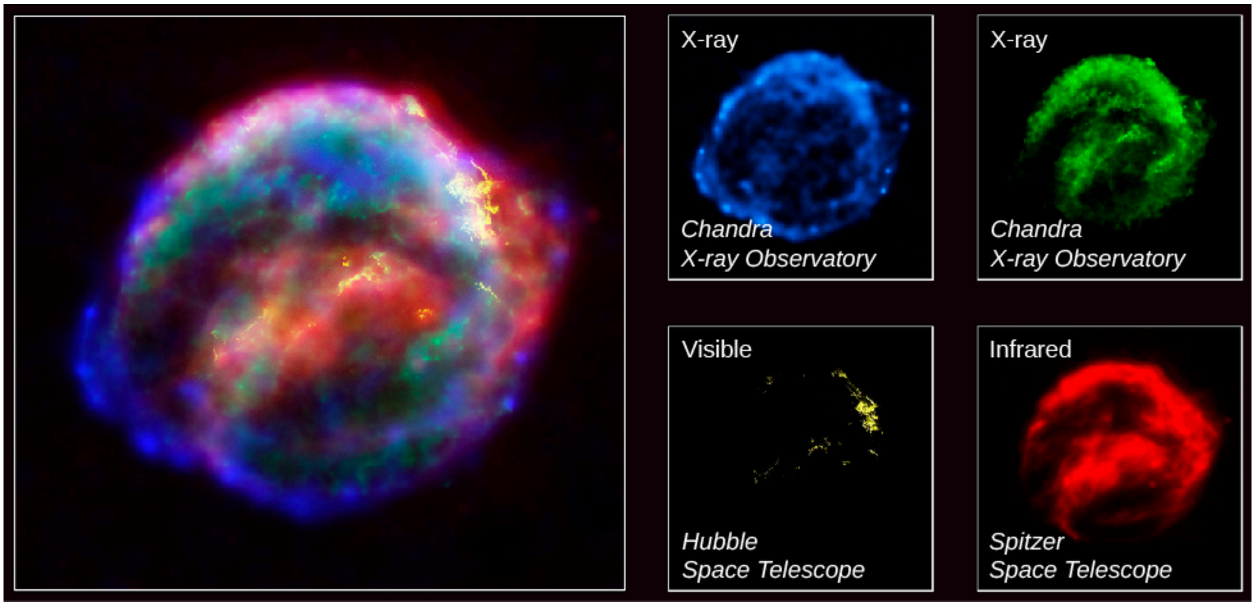


Figure 23.8 Kepler Supernova Remant. This image shows the expanding remains of a supernova explosion, which was first seen about 400 years ago by sky watchers, including the famous astronomer Johannes Kepler. The bubble-shaped shroud of gas and dust is now 14 light-years wide and is expanding at 2,000 kilometers per second (4 million miles per hour). The remnant emits energy at wavelengths from X-rays (shown in blue and green) to visible light (yellow) and into the infrared (red). The expanding shell is rich in iron, which was produced in the star that exploded. The main image combines the individual single-color images seen at the bottom into one multi-wavelength picture. (credit: modification of work by NASA, ESA, R. Sankrit and W. Blair (Johns Hopkins University))

Supernovae are also thought to be the source of many of the high-energy *cosmic ray* particles discussed in Cosmic Rays. Trapped by the magnetic field of the Galaxy, the particles from exploded stars continue to circulate around the vast spiral of the Milky Way. Scientists speculate that high-speed cosmic rays hitting the genetic material of Earth organisms over billions of years may have contributed to the steady *mutations*—subtle changes in the genetic code—that drive the evolution of life on our planet. In all the ways we have mentioned, supernovae have played a part in the development of new generations of stars, planets, and life.

But supernovae also have a dark side. Suppose a life form has the misfortune to develop around a star that happens to lie near a massive star destined to become a supernova. Such life forms may find themselves snuffed out when the harsh radiation and high-energy particles from the neighboring star's explosion reach their world. If, as some astronomers speculate, life can develop on many planets around long-lived (lower-mass) stars, then the suitability of that life's *own star* and planet may not be all that matters for its long-term evolution and survival. Life may well have formed around a number of pleasantly stable stars only to be wiped out because a massive nearby star suddenly went supernova. Just as children born in a war zone may find themselves the unjust victims of their violent neighborhood, life too close to a star that goes supernova may fall prey to having been born in the wrong place at the wrong time.

What is a safe distance to be from a supernova explosion? A lot depends on the violence of the particular explosion, what type of supernova it is (see The Evolution of Binary Star Systems), and what level of destruction we are willing to accept. Calculations suggest that a supernova less than 50 light-years away from us would certainly end all life on Earth, and that even one 100 light-years away would have drastic consequences for the radiation levels here. One minor extinction of sea creatures about 2 million years ago on Earth may actually have been caused by a supernova at a distance of about 120 light-years.

The good news is that there are at present no massive stars that promise to become supernovae within 50 light-years of the Sun. (This is in part because the kinds of massive stars that become supernovae are overall quite rare.) The massive star closest to us, Spica (in the constellation of Virgo), is about 260 light-years away, probably a safe distance, even if it were to explode as a supernova in the near future.

EXAMPLE 23.1

Extreme Gravity

In this section, you were introduced to some very dense objects. How would those objects' gravity affect you? Recall that the force of gravity, *F*, between two bodies is calculated as

$$F = \frac{GM_1 M_2}{R^2}$$

where *G* is the gravitational constant, 6.67 × 10^{-11} Nm^2/kg^2, M_1 and M_2 are the masses of the two bodies, and *R* is their separation. Also, from Newton's second law,

$$F = M \times a$$

where *a* is the acceleration of a body with mass *M*.

So let's consider the situation of a mass—say, you—standing on a body, such as Earth or a white dwarf (where we assume you will be wearing a heat-proof space suit). You are M_1 and the body you are standing on is M_2. The distance between you and the center of gravity of the body on which you stand is its radius, *R*. The force exerted on you is

$$F = M_1 \times a = \text{GM}_1 M_2 / R^2$$

Solving for *a*, the acceleration of gravity on that world, we get

$$g = \frac{(G \times M)}{R^2}$$

Note that we have replaced the general symbol for acceleration, *a*, with the symbol scientists use for the acceleration of gravity, *g*.

Say that a particular white dwarf has the mass of the Sun (2 × 10^{30} kg) but the radius of Earth (6.4 × 10^6 m). What is the acceleration of gravity at the surface of the white dwarf?

Solution

The acceleration of gravity at the surface of the white dwarf is

$$\text{g(white dwarf)} = \frac{(G \times M_{\text{Sun}})}{{R_{\text{Earth}}}^2} = \frac{\left(6.67 \times 10^{-11} \text{ m}^2/\text{kg s}^2 \times 2 \times 10^{30} \text{ kg}\right)}{\left(6.4 \times 10^6 \text{ m}\right)^2} = 3.26 \times 10^6 \text{ m/s}^2$$

Compare this to *g* on the surface of Earth, which is 9.8 m/s^2.

Check Your Learning

What is the acceleration of gravity at the surface if the white dwarf has the twice the mass of the Sun and is only half the radius of Earth?

Answer:

$$\text{g(white dwarf)} = \frac{(G \times 2M_{\text{Sun}})}{(0.5R_{\text{Earth}})^2} = \frac{\left(6.67 \times 10^{-11} \text{m}^2/\text{kg s}^2 \times 4 \times 10^{30} \text{ kg}\right)}{\left(3.2 \times 10^6\right)^2} = 2.61 \times 10^7 \text{ m/s}^2$$

23.3 Supernova Observations

Learning Objectives

By the end of this section, you will be able to:

- Describe the observed features of SN 1987A both before and after the supernova
- Explain how observations of various parts of the SN 1987A event helped confirm theories about supernovae

Supernovae were discovered long before astronomers realized that these spectacular cataclysms mark the death of stars (see Making Connections: Supernovae in History). The word *nova* means “new” in Latin; before telescopes, when a star too dim to be seen with the unaided eye suddenly flared up in a brilliant explosion, observers concluded it must be a brand-new star. Twentieth-century astronomers reclassified the explosions with the greatest luminosity as *super*novae.

From historical records of such explosions, from studies of the remnants of supernovae in our Galaxy, and from analyses of supernovae in other galaxies, we estimate that, on average, one supernova explosion occurs somewhere in the Milky Way Galaxy every 25 to 100 years. Unfortunately, however, no supernova explosion has been observable in our Galaxy since the invention of the telescope. Either we have been exceptionally unlucky or, more likely, recent explosions have taken place in parts of the Galaxy where interstellar dust blocks light from reaching us.

MAKING CONNECTIONS

Supernovae in History

Although many supernova explosions in our own Galaxy have gone unnoticed, a few were so spectacular that they were clearly seen and recorded by sky watchers and historians at the time. We can use these records, going back two millennia, to help us pinpoint where the exploding stars were and thus where to look for their remnants today.

The most dramatic supernova was observed in the year 1006. It appeared in May as a brilliant point of light visible during the daytime, perhaps 100 times brighter than the planet Venus. It was bright enough to cast shadows on the ground during the night and was recorded with awe and fear by observers all over Europe and Asia. No one had seen anything like it before; Chinese astronomers, noting that it was a temporary spectacle, called it a “guest star.”

Astronomers David Clark and Richard Stephenson have scoured records from around the world to find more than 20 reports of the 1006 supernova (SN 1006) (Figure 23.9). This has allowed them to determine with some accuracy where in the sky the explosion occurred. They place it in the modern constellation of Lupus; at roughly the position they have determined, we find a supernova remnant, now quite faint. From the way its filaments are expanding, it indeed appears to be about 1000 years old.

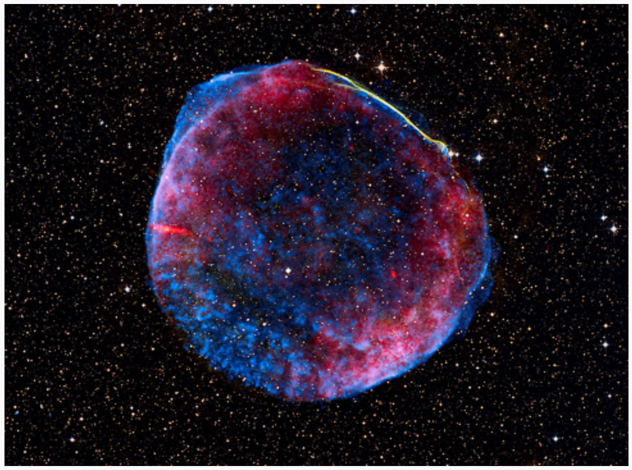


Figure 23.9 Supernova 1006 Remnant. This composite view of SN 1006 from the Chandra X-Ray Observatory shows the X-rays coming from the remnant in blue, visible light in white-yellow, and radio emission in red. (credit: modification of work by NASA, ESA, Zolt Levay(STScI))

Another guest star, now known as SN 1054, was clearly recorded in Chinese records in July 1054. The remnant of that star is one of the most famous and best-studied objects in the sky, called the Crab Nebula (Figure 23.14). It is a marvelously complex object, which has been key to understanding the death of massive stars. When its explosion was first seen, we estimate that it was about as bright as the planet Jupiter: nowhere near as dazzling as the 1006 event but still quite dramatic to anyone who kept track of objects in the sky. Another fainter supernova was seen in 1181.

The next supernova became visible in November 1572 and, being brighter than the planet Venus, was quickly spotted by a number of observers, including the young Tycho Brahe (see Orbits and Gravity). His careful measurements of the star over a year and a half showed that it was not a comet or something in Earth’s atmosphere since it did not move relative to the stars. He correctly deduced that it must be a phenomenon belonging to the realm of the stars, not of the solar system. The remnant of Tycho’s Supernova (as it is now called) can still be detected in many different bands of the electromagnetic spectrum.

Not to be outdone, Johannes Kepler, Tycho Brahe’s scientific heir, found his own supernova in 1604, now known as Kepler’s Supernova (Figure 23.8). Fainter than Tycho’s, it nevertheless remained visible for about a year. Kepler wrote a book about his observations that was read by many with an interest in the heavens, including Galileo.

No supernova has been spotted in our Galaxy for the past 300 years. Since the explosion of a visible supernova is a chance event, there is no way to say when the next one might occur. Around the world, dozens of professional and amateur astronomers keep a sharp lookout for “new” stars that appear overnight, hoping to be the first to spot the next guest star in our sky and make a little history themselves.

At their maximum brightness, the most luminous supernovae have about 10 billion times the luminosity of the Sun. For a brief time, a supernova may outshine the entire galaxy in which it appears. After maximum brightness, the star’s light fades and disappears from telescopic visibility within a few months or years. At the time of their outbursts, supernovae eject material at typical velocities of 10,000 kilometers per second (and speeds twice that have been observed). A speed of 20,000 kilometers per second corresponds to about 45 million miles per hour, truly an indication of great cosmic violence.

Supernovae are classified according to the appearance of their spectra, but in this chapter, we will focus on the two main causes of supernovae. Type Ia supernovae are ignited when a lot of material is dumped on degenerate white dwarfs (Figure 23.10); these supernovae will be discussed later in this chapter. For now, we will continue our story about the death of massive stars and focus on type II supernovae, which are produced when the core of a massive star collapses.

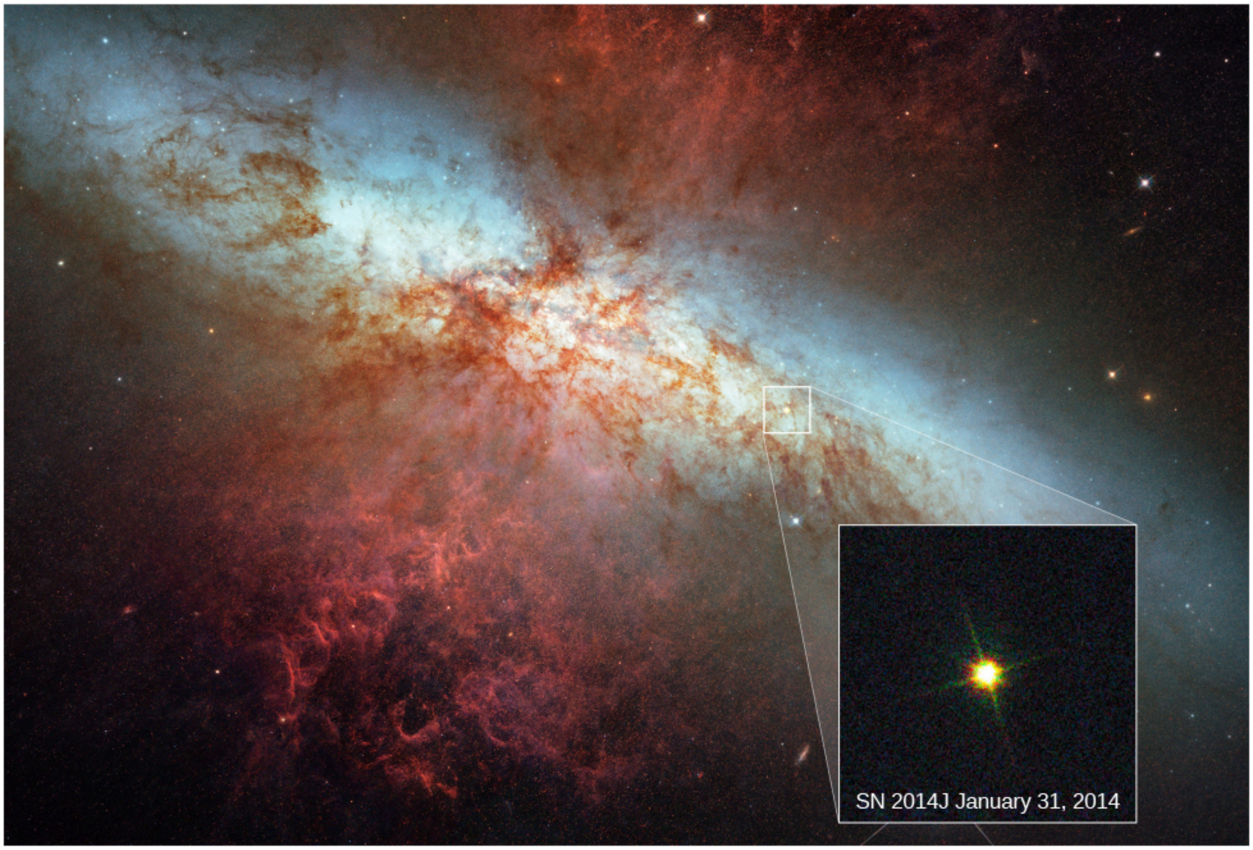


Figure 23.10 Supernova 2014J. This image of supernova 2014J, located in Messier 82 (M82), which is also known as the Cigar galaxy, was taken by the Hubble Space Telescope and is superposed on a mosaic image of the galaxy also taken with Hubble. The supernova event is indicated by the box and the inset. This explosion was produced by a type Ia supernova, which is theorized to be triggered in binary systems consisting of a white dwarf and another star—and could be a second white dwarf, a star like our Sun, or a giant star. This type of supernova will be discussed later in this chapter. At a distance of approximately 11.5 million light-years from Earth, this is the closest supernova of type Ia discovered in the past few decades. In the image, you can see reddish plumes of hydrogen coming from the central region of the galaxy, where a considerable number of young stars are being born. (credit: modification of work by NASA, ESA, A. Goobar (Stockholm University), and the Hubble Heritage Team (STScI/AURA))

Supernova 1987A

Our most detailed information about what happens when a type II supernova occurs comes from an event that was observed in 1987. Before dawn on February 24, Ian Shelton, a Canadian astronomer working at an observatory in Chile, pulled a photographic plate from the developer. Two nights earlier, he had begun a survey of the Large Magellanic Cloud, a small galaxy that is one of the Milky Way’s nearest neighbors in space. Where he expected to see only faint stars, he saw a large bright spot. Concerned that his photograph was flawed, Shelton went outside to look at the Large Magellanic Cloud . . . and saw that a new object had indeed appeared in the sky (see Figure 23.11). He soon realized that he had discovered a supernova, one that could be seen with the unaided eye even though it was about 160,000 light-years away.

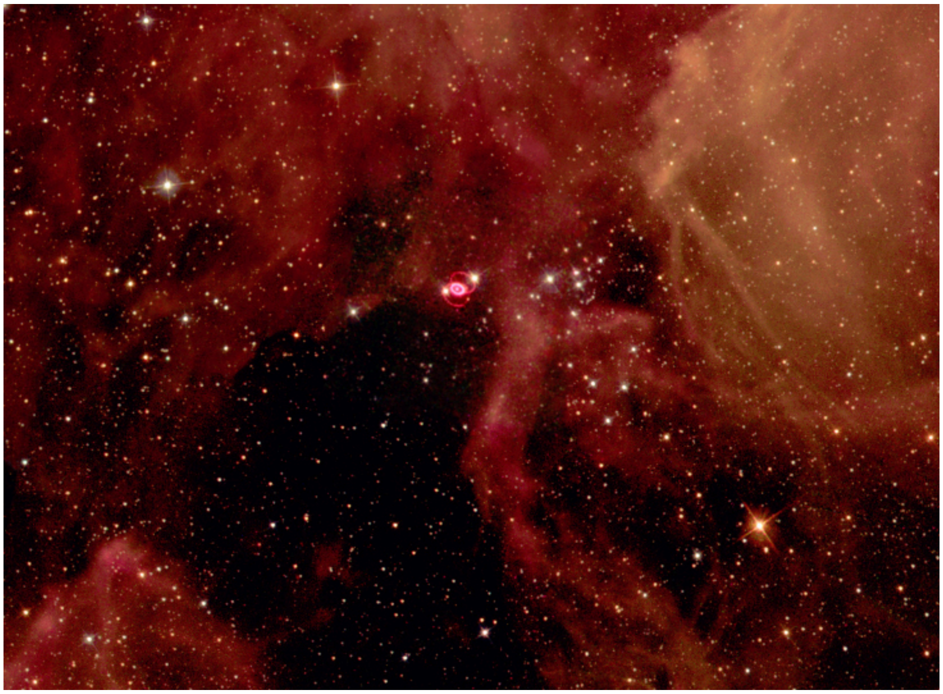


Figure 23.11 Hubble Space Telescope Image of SN 1987A. The supernova remnant with its inner and outer red rings of material is located in the Large Magellanic Cloud. This image is a composite of several images taken in 1994, 1996, and 1997—about a decade after supernova 1987A was first observed. (credit: modification of work by the Hubble Heritage Team (AURA/STScI/NASA/ESA))

Now known as SN 1987A, since it was the first supernova discovered in 1987, this brilliant newcomer to the southern sky gave astronomers their first opportunity to study the death of a relatively nearby star with modern instruments. It was also the first time astronomers had observed a star *before* it became a supernova. The star that blew up had been included in earlier surveys of the Large Magellanic Cloud, and as a result, we know the star was a blue supergiant just before the explosion.

By combining theory and observations at many different wavelengths, astronomers have reconstructed the life story of the star that became SN 1987A. Formed about 10 million years ago, it originally had a mass of about 20 M_{Sun}. For 90% of its life, it lived quietly on the main sequence, converting hydrogen into helium. At this time, its luminosity was about 60,000 times that of the Sun (L_{Sun}), and its spectral type was O. When the hydrogen in the center of the star was exhausted, the core contracted and ultimately became hot enough to fuse helium. By this time, the star was a red supergiant, emitting about 100,000 times more energy than the Sun. While in this stage, the star lost some of its mass.

This lost material has actually been detected by observations with the Hubble Space Telescope (Figure 23.12). The gas driven out into space by the subsequent supernova explosion is currently colliding with the material the star left behind when it was a red giant. As the two collide, we see a glowing ring.

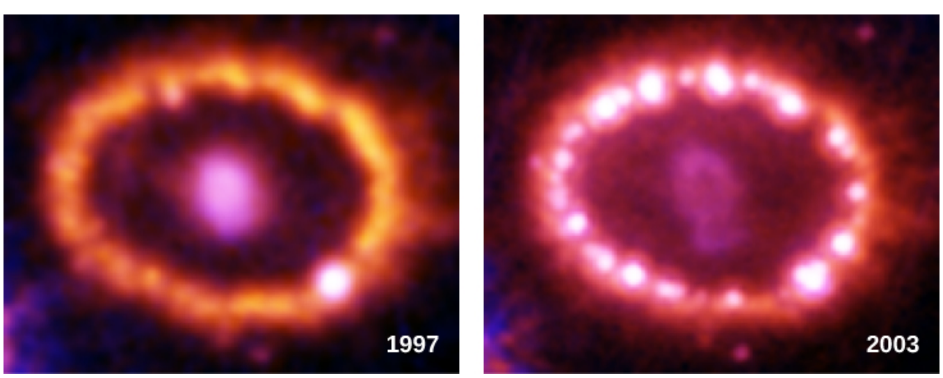


Figure 23.12 Ring around Supernova 1987A. These two images show a ring of gas expelled by a red giant star about 30,000 years before the star exploded and was observed as Supernova 1987A. The supernova, which has been artificially dimmed, is located at the

center of the ring. The left-hand image was taken in 1997 and the right-hand image in 2003. Note that the number of bright spots has increased from 1 to more than 15 over this time interval. These spots occur where high-speed gas ejected by the supernova and moving at millions of miles per hour has reached the ring and blasted into it. The collision has heated the gas in the ring and caused it to glow more brightly. The fact that we see individual spots suggests that material ejected by the supernova is first hitting narrow, inward-projecting columns of gas in the clumpy ring. The hot spots are the first signs of a dramatic and violent collision between the new and old material that will continue over the next few years. By studying these bright spots, astronomers can determine the composition of the ring and hence learn about the nuclear processes that build heavy elements inside massive stars. (credit: modification of work by NASA, P. Challis, R. Kirshner (Harvard-Smithsonian Center for Astrophysics) and B. Sugerman (STScI))

Helium fusion lasted only about 1 million years. When the helium was exhausted at the center of the star, the core contracted again, the radius of the surface also decreased, and the star became a blue supergiant with a luminosity still about equal to 100,000 L_{Sun}. This is what it still looked like on the outside when, after brief periods of further fusion, it reached the iron crisis we discussed earlier and exploded.

Some key stages of evolution of the star that became SN 1987A, including the ones following helium exhaustion, are listed in Table 23.2. While we don't expect you to remember these numbers, note the patterns in the table: each stage of evolution happens more quickly than the preceding one, the temperature and pressure in the core increase, and progressively heavier elements are the source of fusion energy. Once iron was created, the collapse began. It was a catastrophic collapse, lasting only a few tenths of a second; the speed of infall in the outer portion of the iron core reached 70,000 kilometers per second, about one-fourth the speed of light.

Evolution of the Star That Exploded as SN 1987A

Phase	Central Temperature (K)	Central Density (g/cm^3)	Time Spent in This Phase
Hydrogen fusion	40×10^6	5	8×10^6 years
Helium fusion	190×10^6	970	10^6 years
Carbon fusion	870×10^6	170,000	2000 years
Neon fusion	1.6×10^9	3.0×10^6	6 months
Oxygen fusion	2.0×10^9	5.6×10^6	1 year
Silicon fusion	3.3×10^9	4.3×10^7	Days
Core collapse	200×10^9	2×10^{14}	Tenths of a second

Table 23.2

In the meantime, as the core was experiencing its last catastrophe, the outer shells of neon, oxygen, carbon, helium, and hydrogen in the star did not yet know about the collapse. Information about the physical movement of different layers travels through a star at the speed of sound and cannot reach the surface in the few tenths of a second required for the core collapse to occur. Thus, the surface layers of our star hung briefly suspended, much like a cartoon character who dashes off the edge of a cliff and hangs momentarily in space before realizing that he is no longer held up by anything.

The collapse of the core continued until the densities rose to several times that of an atomic nucleus. The resistance to further collapse then became so great that the core rebounded. Infalling material ran into the "brick wall" of the rebounding core and was thrown outward with a great shock wave. Neutrinos poured out of the core, helping the shock wave blow the star apart. The shock reached the surface of the star a few hours later, and the star began to brighten into the supernova Ian Shelton observed in 1987.

The Synthesis of Heavy Elements

The variations in the brightness of SN 1987A in the days and months after its discovery, which are shown in Figure 23.13, helped confirm our ideas about heavy element production. In a single day, the star soared in brightness by a factor of about 1000 and became just visible without a telescope. The star then continued to increase slowly in brightness until it was about the same apparent brightness as the stars in the Little Dipper. Up until about day 40 after the outburst, the energy being radiated away was produced by the explosion itself. But then SN 1987A did not continue to fade away, as we might have expected the light from the explosion to do. Instead, SN 1987A remained bright as energy from newly created radioactive elements came into play.

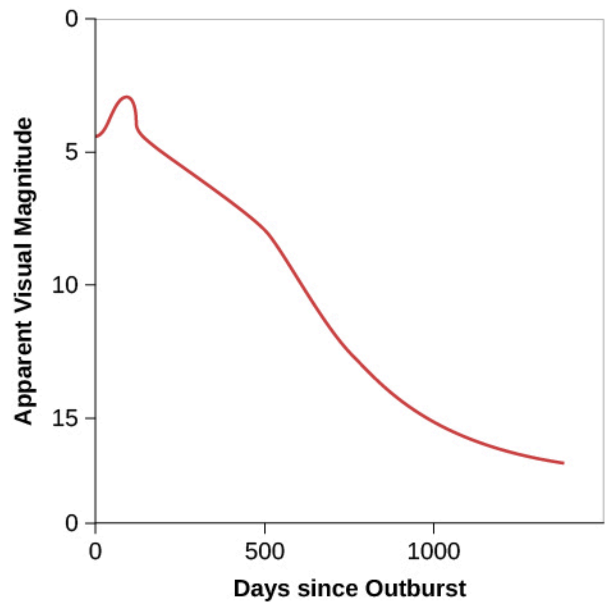


Figure 23.13 Change in the Brightness of SN 1987A over Time. Note how the rate of decline of the supernova's light slowed between days 40 and 500. During this time, the brightness was mainly due to the energy emitted by newly formed (and quickly decaying) radioactive elements. Remember that magnitudes are a backward measure of brightness: the larger the magnitude, the dimmer the object looks.

One of the elements formed in a supernova explosion is radioactive nickel, with an atomic mass of 56 (that is, the total number of protons plus neutrons in its nucleus is 56). Nickel-56 is unstable and changes spontaneously (with a half-life of about 6 days) to cobalt-56. (Recall that a half-life is the time it takes for half the nuclei in a sample to undergo radioactive decay.) Cobalt-56 in turn decays with a half-life of about 77 days to iron-56, which is stable. Energetic gamma rays are emitted when these radioactive nuclei decay. Those gamma rays then serve as a new source of energy for the expanding layers of the supernova. The gamma rays are absorbed in the overlying gas and re-emitted at visible wavelengths, keeping the remains of the star bright.

As you can see in Figure 23.13, astronomers did observe brightening due to radioactive nuclei in the first few months following the supernova's outburst and then saw the extra light die away as more and more of the radioactive nuclei decayed to stable iron. The gamma-ray heating was responsible for virtually all of the radiation detected from SN 1987A after day 40. Some gamma rays also escaped directly without being absorbed. These were detected by Earth-orbiting telescopes at the wavelengths expected for the decay of radioactive nickel and cobalt, clearly confirming our understanding that new elements were indeed formed in the crucible of the supernova.

Neutrinos from SN 1987A

If there had been any human observers in the Large Magellanic Cloud about 160,000 years ago, the explosion we call SN 1987A would have been a brilliant spectacle in their skies. Yet we know that less than 1/10 of 1% of the energy of the explosion appeared as visible light. About 1% of the energy was required to destroy the star, and the rest was carried away by neutrinos. The overall energy in these neutrinos was truly astounding. In the initial second of the event, as we noted earlier in our general discussion of supernovae, their total luminosity exceeded the luminosity of all the stars in over a billion galaxies. And the supernova generated this energy in a volume less than 50 kilometers in diameter! Supernovae are one of the most violent events in the universe, and their *light* turns out to be only the tip of the iceberg in revealing how much energy they produce.

In 1987, the neutrinos from SN 1987A were detected by two instruments—which might be called "neutrino telescopes"—almost a full day before Shelton's observations. (This is because the neutrinos get out of the exploding star more easily than light does, and also because you don't need to wait until nightfall to catch a "glimpse" of them.) Both neutrino telescopes, one in a deep mine in Japan and the other under Lake Erie, consist of several thousand tons of purified water surrounded by several hundred light-sensitive detectors. Incoming neutrinos interact with the water to produce positrons and electrons, which move rapidly through the water and emit deep blue light.

Altogether, 19 neutrinos were detected. Since the neutrino telescopes were in the Northern Hemisphere and the supernova occurred in the Southern Hemisphere, the detected neutrinos had already passed through Earth and were on their way back out into space when they were captured.

Only a few neutrinos were detected because the probability that they will interact with ordinary matter is very, very low. It is estimated that the supernova actually released 10^{58} neutrinos. A tiny fraction of these, about 30 billion, eventually passed through each square centimeter of Earth's surface. About a million people actually experienced a neutrino interaction within their bodies as a result of the supernova. This interaction happened to only a single nucleus in each person and thus had absolutely no biological effect; it went completely unnoticed by everyone concerned.

Since the neutrinos come directly from the heart of the supernova, their energies provided a measure of the temperature of the core as the star was exploding. The central temperature was about 200 billion K, a stunning figure to which no earthly analog can bring much meaning. With neutrino telescopes, we are peering into the final moment in the life stories of massive stars and observing conditions beyond all human experience. Yet we are also seeing the unmistakable hints of our own origins.

23.4 Pulsars and the Discovery of Neutron Stars

Learning Objectives

By the end of this section, you will be able to:

- Explain the research method that led to the discovery of neutron stars, located hundreds or thousands of light-years away
- Describe the features of a neutron star that allow it to be detected as a pulsar
- List the observational evidence that links pulsars and neutron stars to supernovae

After a type II supernova explosion fades away, all that is left behind is either a neutron star or something even more strange, a black hole. We will describe the properties of black holes in Black Holes and Curved Spacetime, but for now, we want to examine how the neutron stars we discussed earlier might become observable.

Neutron stars are the densest objects in the universe; the force of gravity at their surface is 10^{11} times greater than what we experience at Earth's surface. The interior of a neutron star is composed of about 95% neutrons, with a small number of protons and electrons mixed in. In effect, a neutron star is a giant atomic nucleus, with a mass about 10^{57} times the mass of a proton. Its diameter is more like the size of a small town or an asteroid than a star. (Table 23.3 compares the properties of neutron stars and white dwarfs.) Because it is so small, a neutron star probably strikes you as the object least likely to be observed from thousands of light-years away. Yet neutron stars do manage to signal their presence across vast gulfs of space.

Properties of a Typical White Dwarf and a Neutron Star

Property	White Dwarf	Neutron Star
Mass (Sun = 1)	0.6 (always <1.4)	Always >1.4 and <3
Radius	7000 km	10 km
Density	8×10^5 g/cm^3	10^{14} g/cm^3

Table 23.3

The Discovery of Neutron Stars

In 1967, Jocelyn Bell, a research student at Cambridge University, was studying distant radio sources with a special detector that had been designed and built by her advisor Antony Hewish to find rapid variations in radio signals. The project computers spewed out reams of paper showing where the telescope had surveyed the sky, and it was the job of Hewish's graduate students to go through it all, searching for interesting phenomena. In September 1967, Bell discovered what she called "a bit of scruff"—a strange radio signal unlike anything seen before.

What Bell had found, in the constellation of Vulpecula, was a source of rapid, sharp, intense, and extremely regular pulses of radio radiation. Like the regular ticking of a clock, the pulses arrived precisely every 1.33728 seconds. Such exactness first led the scientists to speculate that perhaps they had found signals from an intelligent civilization. Radio astronomers even half-jokingly dubbed the source "LGM" for "little green men." Soon, however, three similar sources were discovered in widely separated directions in the sky.

When it became apparent that this type of radio source was fairly common, astronomers concluded that they were highly unlikely to be signals from other civilizations. By today, nearly 3000 such sources have been discovered; they are now called **pulsars**, short for "pulsating radio sources."

The pulse periods of different pulsars range from a little longer than 1/1000 of a second to nearly 10 seconds. At first, the pulsars seemed particularly mysterious because nothing could be seen at their location on visible-light photographs. But then a pulsar was discovered right in the center of the Crab Nebula, a cloud of gas produced by SN 1054, a supernova that was recorded by the Chinese in 1054 (Figure 23.14). The energy from the Crab Nebula pulsar arrives in sharp bursts that occur 30 times each second—with a regularity that would be the envy of a Swiss watchmaker. In addition to pulses of radio energy, we can observe pulses of visible light and X-rays from the Crab Nebula. The fact that the pulsar was just in the region of the supernova remnant where we expect the leftover neutron star to be immediately alerted astronomers that pulsars might be connected with these elusive "corpses" of massive stars.

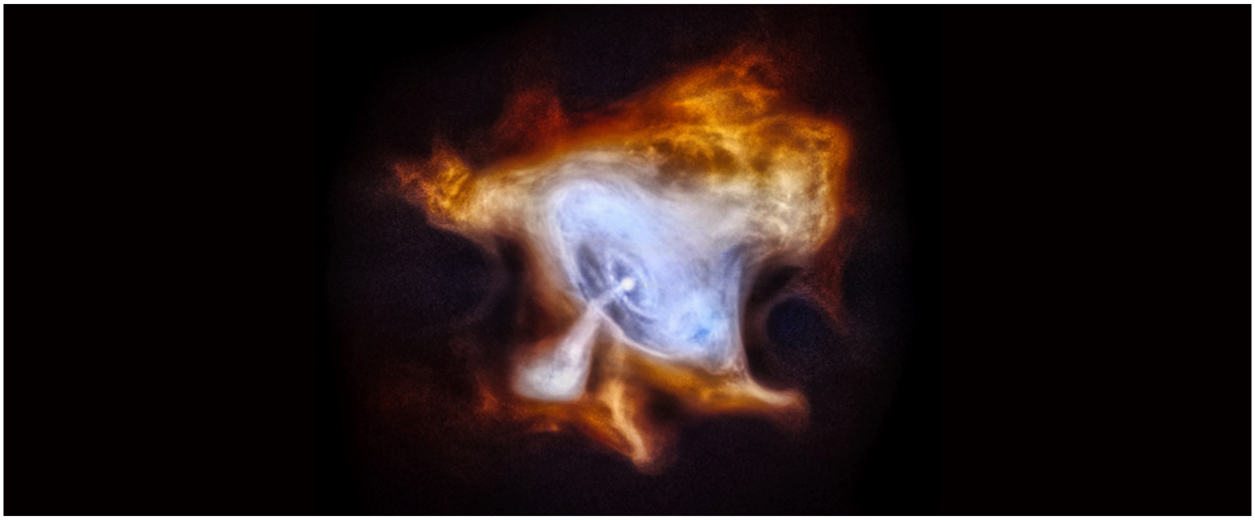


Figure 23.14 Crab Nebula. This image shows X-ray emissions from the Crab Nebula, which is about 6500 light-years away. The pulsar is the bright spot at the center of the concentric rings. Data taken over about a year show that particles stream away from the inner ring at about half the speed of light. The jet that is perpendicular to this ring is a stream of matter and antimatter electrons also moving at half the speed of light. (credit: modification of work by NASA/CXC/SAO)

The Crab Nebula is a fascinating object. The whole nebula glows with radiation at many wavelengths, and its overall energy output is more than 100,000 times that of the Sun—not a bad trick for the remnant of a supernova that exploded almost a thousand years ago. Astronomers soon began to look for a connection between the pulsar and the large energy output of the surrounding nebula.

LINK TO LEARNING

Read the transcript of an interesting interview (https://openstax.org/l/30jocbellint) with Jocelyn Bell (Burnell) to learn about her life and work (this is part of a project at the American Institute of Physics to record interviews with pathbreaking scientists while they are still alive).

A Spinning Lighthouse Model

By applying a combination of theory and observation, astronomers eventually concluded that pulsars must be *spinning neutron stars*. According to this model, a neutron star is something like a lighthouse on a rocky coast (Figure 23.15). To warn ships in all directions and yet not cost too much to operate, the light in a modern lighthouse turns, sweeping its beam across the dark sea. From the vantage point of a ship, you see a pulse of light each time the beam points in your direction. In the same way, radiation from a small region on a neutron star sweeps across the oceans of space, giving us a pulse of radiation each time the beam points toward Earth.

Figure 23.15 Lighthouse. A lighthouse in California warns ships on the ocean not to approach too close to the dangerous shoreline. The lighted section at the top rotates so that its beam can cover all directions. (credit: Anita Ritenour)

Neutron stars are ideal candidates for such a job because the collapse has made them so small that they can turn very rapidly. Recall the principle of the *conservation of angular momentum* from Newton's Great Synthesis: if an object gets smaller, it can spin more rapidly. Even if the parent star was rotating very slowly when it was on the main sequence, its rotation had to speed up as it collapsed to form a neutron star. With a diameter of only 10 to 20 kilometers, a neutron star can complete one full spin in only a fraction of a second. This is just the sort of time period we observe between pulsar pulses.

Any magnetic field that existed in the original star will be highly compressed when the core collapses to a neutron star. At the surface of the neutron star, in the outer layer consisting of ordinary matter (and not just pure neutrons), protons and electrons are caught up in this spinning field and accelerated nearly to the speed of light. In only two places—the north and south magnetic poles—can the trapped particles escape the strong hold of the magnetic field (Figure 23.16). The same effect can be seen (in reverse) on Earth, where charged particles from space are *kept out* by our planet's magnetic field everywhere except near the poles. As a result, Earth's auroras (caused when charged particles hit the atmosphere at high speed) are seen mainly near the poles.

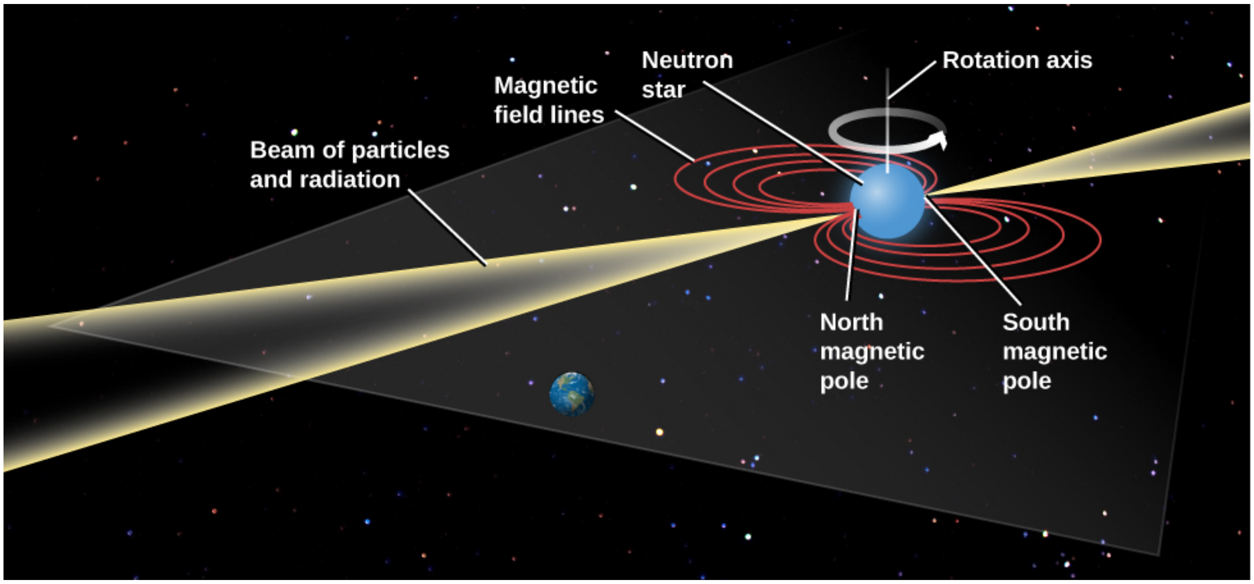


Figure 23.16 Model of a Pulsar. A diagram showing how beams of radiation at the magnetic poles of a neutron star can give rise to pulses of emission as the star rotates. As each beam sweeps over Earth, like a lighthouse beam sweeping over a distant ship, we see a short pulse of radiation. This model requires that the magnetic poles be located in different places from the rotation poles. (credit "stars": modification of work by Tony Hisgett)

Note that in a neutron star, the magnetic north and south poles do not have to be anywhere close to the north and south poles defined by the star's rotation. In the same way, we discussed in the chapter on The Giant Planets that the magnetic poles on the planets Uranus and Neptune are not lined up with the poles of the planet's spin. Figure 23.16 shows the poles of the magnetic field perpendicular to the poles of rotation, but the two kinds of poles could make any angle.

In fact, the misalignment of the rotational axis with the magnetic axis plays a crucial role in the generation of the observed pulses in this model. At the two magnetic poles, the particles from the neutron star are focused into a narrow beam and come streaming out of the whirling magnetic region at enormous speeds. They emit energy over a broad range of the electromagnetic spectrum. The radiation itself is also confined to a narrow beam, which explains why the pulsar acts like a lighthouse. As the rotation carries first one and then the other magnetic pole of the star into our view, we see a pulse of radiation each time.

Tests of the Model

This explanation of pulsars in terms of beams of radiation from highly magnetic and rapidly spinning neutron stars is a very clever idea. But what evidence do we have that it is the correct model? First, we can measure the masses of some pulsars, and they do turn out be in the range of 1.4 to 1.8 times that of the Sun—just what theorists predict for neutron stars. The masses are found using Kepler's law for those few pulsars that are members of binary star systems.

But there is an even-better confirming argument, which brings us back to the Crab Nebula and its vast energy output. When the high-energy charged particles from the neutron star pulsar hit the slower-moving material from the supernova, they energize this material and cause it to "glow" at many different wavelengths—just what we observe from the Crab Nebula. The pulsar beams are a power source that "light up" the nebula long after the initial explosion of the star that made it.

Who "pays the bills" for all the energy we see coming out of a remnant like the Crab Nebula? After all, when energy emerges from one place, it must be depleted in another. The ultimate energy source in our model is the rotation of the neutron star, which propels charged particles outward and spins its magnetic field at enormous speeds. As its rotational energy is used to excite the Crab Nebula year after year, the pulsar inside the nebula slows down. As it slows, the pulses come a little less often; more time elapses before the slower neutron star brings its beam back around.

Several decades of careful observations have now shown that the Crab Nebula pulsar is not a perfectly regular clock as we originally thought: instead, it is gradually slowing down. Having measured how much the pulsar is slowing down, we can calculate how much rotation energy the neutron star is losing. Remember that it is very densely packed and spins amazingly quickly. Even a tiny slowing down can mean an immense loss of energy.

To the satisfaction of astronomers, the rotational energy lost by the pulsar turns out to be the same as the amount of energy emerging from the nebula surrounding it. In other words, the slowing down of a rotating neutron star can explain precisely why the Crab Nebula is glowing with the amount of energy we observe.

The Evolution of Pulsars

From observations of the pulsars discovered so far, astronomers have concluded that one new pulsar is born somewhere in the Galaxy every 25 to 100 years, the same rate at which supernovae are estimated to occur. Calculations suggest that the typical lifetime of a pulsar is about 10 million years; after that, the neutron star no longer rotates fast enough to produce significant beams of particles and energy, and is no longer observable. We estimate that there are about 100 million neutron stars in our Galaxy, most of them rotating too slowly to come to our notice.

The Crab pulsar is rather young (only about 960 years old) and has a short period, whereas other, older pulsars have already slowed to longer periods. Pulsars thousands of years old have lost too much energy to emit appreciably in the visible and X-ray wavelengths, and they are observed only as radio pulsars; their periods are a second or longer.

There is one other reason we can see only a fraction of the pulsars in the Galaxy. Consider our lighthouse model again. On Earth, all ships approach on the same plane—the surface of the ocean—so the lighthouse can be built to sweep its beam over that surface. But in space, objects can be anywhere in three dimensions. As a given pulsar’s beam sweeps over a circle in space, there is absolutely no guarantee that this circle will include the direction of Earth. In fact, if you think about it, many more circles in space will *not* include Earth than will include it. Thus, we estimate that we are unable to observe a large number of neutron stars because their pulsar beams miss us entirely.

At the same time, it turns out that only a few of the pulsars discovered so far are embedded in the visible clouds of gas that mark the remnant of a supernova. This might at first seem mysterious, since we know that supernovae give rise to neutron stars and we should expect each pulsar to have begun its life in a supernova explosion. But the lifetime of a pulsar turns out to be about 100 times longer than the length of time required for the expanding gas of a supernova remnant to disperse into interstellar space. Thus, most pulsars are found with no other trace left of the explosion that produced them.

In addition, some pulsars are ejected by a supernova explosion that is not the same in all directions. If the supernova explosion is stronger on one side, it can kick the pulsar entirely out of the supernova remnant (some astronomers call this “getting a birth kick”). We know such kicks happen because we see a number of young supernova remnants in nearby galaxies where the pulsar is to one side of the remnant and racing away at several hundred miles per second (Figure 23.17).

Figure 23.17 Speeding Pulsar. This intriguing image (which combines X-ray, visible, and radio observations) shows the jet trailing behind a pulsar (at bottom right, lined up between the two bright stars). With a length of 37 light-years, the jet trail (seen in purple) is the longest ever observed from an object in the Milky Way. (There is also a mysterious shorter, comet-like tail that is almost perpendicular to the purple jet.) Moving at a speed between 2.5 and 5 million miles per hour, the pulsar is traveling away from the core of the supernova remnant where it originated. (credit: X-ray: NASA/CXC/ISDC/L.Pavan et al, Radio: CSIRO/ATNF/ATCA Optical: 2MASS/UMass/IPAC-Caltech/NASA/NSF)

MAKING CONNECTIONS

Touched by a Neutron Star

On December 27, 2004, Earth was bathed with a stream of X-ray and gamma-ray radiation from a neutron star known as SGR 1806-20. What made this event so remarkable was that, despite the distance of the source, its tidal wave of radiation had measurable effects on Earth’s atmosphere. The apparent brightness of this gamma-ray flare was greater than any historical star explosion.

The primary effect of the radiation was on a layer high in Earth’s atmosphere called the *ionosphere*. At night, the ionosphere is normally at a height of about 85 kilometers, but during the day, energy from the Sun ionizes more molecules and lowers the boundary of the ionosphere to a height of about 60 kilometers. The pulse of X-ray and gamma-ray radiation produced about the same level of ionization as the daytime Sun. It also caused some sensitive satellites above the atmosphere to shut down their electronics.

Measurements by telescopes in space indicate that SGR 1806-20 was a special type of fast-spinning neutron star called a *magnetar*. Astronomers Robert Duncan and Christopher Thomson gave them this name because their magnetic fields are stronger than that of any other type of astronomical source—in this case, about 800 trillion times stronger than the magnetic field of Earth.

A magnetar is thought to consist of a superdense core of neutrons surrounded by a rigid crust of atoms about a mile deep with a surface made of iron. The magnetar’s field is so strong that it creates huge stresses inside that can sometimes crack open the hard crust, causing a starquarke. The vibrating crust produces an enormous blast of radiation. An astronaut 0.1 light-year from this particular magnetar would have received a fatal does from the blast in less than a second.

Fortunately, we were far enough away from magnetar SGR 1806-20 to be safe. Could a magnetar ever present a real danger to Earth? To produce enough energy to disrupt the ozone layer, a magnetar would have to be located within the cloud of comets that surround the solar system, and we know no magnetars are that close. Nevertheless, it is a fascinating discovery that events on distant star corpses can have measurable effects on Earth.

23.5 The Evolution of Binary Star Systems

Learning Objectives

By the end of this section, you will be able to:

- Describe the kind of binary star system that leads to a nova event
- Describe the type of binary star system that leads to a type Ia supernovae event
- Indicate how type Ia supernovae differ from type II supernovae

The discussion of the life stories of stars presented so far has suffered from a bias—what we might call "single-star chauvinism." Because the human race developed around a star that goes through life alone, we tend to think of most stars in isolation. But as we saw in The Stars: A Celestial Census, it now appears that as many as half of all stars may develop in *binary* systems—those in which two stars are born in each other's gravitational embrace and go through life orbiting a common center of mass.

For these stars, the presence of a close-by companion can have a profound influence on their evolution. Under the right circumstances, stars can exchange material, especially during the stages when one of them swells up into a giant or supergiant, or has a strong wind. When this happens and the companion stars are sufficiently close, material can flow from one star to another, decreasing the mass of the donor and increasing the mass of the recipient. Such *mass transfer* can be especially dramatic when the recipient is a stellar remnant such as a white dwarf or a neutron star. While the detailed story of how such binary stars evolve is beyond the scope of our book, we do want to mention a few examples of how the stages of evolution described in this chapter may change when there are two stars in a system.

White Dwarf Explosions: The Mild Kind

Let's consider the following system of two stars: one has become a white dwarf and the other is gradually transferring material onto it. As fresh hydrogen from the outer layers of its companion accumulates on the surface of the hot white dwarf, it begins to build up a layer of hydrogen. As more and more hydrogen accumulates and heats up on the surface of the degenerate star, the new layer eventually reaches a temperature that causes fusion to begin in a sudden, explosive way, blasting much of the new material away.

In this way, the white dwarf quickly (but only briefly) becomes quite bright, hundreds or thousands of times its previous luminosity. To observers before the invention of the telescope, it seemed that a new star suddenly appeared, and they called it a **nova**.[3] Novae fade away in a few months to a few years.

Hundreds of novae have been observed, each occurring in a binary star system and each later showing a shell of expelled material. A number of stars have more than one nova episode, as more material from its neighboring star accumulates on the white dwarf and the whole process repeats. As long as the episodes do not increase the mass of the white dwarf beyond the Chandrasekhar limit (by transferring too much mass too quickly), the dense white dwarf itself remains pretty much unaffected by the explosions on its surface.

White Dwarf Explosions: The Violent Kind

If a white dwarf accumulates matter from a companion star at a much faster rate, it can be pushed over the Chandrasekhar limit. The evolution of such a binary system is shown in Figure 23.18. When its mass approaches the Chandrasekhar mass limit (exceeds 1.4 M_{Sun}), such an object can no longer support itself as a white dwarf, and it begins to contract. As it does so, it heats up, and new nuclear reactions can begin in the

3 We now know that this historical terminology is quite misleading since novae do not originate from new stars. In fact, quite to the contrary, novae originate from white dwarfs, which are actually the endpoint of stellar evolution for low-mass stars. But since the system of two stars was too faint to be visible to the naked eye, it did seem to people, before telescopes were invented, that a star had appeared where nothing had been visible.

degenerate core. The star “simmers” for the next century or so, building up internal temperature. This simmering phase ends in less than a second, when an enormous amount of fusion (especially of carbon) takes place all at once, resulting in an explosion. The fusion energy produced during the final explosion is so great that it completely destroys the white dwarf. Gases are blown out into space at velocities of about 10,000 kilometers per second, and afterward, no trace of the white dwarf remains.

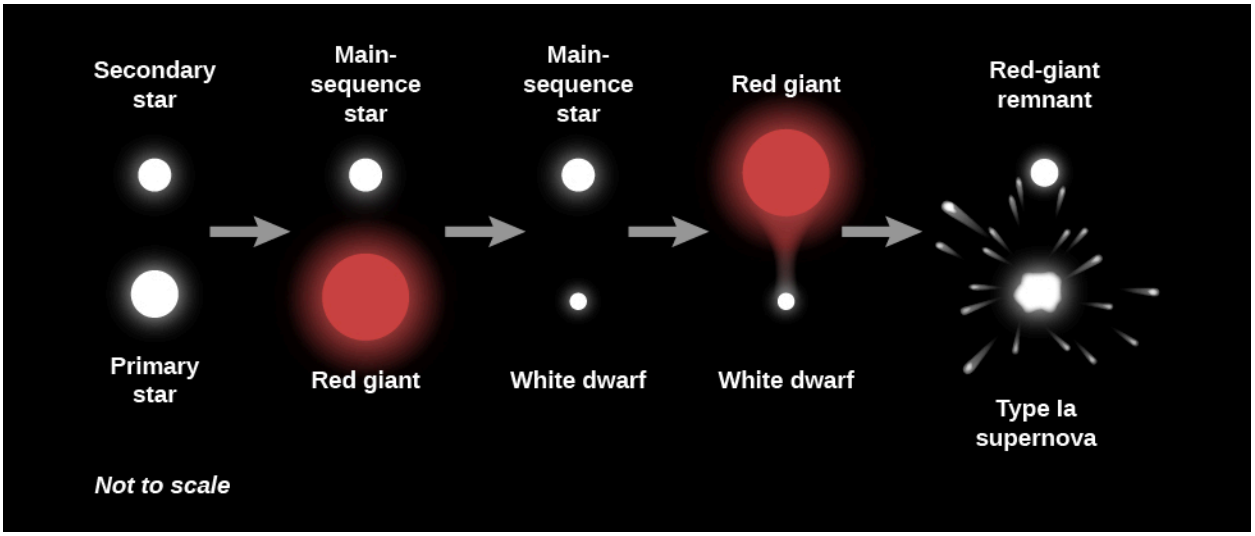


Figure 23.18 Evolution of a Binary System. The more massive star evolves first to become a red giant and then a white dwarf. The white dwarf then begins to attract material from its companion, which in turn evolves to become a red giant. Eventually, the white dwarf acquires so much mass that it is pushed over the Chandrasekhar limit and becomes a type Ia supernova.

Such an explosion is also called a supernova, since, like the destruction of a high-mass star, it produces a huge amount of energy in a very short time. However, unlike the explosion of a high-mass star, which can leave behind a neutron star or black hole remnant, the white dwarf is completely destroyed in the process, leaving behind no remnant. We call these white dwarf explosions type Ia supernovae.

We distinguish type I supernovae from those of supernovae of type II originating from the death of massive stars discussed earlier by the absence of hydrogen in their observed spectra. Hydrogen is the most common element in the universe and is a major component of massive, evolved stars. However, as we learned earlier, hydrogen is absent from the white dwarf remnant, which is primarily composed of carbon and oxygen for masses comparable to the Chandrasekhar mass limit.

The “a” subdesignation of type Ia supernovae further refers to the presence of strong silicon absorption lines, which are absent from supernovae originating from the collapse of massive stars. Silicon is one of the products that results from the fusion of carbon and oxygen, which bears out the scenario we described above—that there is a sudden onset of the fusion of the carbon (and oxygen) of which the white dwarf was made.

Observational evidence now strongly indicates that SN 1006, Tycho’s Supernova, and Kepler’s Supernova (see Supernovae in History) were all type Ia supernovae. For instance, in contrast to the case of SN 1054, which yielded the spinning pulsar in the Crab Nebula, none of these historical supernovae shows any evidence of stellar remnants that have survived their explosions. Perhaps even more puzzling is that, so far, astronomers have not been able to identify the companion star feeding the white dwarf in any of these historical supernovae.

Consequently, in order to address the mystery of the absent companion stars and other outstanding puzzles, astronomers have recently begun to investigate alternative mechanisms of generating type Ia supernovae. All proposed mechanisms rely upon white dwarfs composed of carbon and oxygen, which are needed to meet the observed absence of hydrogen in the type Ia spectrum. And because any isolated white dwarf below the Chandrasekhar mass is stable, all proposed mechanisms invoke a binary companion to explode the white dwarf. The leading alternative mechanism scientists believe creates a type Ia supernova is the merger of two white dwarf stars in a binary system. The two white dwarfs may have unstable orbits, such that over time, they would slowly move closer together until they merge. If their combined mass is greater than the Chandrasekhar limit, the result could also be a type Ia supernova explosion.

LINK TO LEARNING

You can watch a short video (https://openstax.org/l/30supernovavid) about Supernova SN 2014J, a type Ia supernova discovered in the Messier 82 (M82) galaxy on January 21, 2014, as well as see brief animations of the two mechanisms by which such a supernova could form.

Type Ia supernovae are of great interest to astronomers in other areas of research. This type of supernova is brighter than supernovae produced by the collapse of a massive star. Thus, type Ia supernovae can be seen at very large distances, and they are found in all types of galaxies. The energy output from most type Ia supernovae is consistent, with little variation in their maximum luminosities, or in how their light output initially increases and then slowly decreases over time. These properties make type Ia supernovae extremely valuable "standard bulbs" for astronomers looking out at great distances—well beyond the limits of our own Galaxy. You'll learn more about their use in measuring distances to other galaxies in The Big Bang.

In contrast, type II supernovae are about 5 times less luminous than type Ia supernovae and are only seen in galaxies that have recent, massive star formation. Type II supernovae are also less consistent in their energy output during the explosion and can have a range a peak luminosity values.

Neutron Stars with Companions

Now let's look at an even-more mismatched pair of stars in action. It is possible that, under the right circumstances, a binary system can even survive the explosion of one of its members as a type II supernova. In that case, an ordinary star can eventually share a system with a neutron star. If material is then transferred from the "living" star to its "dead" (and highly compressed) companion, this material will be pulled in by the strong gravity of the neutron star. Such infalling gas will be compressed and heated to incredible temperatures. It will quickly become so hot that it will experience an explosive burst of fusion. The energies involved are so great that we would expect much of the radiation from the burst to emerge as X-rays. And indeed, high-energy observatories above Earth's atmosphere (see Astronomical Instruments) have recorded many objects that undergo just these types of X-ray *bursts*.

If the neutron star and its companion are positioned the right way, a significant amount of material can be transferred to the neutron star and can set it spinning faster (as spin energy is also transferred). The radius of the neutron star would also decrease as more mass was added. Astronomers have found pulsars in binary systems that are spinning at a rate of more than 500 times per second! (These are sometimes called **millisecond pulsars** since the pulses are separated by a few thousandths of a second.)

Such a rapid spin could not have come from the birth of the neutron star; it must have been externally caused. (Recall that the Crab Nebula pulsar, one of the youngest pulsars known, was spinning "only" 30 times per second.) Indeed, some of the fast pulsars are observed to be part of binary systems, while others may be alone only because they have "fully consumed" their former partner stars through the mass transfer process. (These have sometimes been called "black widow pulsars.")

LINK TO LEARNING

View this short video (https://openstax.org/l/30scotronvid) to see Dr. Scott Ransom, of the National Radio Astronomy Observatory, explain how millisecond pulsars come about, with some nice animations.

And if you thought that a neutron star interacting with a “normal” star was unusual, there are also binary systems that consist of two neutron stars. One such system has the stars in very close orbits to one another, so much that they continually alter each other’s orbit. Another binary neutron star system includes two pulsars that are orbiting each other every 2 hours and 25 minutes. As we discussed earlier, pulsars radiate away their energy, and these two pulsars are slowly moving toward one another, such that in about 85 million years, they will actually merge (see Gravitational Wave Astronomy for our first observations of such a merger).

We have now reached the end of our description of the final stages of stars, yet one piece of the story remains to be filled in. We saw that stars whose core masses are less than 1.4 M_{Sun} at the time they run out of fuel end their lives as white dwarfs. Dying stars with core masses between 1.4 and about 3 M_{Sun} become neutron stars. But there are stars whose core masses are greater than 3 M_{Sun} when they exhaust their fuel supplies. What becomes of them? The truly bizarre result of the death of such massive stellar cores (called a black hole) is the subject of our next chapter. But first, we will look at an astronomical mystery that turned out to be related to the deaths of stars and was solved through clever sleuthing and a combination of observation and theory.

23.6 The Mystery of the Gamma-Ray Bursts

Learning Objectives

By the end of this section, you will be able to:

- Give a brief history of how gamma-ray bursts were discovered and what instruments made the discovery possible
- Explain why astronomers think that gamma-ray bursts beam their energy rather than it radiating uniformly in all directions
- Describe how the radiation from a gamma-ray burst and its afterglow is produced
- Explain how short-duration gamma-ray bursts differ from longer ones, and describe the process that makes short-duration gamma-ray bursts
- Explain why gamma-ray bursts may help us understand the early universe

Everybody loves a good mystery, and astronomers are no exception. The mystery we will discuss in this section was first discovered in the mid-1960s, not via astronomical research, but as a result of a search for the tell-tale signs of nuclear weapon explosions. The US Defense Department launched a series of *Vela* satellites to make sure that no country was violating a treaty that banned the detonation of nuclear weapons in space.

Since nuclear explosions produce the most energetic form of electromagnetic waves called *gamma rays* (see Radiation and Spectra), the *Vela* satellites contained detectors to search for this type of radiation. The satellites did not detect any confirmed events from human activities, but they did—to everyone’s surprise—detect short bursts of gamma rays coming from random directions in the sky. News of the discovery was first published in 1973; however, the origin of the bursts remained a mystery. No one knew what produced the brief flashes of gamma rays or how far away the sources were.

From a Few Bursts to Thousands

With the launch of the Compton Gamma-Ray Observatory by NASA in 1991, astronomers began to identify many more bursts and to learn more about them (Figure 23.19). Approximately once per day, the NASA satellite detected a flash of gamma rays somewhere in the sky that lasted from a fraction of a second to several hundred seconds. Before the Compton measurements, astronomers had expected that the most likely place for the bursts to come from was the main disk of our own (pancake-shaped) Galaxy. If this had been the case, however, more bursts would have been seen in the crowded plane of the Milky Way than above or below it. Instead, the sources of the bursts were distributed *isotropically*; that is, they could appear anywhere in the sky with no preference for one region over another. Almost never did a second burst come from the same location.

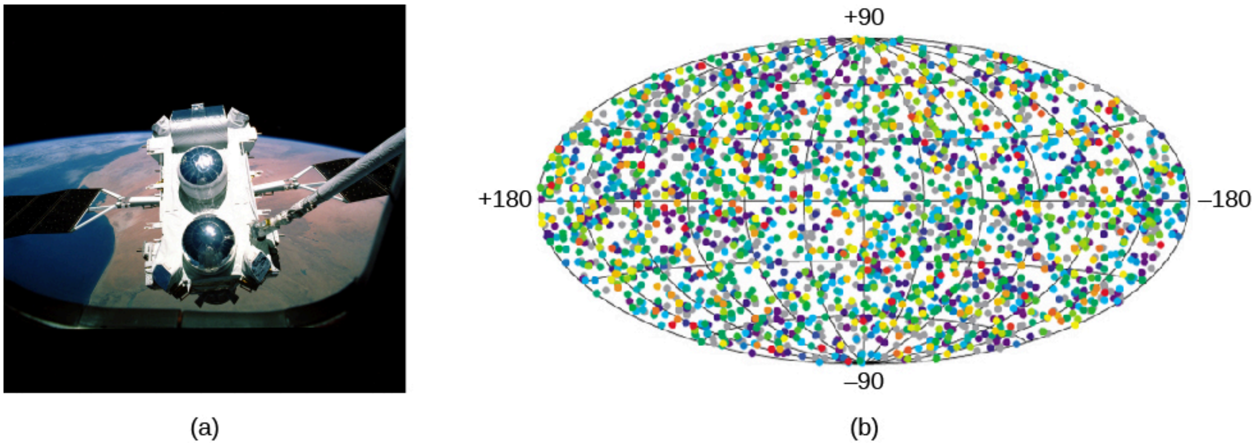


Figure 23.19 Compton Detects Gamma-Ray Bursts. (a) In 1991, the Compton Gamma-Ray Observatory was deployed by the Space Shuttle Atlantis. Weighing more than 16 tons, it was one of the largest scientific payloads ever launched into space. (b) This map of gamma-ray burst positions measured by the Compton Gamma-Ray Observatory shows the isotropic (same in all directions), uniform distribution of bursts on the sky. The map is oriented so that the disk of the Milky Way would stretch across the center line (or equator) of the oval. Note that the bursts show no preference at all for the plane of the Milky Way, as many other types of objects in the sky do. Colors indicate the total energy in the burst: red dots indicate long-duration, bright bursts; blue and purple dots show short, weaker bursts. (credit a: modification of work by NASA; credit b: modification of work by NASA/GSFC)

LINK TO LEARNING

To get a good visual sense of the degree to which the bursts come from all over the sky, watch this short animated NASA video (https://openstax.org/l/30swiftnasavid) showing the location of the first 500 bursts found by the later *Swift* satellite.

For several years, astronomers actively debated whether the burst sources were relatively nearby or very far away—the two possibilities for bursts that are isotropically distributed. Nearby locations might include the cloud of comets that surrounds the solar system or the halo of our Galaxy, which is large and spherical, and also surrounds us in all directions. If, on the other hand, the bursts occurred at very large distances, they could come from faraway galaxies, which are also distributed uniformly in all directions.

Both the very local and the very distant hypotheses required something strange to be going on. If the bursts were coming from the cold outer reaches of our own solar system or from the halo of our Galaxy, then astronomers had to hypothesize some new kind of physical process that could produce unpredictable flashes of high-energy gamma rays in these otherwise-quiet regions of space. And if the bursts came from galaxies millions or billions of light-years away, then they must be extremely powerful to be observable at such large distances; indeed they had to be the among the biggest explosions in the universe.

The First Afterglows

The problem with trying to figure out the source of the gamma-ray bursts was that our instruments for detecting gamma rays could not pinpoint the exact place in the sky where the burst was happening. Early gamma-ray telescopes did not have sufficient *resolution.* This was frustrating because astronomers suspected that if they *could* pinpoint the exact position of one of these rapid bursts, then they would be able to identify a counterpart (such as a star or galaxy) at other wavelengths and learn much more about the burst, including where it came from. This would, however, require either major improvements in gamma-ray detector technology to provide better resolution or detection of the burst at some other wavelength. In the end, both techniques played a role.

The breakthrough came with the launch of the Italian Dutch *BeppoSAX* satellite in 1996. *BeppoSAX* included a new type of gamma-ray telescope capable of identifying the position of a source much more accurately than previous instruments, to within a few minutes of arc on the sky. By itself, however, it was still not sophisticated enough to determine the exact source of the gamma-ray burst. After all, a box a few minutes of arc on a side could still contain many stars or other celestial objects.

However, the angular resolution of *BeppoSAX* was good enough to tell astronomers where to point other, more precise telescopes in the hopes of detecting longer-lived electromagnetic emission from the bursts at other wavelengths. Detection of a burst at visible-light or radio wavelengths could provide a position accurate to a few *seconds* of arc and allow the position to be pinpointed to an individual star or galaxy. *BeppoSAX* carried its own X-ray telescope onboard the spacecraft to look for such a counterpart, and astronomers using visible-light and radio facilities on the ground were eager to search those wavelengths as well.

Two crucial *BeppoSAX* burst observations in 1997 helped to resolve the mystery of the gamma-ray bursts. The first burst came in February from the direction of the constellation Orion. Within 8 hours, astronomers working with the satellite had identified the position of the burst, and reoriented the spacecraft to focus *BeppoSAX*'s X-ray detector on the source. To their excitement, they detected a slowly fading X-ray source 8 hours after the event—the first successful detection of an afterglow from a gamma-ray burst. This provided an even-better location of the burst (accurate to about 40 seconds of arc), which was then distributed to astronomers across the world to try to detect it at even longer wavelengths.

That very night, the 4.2-meter William Herschel Telescope on the Canary Islands found a fading visible-light source at the same position as the X-ray afterglow, confirming that such an afterglow could be detected in visible light as well. Eventually, the afterglow faded away, but left behind at the location of the original gamma-ray burst was a faint, fuzzy source right where the fading point of light had been—a distant galaxy (Figure 23.20). This was the first piece of evidence that gamma-ray bursts were indeed very energetic objects from very far away. However, it also remained possible that the burst source was much closer to us and just happened to align with a more distant galaxy, so this one observation alone was not a conclusive demonstration of the extragalactic origin of gamma-ray bursts.

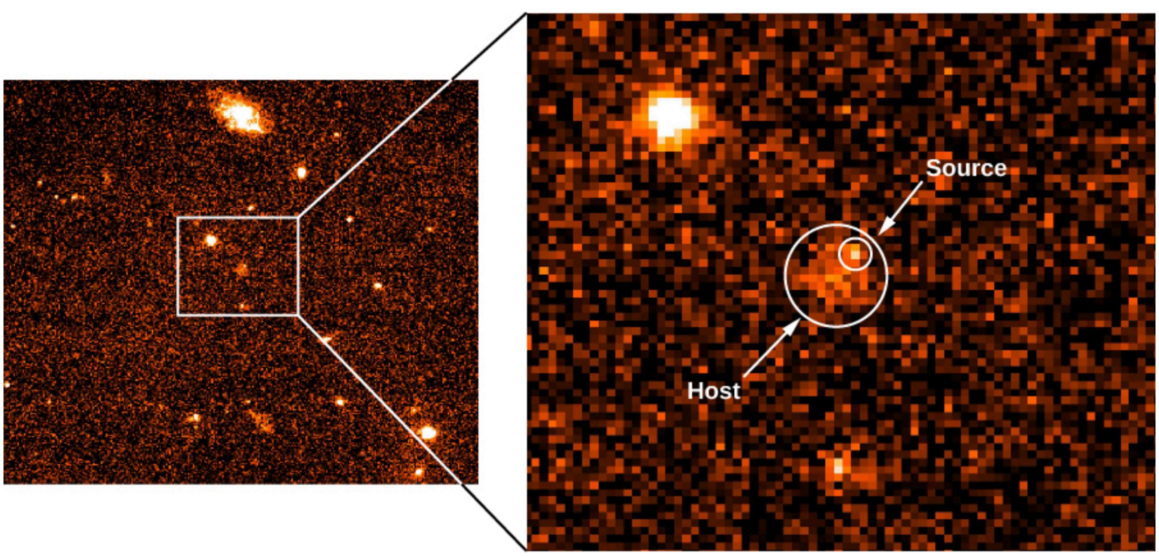


Figure 23.20 Gamma-Ray Burst. This false-color Hubble Space Telescope image, taken in September 1997, shows the fading afterglow of the gamma-ray burst of February 28, 1997 and the host galaxy in which the burst originated. The left view shows the region of the burst. The enlargement shows the burst source and what appears to be its host galaxy. Note that the gamma-ray

source is not in the center of the galaxy. (credit: modification of work by Andrew Fruchter (STScI), Elena Pian (ITSRE-CNR), and NASA, ESA)

On May 8 of the same year, a burst came from the direction of the constellation Camelopardalis. In a coordinated international effort, *BeppoSAX* again fixed a reasonably precise position, and almost immediately a telescope on Kitt Peak in Arizona was able to catch the visible-light afterglow. Within 2 days, the largest telescope in the world (the Keck in Hawaii) collected enough light to record a spectrum of the burst. The May gamma-ray burst afterglow spectrum showed absorption features from a fuzzy object that was 4 billion light-years from the Sun, meaning that the location of the burst had to be at least this far away—and possibly even farther. (How astronomers can get the distance of such an object from the Doppler shift in the spectrum is something we will discuss in Galaxies.) What that spectrum showed was clear evidence that the gamma-ray burst had taken place in a distant galaxy.

Networking to Catch More Bursts

After initial observations showed that the precise locations and afterglows of gamma-ray bursts could be found, astronomers set up a system to catch and pinpoint bursts on a regular basis. But to respond as quickly as needed to obtain usable results, astronomers realized that they needed to rely on automated systems rather than human observers happening to be in the right place at the right time.

Now, when an orbiting high-energy telescope discovers a burst, its rough location is immediately transmitted to a *Gamma-Ray Coordinates Network* based at NASA's Goddard Space Flight Center, alerting observers on the ground within a few seconds to look for the visible-light afterglow.

The first major success with this system was achieved by a team of astronomers from the University of Michigan, Lawrence Livermore National Laboratory, and Los Alamos National Laboratories, who designed an automated device they called the *Robotic Optical Transient Search Experiment* (*ROTSE*), which detected a very bright visible-light counterpart in 1999. At peak, the burst was almost as bright as Neptune—despite a distance (measured later by spectra from larger telescopes) of 9 billion light-years.

More recently, astronomers have been able to take this a step further, using wide-field-of-view telescopes to stare at large fractions of the sky in the hope that a gamma-ray burst will occur at the right place and time, and be recorded by the telescope's camera. These wide-field telescopes are not sensitive to faint sources, but ROTSE showed that gamma-ray burst afterglows could sometimes be very bright.

Astronomers' hopes were vindicated in March 2008, when an extremely bright gamma-ray burst occurred and its light was captured by two wide-field camera systems in Chile: the Polish "Pi of the Sky" and the Russian-Italian TORTORA [Telescopio Ottimizzato per la Ricerca dei Transienti Ottici Rapidi (Italian for Telescope Optimized for the Research of Rapid Optical Transients)] (see Figure 23.21). According to the data taken by these telescopes, for a period of about 30 seconds, the light from the gamma-ray burst was bright enough that it could have been seen by the unaided eye had a person been looking in the right place at the right time. Adding to our amazement, later observations by larger telescopes demonstrated that the burst occurred at a distance of 8 billion light-years from Earth!

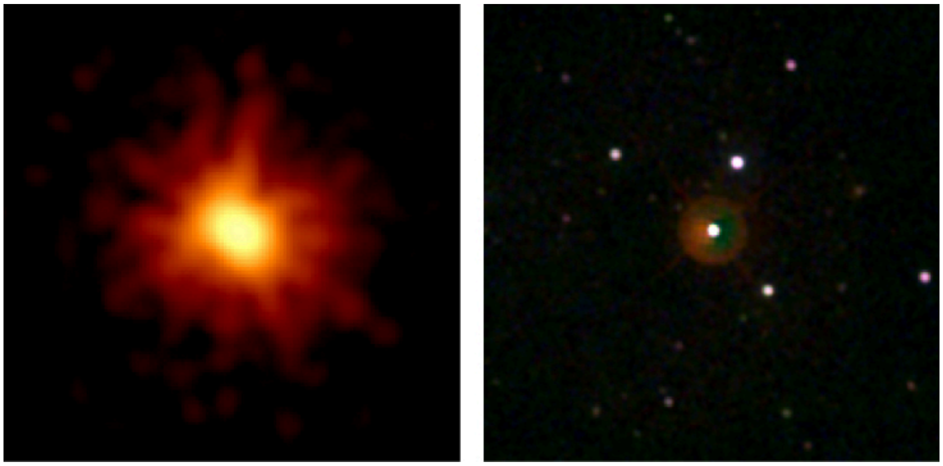


Figure 23.21 Gamma-Ray Burst Observed in March 2008. The extremely luminous afterglow of GRB 080319B was imaged by the Swift Observatory in X-rays (left) and visible light/ultraviolet (right). (credit: modification of work by NASA/Swift/Stefan Immler, et al.)

To Beam or Not to Beam

The enormous distances to these events meant they had to have been astoundingly energetic to appear as bright as they were across such an enormous distance. In fact, they required so much energy that it posed a problem for gamma-ray burst models: if the source was radiating energy in all directions, then the energy released in gamma rays alone during a bright burst (such as the 1999 or 2008 events) would have been equivalent to the energy produced if the entire mass of a Sun-like star were suddenly converted into pure radiation.

For a source to produce this much energy this quickly (in a burst) is a real challenge. Even if the star producing the gamma-ray burst was much more massive than the Sun (as is probably the case), there is no known means of converting so much mass into radiation within a matter of seconds. However, there is one way to reduce the power required of the "mechanism" that makes gamma-ray bursts. So far, our discussion has assumed that the source of the gamma rays gives off the same amount of energy in all directions, like an incandescent light bulb.

But as we discuss in Pulsars and the Discovery of Neutron Stars, not all sources of radiation in the universe are like this. Some produce thin beams of radiation that are concentrated into only one or two directions. A laser pointer and a lighthouse on the ocean are examples of such beamed sources on Earth (Figure 23.22). If, when a burst occurs, the gamma rays come out in only one or two narrow beams, then our estimates of the luminosity of the source can be reduced, and the bursts may be easier to explain. In that case, however, the beam has to point toward Earth for us to be able to see the burst. This, in turn, would imply that for every burst we see from Earth, there are probably many others that we never detect because their beams point in other directions.

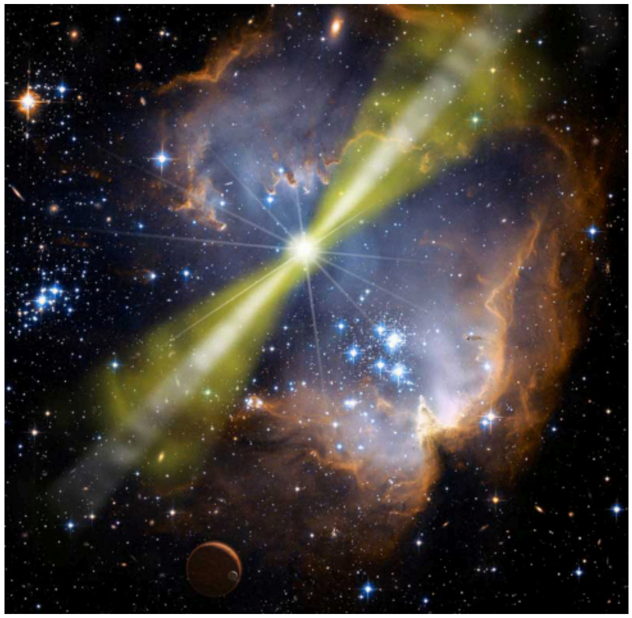


Figure 23.22 Burst That Is Beamed. This artist's conception shows an illustration of one kind of gamma-ray burst. The collapse of the core of a massive star into a black hole has produced two bright beams of light originating from the star's poles, which an observer pointed along one of these axes would see as a gamma-ray burst. The hot blue stars and gas clouds in the vicinity are meant to show that the event happened in an active star-forming region. (credit: NASA/Swift/Mary Pat Hrybyk-Keith and John Jones)

Long-Duration Gamma-Ray Bursts: Exploding Stars

After identifying and following large numbers of gamma-ray bursts, astronomers began to piece together clues about what kind of event is thought to be responsible for producing the gamma-ray burst. Or, rather, what kind of *events*, because there are at least two distinct types of gamma-ray bursts. The two—like the different types of supernovae—are produced in completely different ways.

Observationally, the crucial distinction is how long the burst lasts. Astronomers now divide gamma-ray bursts into two categories: short-duration ones (defined as lasting less than 2 seconds, but typically a fraction of a second) and long-duration ones (defined as lasting more than 2 seconds, but typically about a minute).

All of the examples we have discussed so far concern the long-duration gamma-ray bursts. These constitute most of the gamma-ray bursts that our satellites detect, and they are also brighter and easier to pinpoint. Many hundreds of long-duration gamma-ray bursts, and the properties of the galaxies in which they occurred, have now been studied in detail. Long-duration gamma-ray bursts are universally observed to come from distant galaxies that are still actively making stars. They are usually found to be located in regions of the galaxy with strong star-formation activity (such as spiral arms). Recall that the more massive a star is, the less time it spends in each stage of its life. This suggests that the bursts come from a young and short-lived, and therefore massive type of star.

Furthermore, in several cases when a burst has occurred in a galaxy relatively close to Earth (within a few billion light-years), it has been possible to search for a supernova at the same position—and in nearly all of these cases, astronomers have found evidence of a supernova of type Ic going off. A type Ic is a particular type of supernova, which we did not discuss in the earlier parts of this chapter; these are produced by a massive star that has been stripped of its outer hydrogen layer. However, only a tiny fraction of type Ic supernovae produce gamma-ray bursts.

Why would a massive star with its outer layers missing sometimes produce a gamma-ray burst at the same time that it explodes as a supernova? The explanation astronomers have in mind for the extra energy is the collapse of the star's core to form a spinning, magnetic black hole or neutron star. Because the star corpse is both magnetic and spinning rapidly, its sudden collapse is complex and can produce swirling jets of particles and powerful beams of radiation—just like in a quasar or active galactic nucleus (objects you will learn about

Active Galaxies, Quasars, and Supermassive Black Holes), but on a much faster timescale. A small amount of the infalling mass is ejected in a narrow beam, moving at speeds close to that of light. Collisions among the particles in the beam can produce intense bursts of energy that we see as a gamma-ray burst.

Within a few minutes, the expanding blast from the fireball plows into the interstellar matter in the dying star's neighborhood. This matter might have been ejected from the star itself at earlier stages in its evolution. Alternatively, it could be the gas out of which the massive star and its neighbors formed.

As the high-speed particles from the blast are slowed, they transfer their energy to the surrounding matter in the form of a shock wave. That shocked material emits radiation at longer wavelengths. This accounts for the afterglow of X-rays, visible light, and radio waves—the glow comes at longer and longer wavelengths as the blast continues to lose energy.

Short-Duration Gamma-Ray Bursts: Colliding Stellar Corpses

What about the shorter gamma-ray bursts? The gamma-ray emission from these events lasts less than 2 seconds, and in some cases may last only milliseconds—an amazingly short time. Such a timescale is difficult to achieve if they are produced in the same way as long-duration gamma-ray bursts, since the collapse of the stellar interior onto the black hole should take at least a few seconds.

Astronomers looked fruitlessly for afterglows from short-duration gamma-ray bursts found by *BeppoSAX* and other satellites. Evidently, the afterglows fade away too quickly. Fast-responding visible-light telescopes like ROTSE were not helpful either: no matter how fast these telescopes responded, the bursts were not bright enough at visible wavelengths to be detected by these small telescopes.

Once again, it took a new satellite to clear up the mystery. In this case, it was the *Swift Gamma-Ray Burst Satellite*, launched in 2004 by a collaboration between NASA and the Italian and UK space agencies (Figure 23.23). The design of *Swift* is similar to that of *BeppoSAX*. However, *Swift* is much more agile and flexible: after a gamma-ray burst occurs, the X-ray and UV telescopes can be repointed automatically within a few minutes (rather than a few hours). Thus, astronomers can observe the afterglow much earlier, when it is expected to be much brighter. Furthermore, the X-ray telescope is far more sensitive and can provide positions that are 30 times more precise than those provided by *BeppoSAX*, allowing bursts to be identified even without visible-light or radio observations.

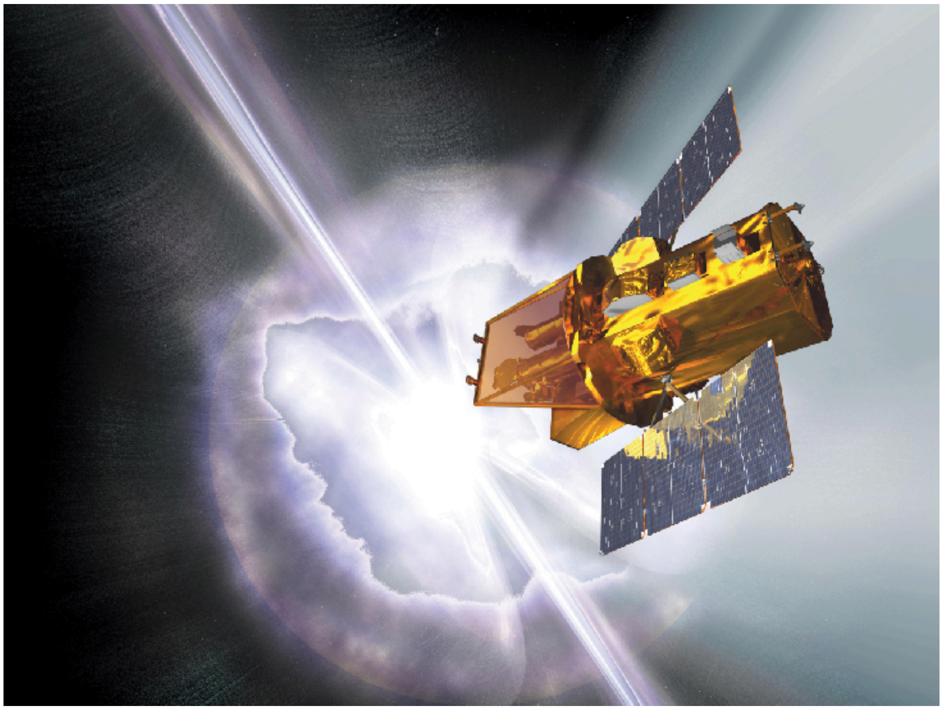


Figure 23.23 Artist's Illustration of *Swift*. The US/UK/Italian spacecraft *Swift* contains on-board gamma-ray, X-ray, and ultraviolet detectors, and has the ability to automatically reorient itself to a gamma-ray burst detected by the gamma-ray instrument. Since its launch in 2005, *Swift* has detected and observed over a thousand bursts, including dozens of short-duration bursts. (credit: NASA, Spectrum Astro)

On May 9, 2005, *Swift* detected a flash of gamma rays lasting 0.13 seconds in duration, originating from the constellation Coma Berenices. Remarkably, the galaxy at the X-ray position looked completely different from any galaxy in which a long-duration burst had been seen to occur. The afterglow originated from the halo of a giant elliptical galaxy 2.7 billion light-years away, with no signs of any young, massive stars in its spectrum. Furthermore, no supernova was ever detected after the burst, despite extensive searching.

What could produce a burst less than a second long, originating from a region with no star formation? The leading model involves the *merger* of two compact stellar corpses: two neutron stars, or perhaps a neutron star and a black hole. Since many stars come in binary or multiple systems, it's possible to have systems where two such star corpses orbit one another. According to general relativity (which will be discussed in Black Holes and Curved Spacetime), the orbits of a binary star system composed of such objects should slowly decay with time, eventually (after millions or billions of years) causing the two objects to slam together in a violent but brief explosion. Because the decay of the binary orbit is so slow, we would expect more of these mergers to occur in old galaxies in which star formation has long since stopped.

LINK TO LEARNING

To learn more about the merger of two neutron stars and how they can produce a burst that lasts less than a second, check out this computer simulation (https://openstax.org/l/30comsimneustr) by NASA.

While it was impossible to be sure of this model based on only a single event (it is possible this burst actually came from a background galaxy and lined up with the giant elliptical only by chance), several dozen more short-duration gamma-ray bursts have since been located by *Swift*, many of which also originate from galaxies with very low star-formation rates. This has given astronomers greater confidence that this model is the correct one. Still, to be fully convinced, astronomers are searching for a "smoking gun" signature for the merger of two ultra-dense stellar remnants.

Astronomers identified two observations that would provide more direct evidence. Theoretical calculations indicate that when two neutron stars collide there will be a very special kind of explosion; neutrons stripped from the neutron stars during the violent final phase of the merger will fuse together into heavy elements and then release heat due to radioactivity, producing a short-lived but red supernova sometimes called a *kilonova*. (The term is used because it is about a thousand times brighter than an ordinary nova, but not quite as "super" as a traditional supernova.) Hubble observations of one short-duration gamma-ray burst in 2013 showed suggestive evidence of such a signature, but needed to be confirmed by future observations.

The second "smoking gun" is the detection of *gravitational waves.* As will be discussed in Black Holes and Curved Spacetime, gravitational waves are ripples in the fabric of spacetime that general relativity predicts should be produced by the acceleration of extremely massive and dense objects—such as two neutron stars or black holes spiraling toward each other and colliding. The construction of instruments to detect gravitational waves is very challenging technically, and gravitational wave astronomy became feasible only in 2015. The first few detected gravitational wave events were produced by mergers of black holes. In 2017, however, gravitational waves were observed from a source that was coincident in time and space with a gamma-ray burst. The source consisted of two objects with the masses of neutron stars. A red supernova was also observed at this location, and the ejected material was rich in heavy elements. This observation not only confirms the theory of the origin of short gamma-ray bursts, but also is a spectacular demonstration of the validity of Einstein's theory of general relativity.

Probing the Universe with Gamma-Ray Bursts

The story of how astronomers came to explain the origin of the different kinds of bursts is a good example of how the scientific process sometimes resembles good detective work. While the mystery of short-duration gamma-ray bursts is still being unraveled, the focus of studies for long-duration gamma-ray bursts has begun to change from understanding the origin of the bursts themselves (which is now fairly well-established) to using them as tools to understand the broader universe.

The reason that long-duration gamma-ray bursts are useful has to do with their extreme luminosities, if only for a short time. In fact, long-duration gamma-ray bursts are so bright that they could easily be seen at distances that correspond to a few hundred million years after the expansion of the universe began, which is when theorists think that the first generation of stars formed. Some theories predict that the first stars are likely to be massive and complete their evolution in only a million years or so. If this turns out to be the case, then gamma-ray bursts (which signal the death of some of these stars) may provide us with the best way of probing the universe when stars and galaxies first began to form.

So far, the most distant gamma-ray burst found (on April 29, 2009) was in a galaxy with a redshift that corresponds to a remarkable 13.2 billion light years—meaning it happened only 600 million years after the Big Bang itself. This is comparable to the earliest and most distant galaxies found by the Hubble Space Telescope. It is not quite old enough to expect that it formed from the first generation of stars, but its appearance at this distance still gives us useful information about the production of stars in the early universe. Astronomers continue to scan the skies, looking for even more distant events signaling the deaths of stars from even further back in time.

Key Terms

Chandrasekhar limit the upper limit to the mass of a white dwarf (equals 1.4 times the mass of the Sun)

degenerate gas a gas that resists further compression because no two electrons can be in the same place at the same time doing the same thing (Pauli exclusion principle)

millisecond pulsar a pulsar that rotates so quickly that it can give off hundreds of pulses per second (and its period is therefore measured in milliseconds)

neutron star a compact object of extremely high density composed almost entirely of neutrons

nova the cataclysmic explosion produced in a binary system, temporarily increasing its luminosity by hundreds to thousands of times

pulsar a variable radio source of small physical size that emits very rapid radio pulses in very regular periods that range from fractions of a second to several seconds; now understood to be a rotating, magnetic neutron star that is energetic enough to produce a detectable beam of radiation and particles

type II supernova a stellar explosion produced at the endpoint of the evolution of stars whose mass exceeds roughly 10 times the mass of the Sun

Summary

23.1 The Death of Low-Mass Stars

During the course of their evolution, stars shed their outer layers and lose a significant fraction of their initial mass. Stars with masses of 8 M_{Sun} or less can lose enough mass to become white dwarfs, which have masses less than the Chandrasekhar limit (about 1.4 M_{Sun}). The pressure exerted by degenerate electrons keeps white dwarfs from contracting to still-smaller diameters. Eventually, white dwarfs cool off to become black dwarfs, stellar remnants made mainly of carbon, oxygen, and neon.

23.2 Evolution of Massive Stars: An Explosive Finish

In a massive star, hydrogen fusion in the core is followed by several other fusion reactions involving heavier elements. Just before it exhausts all sources of energy, a massive star has an iron core surrounded by shells of silicon, sulfur, oxygen, neon, carbon, helium, and hydrogen. The fusion of iron requires energy (rather than releasing it). If the mass of a star's iron core exceeds the Chandrasekhar limit (but is less than 3 M_{Sun}), the core collapses until its density exceeds that of an atomic nucleus, forming a neutron star with a typical diameter of 20 kilometers. The core rebounds and transfers energy outward, blowing off the outer layers of the star in a type II supernova explosion.

23.3 Supernova Observations

A supernova occurs on average once every 25 to 100 years in the Milky Way Galaxy. Despite the odds, no supernova in our Galaxy has been observed from Earth since the invention of the telescope. However, one nearby supernova (SN 1987A) has been observed in a neighboring galaxy, the Large Magellanic Cloud. The star that evolved to become SN 1987A began its life as a blue supergiant, evolved to become a red supergiant, and returned to being a blue supergiant at the time it exploded. Studies of SN 1987A have detected neutrinos from the core collapse and confirmed theoretical calculations of what happens during such explosions, including the formation of elements beyond iron. Supernovae are a main source of high-energy cosmic rays and can be dangerous for any living organisms in nearby star systems.

23.4 Pulsars and the Discovery of Neutron Stars

At least some supernovae leave behind a highly magnetic, rapidly rotating neutron star, which can be observed as a pulsar if its beam of escaping particles and focused radiation is pointing toward us. Pulsars emit rapid pulses of radiation at regular intervals; their periods are in the range of 0.001 to 10 seconds. The rotating neutron star acts like a lighthouse, sweeping its beam in a circle and giving us a pulse of radiation when the beam sweeps over Earth. As pulsars age, they lose energy, their rotations slow, and their periods increase.

23.5 The Evolution of Binary Star Systems

When a white dwarf or neutron star is a member of a close binary star system, its companion star can transfer mass to it. Material falling *gradually* onto a white dwarf can explode in a sudden burst of fusion and make a nova. If material falls *rapidly* onto a white dwarf, it can push it over the Chandrasekhar limit and cause it to explode completely as a type Ia supernova. Another possible mechanism for a type Ia supernova is the merger of two white dwarfs. Material falling onto a neutron star can cause powerful bursts of X-ray radiation. Transfer of material and angular momentum can speed up the rotation of pulsars until their periods are just a few thousandths of a second.

23.6 The Mystery of the Gamma-Ray Bursts

Gamma-ray bursts last from a fraction of a second to a few minutes. They come from all directions and are now known to be associated with very distant objects. The energy is most likely beamed, and, for the ones we can detect, Earth lies in the direction of the beam. Long-duration bursts (lasting more than a few seconds) come from massive stars with their outer hydrogen layers missing that explode as supernovae. Short-duration bursts are believed to be mergers of stellar corpses (neutron stars or black holes).

For Further Exploration

Articles

Death of Stars

Hillebrandt, W., et al. “How To Blow Up a Star.” *Scientific American* (October 2006): 42. On supernova mechanisms.

Irion, R. “Pursuing the Most Extreme Stars.” *Astronomy* (January 1999): 48. On pulsars.

Kalirai, J. “New Light on Our Sun’s Fate.” *Astronomy* (February 2014): 44. What will happen to stars like our Sun between the main sequence and the white dwarf stages.

Kirshner, R. “Supernova 1987A: The First Ten Years.” *Sky & Telescope* (February 1997): 35.

Maurer, S. “Taking the Pulse of Neutron Stars.” *Sky & Telescope* (August 2001): 32. Review of recent ideas and observations of pulsars.

Zimmerman, R. “Into the Maelstrom.” *Astronomy* (November 1998): 44. About the Crab Nebula.

Gamma-Ray Bursts

Fox, D. & Racusin, J. “The Brightest Burst.” *Sky & Telescope* (January 2009): 34. Nice summary of the brightest burst observed so far, and what we have learned from it.

Nadis, S. “Do Cosmic Flashes Reveal Secrets of the Infant Universe?” *Astronomy* (June 2008): 34. On different types of gamma-ray bursts and what we can learn from them.

Naeye, R. “Dissecting the Bursts of Doom.” *Sky & Telescope* (August 2006): 30. Excellent review of gamma-ray bursts—how we discovered them, what they might be, and what they can be used for in probing the universe.

Zimmerman, R. “Speed Matters.” *Astronomy* (May 2000): 36. On the quick-alert networks for finding afterglows.

Zimmerman, R. “Witness to Cosmic Collisions.” *Astronomy* (July 2006): 44. On the Swift mission and what it is teaching astronomers about gamma-ray bursts.

Websites

Death of Stars

Crab Nebula: http://chandra.harvard.edu/xray_sources/crab/crab.html (http://chandra.harvard.edu/xray_sources/crab/crab.html). A short, colorfully written introduction to the history and science involving the best-known supernova remant.

Introduction to Neutron Stars: https://www.astro.umd.edu/~miller/nstar.html (https://www.astro.umd.edu/~miller/nstar.html). Coleman Miller of the University of Maryland maintains this site, which goes from easy to hard as you get into it, but it has lots of good information about corpses of massive stars.

Introduction to Pulsars (by Maryam Hobbs at the Australia National Telescope Facility): http://www.atnf.csiro.au/outreach/education/everyone/pulsars/index.html (http://www.atnf.csiro.au/outreach/education/everyone/pulsars/index.html).

Magnetars, Soft Gamma Repeaters, and Very Strong Magnetic Fields: http://solomon.as.utexas.edu/magnetar.html (http://solomon.as.utexas.edu/magnetar.html). Robert Duncan, one of the originators of the idea of magnetars, assembled this site some years ago.

Gamma-Ray Bursts

Brief Intro to Gamma-Ray Bursts (from PBS' *Seeing in the Dark*): http://www.pbs.org/seeinginthedark/astronomy-topics/gamma-ray-bursts.html (http://www.pbs.org/seeinginthedark/astronomy-topics/gamma-ray-bursts.html).

Discovery of Gamma-Ray Bursts: http://science.nasa.gov/science-news/science-at-nasa/1997/ast19sep97_2/ (http://science.nasa.gov/science-news/science-at-nasa/1997/ast19sep97_2/).

Missions to Detect and Learn More about Gamma-Ray Bursts:

- Fermi Space Telescope: https://www.nasa.gov/content/fermi/overview (https://www.nasa.gov/content/fermi/overview).
- *INTEGRAL* Spacecraft: http://www.esa.int/Science_Exploration/Space_Science/Integral_overview (http://www.esa.int/Science_Exploration/Space_Science/Integral_overview).
- *SWIFT* Spacecraft: https://swift.gsfc.nasa.gov/about_swift/ (https://swift.gsfc.nasa.gov/about_swift/).

Videos

Death of Stars

BBC interview with Antony Hewish: http://www.bbc.co.uk/archive/scientists/10608.shtml (http://www.bbc.co.uk/archive/scientists/10608.shtml). (40:54).

Black Widow Pulsars: The Vengeful Corpses of Stars: https://www.youtube.com/watch?v=Fn-3G_N0hy4 (https://www.youtube.com/watch?v=Fn-3G_N0hy4). A public talk in the Silicon Valley Astronomy Lecture Series by Dr. Roger Romani (Stanford University) (1:01:47).

Hubblecast 64: It all ends with a bang!: http://www.spacetelescope.org/videos/hubblecast64a/ (http://www.spacetelescope.org/videos/hubblecast64a/). HubbleCast Program introducing Supernovae with Dr. Joe Liske (9:48).

Space Movie Reveals Shocking Secrets of the Crab Pulsar: http://hubblesite.org/newscenter/archive/releases/2002/24/video/c/ (http://hubblesite.org/newscenter/archive/releases/2002/24/video/c/). A sequence of Hubble and Chandra Space Telescope images of the central regions of the Crab Nebula have been assembled into a very brief movie accompanied by animation showing how the pulsar affects its environment; it comes with some useful background material (40:06).

Gamma-Ray Bursts

Gamma-Ray Bursts: The Biggest Explosions Since the Big Bang!: https://www.youtube.com/watch?v=ePo_EdgV764 (https://www.youtube.com/watch?v=ePo_EdgV764). Edo Berge in a popular-level lecture at Harvard (58:50).

Gamma-Ray Bursts: Flashes in the Sky: https://www.youtube.com/watch?v=23EhcAP3O8Q (https://www.youtube.com/watch?v=23EhcAP3O8Q). American Museum of Natural History Science Bulletin on the *Swift* satellite (5:59).

Overview Animation of Gamma-Ray Burst: http://news.psu.edu/video/296729/2013/11/27/overview-animation-gamma-ray-burst (http://news.psu.edu/video/296729/2013/11/27/overview-animation-gamma-ray-burst). Brief Animation of what causes a long-duration gamma-ray burst (0:55).

Collaborative Group Activities

A. Someone in your group uses a large telescope to observe an expanding shell of gas. Discuss what measurements you could make to determine whether you have discovered a planetary nebula or the remnant of a supernova explosion.

B. The star Sirius (the brightest star in our northern skies) has a white-dwarf companion. Sirius has a mass of about 2 M_{Sun} and is still on the main sequence, while its companion is already a star corpse. Remember that a white dwarf can't have a mass greater than 1.4 M_{Sun}. Assuming that the two stars formed at the same time, your group should discuss how Sirius could have a white-dwarf companion. Hint: Was the initial mass of the white-dwarf star larger or smaller than that of Sirius?

C. Discuss with your group what people today would do if a brilliant star suddenly became visible during the daytime? What kind of fear and superstition might result from a supernova that was really bright in our skies? Have your group invent some headlines that the tabloid newspapers and the less responsible web news outlets would feature.

D. Suppose a supernova exploded only 40 light-years from Earth. Have your group discuss what effects there may be on Earth when the radiation reaches us and later when the particles reach us. Would there be any way to protect people from the supernova effects?

E. When pulsars were discovered, the astronomers involved with the discovery talked about finding "little green men." If you had been in their shoes, what tests would you have performed to see whether such a pulsating source of radio waves was natural or the result of an alien intelligence? Today, several groups around the world are actively searching for possible radio signals from intelligent civilizations. How might you expect such signals to differ from pulsar signals?

F. Your little brother, who has not had the benefit of an astronomy course, reads about white dwarfs and neutron stars in a magazine and decides it would be fun to go near them or even try to land on them. Is this a good idea for future tourism? Have your group make a list of reasons it would not be safe for children (or adults) to go near a white dwarf and a neutron star.

G. A lot of astronomers' time and many instruments have been devoted to figuring out the nature of gamma-ray bursts. Does your group share the excitement that astronomers feel about these mysterious high-energy events? What are some reasons that people outside of astronomy might care about learning about gamma-ray bursts?

Exercises

Review Questions

1. How does a white dwarf differ from a neutron star? How does each form? What keeps each from collapsing under its own weight?

2. Describe the evolution of a star with a mass like that of the Sun, from the main-sequence phase of its evolution until it becomes a white dwarf.

3. Describe the evolution of a massive star (say, 20 times the mass of the Sun) up to the point at which it becomes a supernova. How does the evolution of a massive star differ from that of the Sun? Why?

4. How do the two types of supernovae discussed in this chapter differ? What kind of star gives rise to each type?

5. A star begins its life with a mass of 5 M_{Sun} but ends its life as a white dwarf with a mass of 0.8 M_{Sun}. List the stages in the star's life during which it most likely lost some of the mass it started with. How did mass loss occur in each stage?

6. If the formation of a neutron star leads to a supernova explosion, explain why only three of the hundreds of known pulsars are found in supernova remnants.

7. How can the Crab Nebula shine with the energy of something like 100,000 Suns when the star that formed the nebula exploded almost 1000 years ago? Who "pays the bills" for much of the radiation we see coming from the nebula?

8. How is a nova different from a type Ia supernova? How does it differ from a type II supernova?

9. Apart from the masses, how are binary systems with a neutron star different from binary systems with a white dwarf?

10. What observations from SN 1987A helped confirm theories about supernovae?

11. Describe the evolution of a white dwarf over time, in particular how the luminosity, temperature, and radius change.

12. Describe the evolution of a pulsar over time, in particular how the rotation and pulse signal changes over time.

13. How would a white dwarf that formed from a star that had an initial mass of 1 M_{Sun} be different from a white dwarf that formed from a star that had an initial mass of 9 M_{Sun}?

14. What do astronomers think are the causes of longer-duration gamma-ray bursts and shorter-duration gamma-ray bursts?

15. How did astronomers finally solve the mystery of what gamma-ray bursts were? What instruments were required to find the solution?

Thought Questions

16. Arrange the following stars in order of their evolution:

A. A star with no nuclear reactions going on in the core, which is made primarily of carbon and oxygen.
B. A star of uniform composition from center to surface; it contains hydrogen but has no nuclear reactions going on in the core.
C. A star that is fusing hydrogen to form helium in its core.
D. A star that is fusing helium to carbon in the core and hydrogen to helium in a shell around the core.
E. A star that has no nuclear reactions going on in the core but is fusing hydrogen to form helium in a shell around the core.

17. Would you expect to find any white dwarfs in the Orion Nebula? (See The Birth of Stars and the Discovery of Planets outside the Solar System to remind yourself of its characteristics.) Why or why not?

18. Suppose no stars more massive than about 2 M_{Sun} had ever formed. Would life as we know it have been able to develop? Why or why not?

19. Would you be more likely to observe a type II supernova (the explosion of a massive star) in a globular cluster or in an open cluster? Why?

20. Astronomers believe there are something like 100 million neutron stars in the Galaxy, yet we have only found about 2000 pulsars in the Milky Way. Give several reasons these numbers are so different. Explain each reason.

21. Would you expect to observe every supernova in our own Galaxy? Why or why not?

22. The Large Magellanic Cloud has about one-tenth the number of stars found in our own Galaxy. Suppose the mix of high- and low-mass stars is exactly the same in both galaxies. Approximately how often does a supernova occur in the Large Magellanic Cloud?

23. Look at the list of the nearest stars in Appendix I. Would you expect any of these to become supernovae? Why or why not?

24. If most stars become white dwarfs at the ends of their lives and the formation of white dwarfs is accompanied by the production of a planetary nebula, why are there more white dwarfs than planetary nebulae in the Galaxy?

25. If a 3 and 8 M_{Sun} star formed together in a binary system, which star would:

A. Evolve off the main sequence first?
B. Form a carbon- and oxygen-rich white dwarf?
C. Be the location for a nova explosion?

26. You have discovered two star clusters. The first cluster contains mainly main-sequence stars, along with some red giant stars and a few white dwarfs. The second cluster also contains mainly main-sequence stars, along with some red giant stars, and a few neutron stars—but no white dwarf stars. What are the relative ages of the clusters? How did you determine your answer?

27. A supernova remnant was recently discovered and found to be approximately 150 years old. Provide possible reasons that this supernova explosion escaped detection.

28. Based upon the evolution of stars, place the following elements in order of least to most common in the Galaxy: gold, carbon, neon. What aspects of stellar evolution formed the basis for how you ordered the elements?

29. What observations or types of telescopes would you use to distinguish a binary system that includes a main-sequence star and a white dwarf star from one containing a main-sequence star and a neutron star?

30. How would the spectra of a type II supernova be different from a type Ia supernova? Hint: Consider the characteristics of the objects that are their source.

Figuring for Yourself

31. The ring around SN 1987A (Figure 23.12) initially became illuminated when energetic photons from the supernova interacted with the material in the ring. The radius of the ring is approximately 0.75 light-year from the supernova location. How long after the supernova did the ring become illuminated?

32. What is the acceleration of gravity (g) at the surface of the Sun? (See Appendix E for the Sun's key characteristics.) How much greater is this than g at the surface of Earth? Calculate what you would weigh on the surface of the Sun. Your weight would be your Earth weight multiplied by the ratio of the acceleration of gravity on the Sun to the acceleration of gravity on Earth. (Okay, we know that the Sun does not have a solid surface to stand on and that you would be vaporized if you were at the Sun's photosphere. Humor us for the sake of doing these calculations.)

33. What is the escape velocity from the Sun? How much greater is it than the escape velocity from Earth?

34. What is the average density of the Sun? How does it compare to the average density of Earth?

35. Say that a particular white dwarf has the mass of the Sun but the radius of Earth. What is the acceleration of gravity at the surface of the white dwarf? How much greater is this than g at the surface of Earth? What would you weigh at the surface of the white dwarf (again granting us the dubious notion that you could survive there)?

36. What is the escape velocity from the white dwarf in Exercise 23.35? How much greater is it than the escape velocity from Earth?

37. What is the average density of the white dwarf in Exercise 23.35? How does it compare to the average density of Earth?

38. Now take a neutron star that has twice the mass of the Sun but a radius of 10 km. What is the acceleration of gravity at the surface of the neutron star? How much greater is this than g at the surface of Earth? What would you weigh at the surface of the neutron star (provided you could somehow not become a puddle of protoplasm)?

39. What is the escape velocity from the neutron star in Exercise 23.38? How much greater is it than the escape velocity from Earth?

40. What is the average density of the neutron star in Exercise 23.38? How does it compare to the average density of Earth?

41. One way to calculate the radius of a star is to use its luminosity and temperature and assume that the star radiates approximately like a blackbody. Astronomers have measured the characteristics of central stars of planetary nebulae and have found that a typical central star is 16 times as luminous and 20 times as hot (about 110,000 K) as the Sun. Find the radius in terms of the Sun's. How does this radius compare with that of a typical white dwarf?

42. According to a model described in the text, a neutron star has a radius of about 10 km. Assume that the pulses occur once per rotation. According to Einstein's theory of relatively, nothing can move faster than the speed of light. Check to make sure that this pulsar model does not violate relativity. Calculate the rotation speed of the Crab Nebula pulsar at its equator, given its period of 0.033 s. (Remember that distance equals velocity × time and that the circumference of a circle is given by $2\pi R$).

43. Do the same calculations as in Exercise 23.42 but for a pulsar that rotates 1000 times per second.

44. If the Sun were replaced by a white dwarf with a surface temperature of 10,000 K and a radius equal to Earth's, how would its luminosity compare to that of the Sun?

45. A supernova can eject material at a velocity of 10,000 km/s. How long would it take a supernova remnant to expand to a radius of 1 AU? How long would it take to expand to a radius of 1 light-years? Assume that the expansion velocity remains constant and use the relationship: $\text{expansion time} = \frac{\text{distance}}{\text{expansion velocity}}$.

46. A supernova remnant was observed in 2007 to be expanding at a velocity of 14,000 km/s and had a radius of 6.5 light-years. Assuming a constant expansion velocity, in what year did this supernova occur?

47. The ring around SN 1987A (Figure 23.12) started interacting with material propelled by the shockwave from the supernova beginning in 1997 (10 years after the explosion). The radius of the ring is approximately 0.75 light-year from the supernova location. How fast is the supernova material moving, assume a constant rate of motion in km/s?

48. Before the star that became SN 1987A exploded, it evolved from a red supergiant to a blue supergiant while remaining at the same luminosity. As a red supergiant, its surface temperature would have been approximately 4000 K, while as a blue supergiant, its surface temperature was 16,000 K. How much did the radius change as it evolved from a red to a blue supergiant?

49. What is the radius of the progenitor star that became SN 1987A? Its luminosity was 100,000 times that of the Sun, and it had a surface temperature of 16,000 K.

50. What is the acceleration of gravity at the surface of the star that became SN 1987A? How does this *g* compare to that at the surface of Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.

51. What was the escape velocity from the surface of the SN 1987A progenitor star? How much greater is it than the escape velocity from Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.

52. What was the average density of the star that became SN 1987A? How does it compare to the average density of Earth? The mass was 20 times that of the Sun and the radius was 41 times that of the Sun.

53. If the pulsar shown in Figure 23.16 is rotating 100 times per second, how many pulses would be detected in one minute? The two beams are located along the pulsar’s equator, which is aligned with Earth.