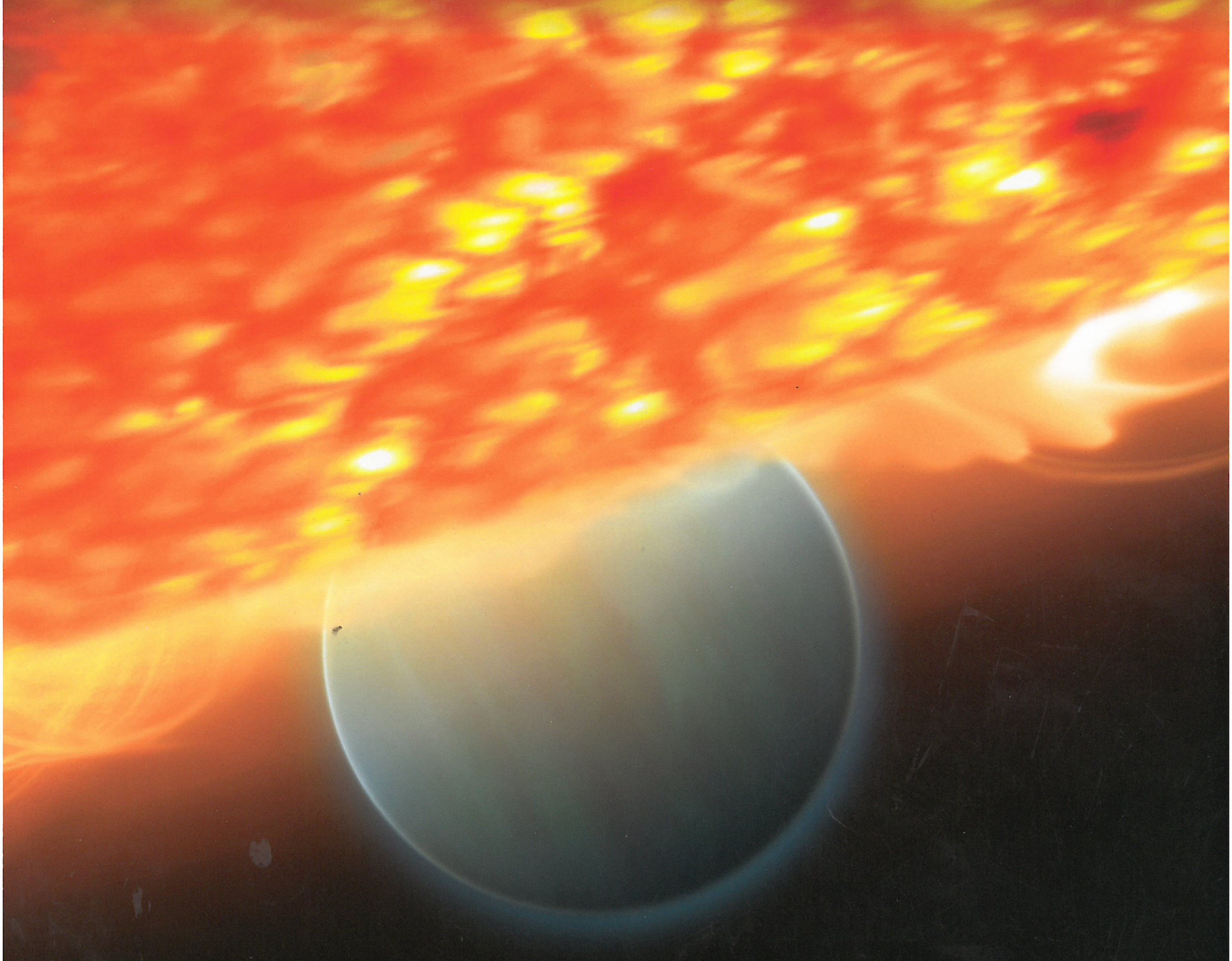
MICHAEL SEEDS DANA BACKMAN



HORIZONS

EXPLORING THE UNIVERSE 12e

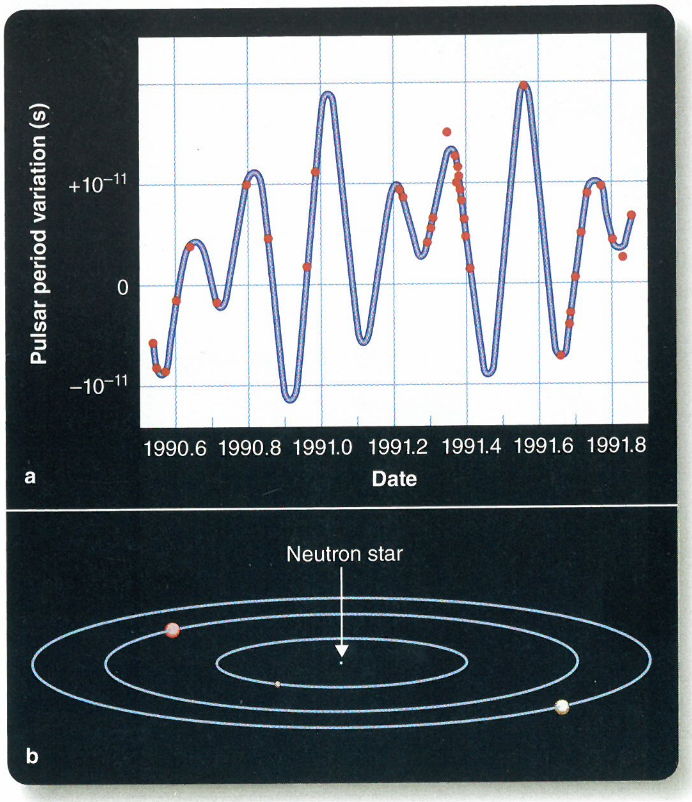


Figure 11-11

(a) The dots in this graph are observations showing that the period of pulsar PSR 1257+12 varies from its average value by a fraction of a billionth of a second. The blue line shows the variation that would be produced by planets orbiting the pulsar. (b) As the planets orbit the pulsar, they cause it to wobble by less than 800 km, a distance that is invisibly small in this diagram. (Adapted from data by Alexander Wolszczan)

further confirming the existence of the planets. In fact, later data revealed the presence of a third planet with only 1/40 the mass of Earth, about twice the mass of Earth's moon. This illustrates the astonishing precision of studies based on pulsar timing.

Astronomers wonder how a neutron star can have planets. The three planets that orbit PSR B1257+12 are closer to the pulsar than Venus is to the sun. Any planets that orbited a star that closely would have been absorbed or vaporized when the star expanded to become a supergiant. Furthermore, the supernova explosion would have suddenly reduced the mass of the star and allowed any orbiting planets to escape from their orbits. So how can planets exist there? One suggestion is that these planets are the remains of a stellar companion that was devoured by the neutron star. In fact, PSR B1257+12 spins very fast (161 pulses per second), suggesting that it was spun up in a binary system. However, the Spitzer Space Telescope observing in the infrared has detected a ring of gas and dust around a different rapidly spinning neutron star. If supernova explosions can leave such rings of material behind, then perhaps planets can form from the accumulation of matter in the rings.

PSR B1257+12 is not unique. Another planet has been found orbiting a pulsar that is part of a binary system with a white dwarf in a very old star cluster. The characteristics of this system indicate, however, that the planet may have been captured rather than being debris from the supernova explosion that made the neutron star. Planets probably orbit other neutron stars, and small shifts in the timing of the pulses may eventually reveal their presence.

You can imagine what these worlds might be like. Formed from the remains of elderly stars, they might have chemical compositions richer in heavy elements than Earth. You can imagine visiting these worlds, landing on their surfaces, and hiking across their valleys and mountains. Above you, the neutron star would glitter in the sky, a tiny point of light.

SCIENTIFIC ARGUMENT

Why are neutron stars easier to detect at X-ray wavelengths?
This argument draws together a number of ideas you know from previous chapters. First, recall that a neutron star is very hot because of the heat released when it contracts to a radius of 10 km. It could easily have a surface temperature of 1,000,000 K, and Wien's law (look back to Chapter 6) tells you that such an object will radiate most intensely at a very short wavelength—X-rays and gamma rays. Normal stars are much cooler and emit only weak X-rays unless they have hot accretion disks. At visual wavelengths, stars are bright, and neutron stars are faint, but at X-ray wavelengths, the neutron stars stand out from the crowd.

Now build a new argument as if you were seeking funds for a research project. **What observations would you make to determine whether a newly discovered pulsar was young or old, single or a member of a binary system, alone or accompanied by planets?**

11-2 Black Holes

YOU HAVE NOW STUDIED white dwarfs and neutron stars, two of the three end states of dying stars. Now it's time to think about the third end state—black holes.

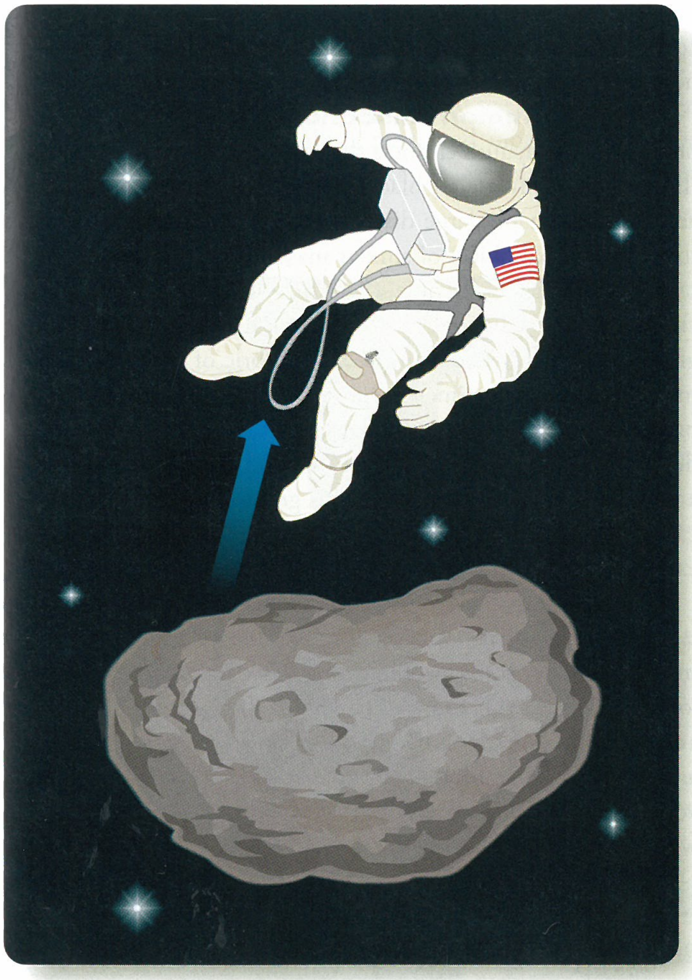
Although the physics of black holes is difficult to discuss without using sophisticated mathematics, simple logic is sufficient to predict that they should exist. The problem is to confirm that they are real. What objects observed in the heavens could be real black holes? More difficult than the search for neutron stars, the quest for black holes has nevertheless met with success.

You can begin by considering a simple question. How fast must an object travel to escape from the surface of a celestial body?

Escape Velocity

Suppose you threw a baseball straight up. How fast must you throw it if it is not to come down? Of course, gravity will always pull back on the ball, slowing it, but if the ball is traveling fast enough to start with, it will never come to a stop and fall back. Such a ball will escape from Earth.

In Chapter 4 you learned that the escape velocity is the initial velocity an object needs to escape from a celestial body (■ Figure 11-12). Whether you are discussing a baseball leaving Earth or a particle escaping a collapsing star, escape velocity depends on two things, the mass of the celestial body and the distance from the center of mass to the escaping object. If the celestial body has a large mass, its gravity is strong, and you need a high velocity to escape, but if you begin your journey farther from the center of mass, the velocity needed is less. For example, to escape from Earth, a spaceship would have to leave Earth's surface at 11 km/s (25,000 mph), but if you could launch spaceships from the top of a tower 1000 miles high, the escape velocity would be only 10 km/s (22,000 mph).



■ Figure 11-12

Escape velocity, the velocity needed to escape from a celestial body, depends on mass. The escape velocity at the surface of a very small body would be so low you could jump into space. Earth's escape velocity is much larger, about 11 km/s (25,000 mph).

If you could make an object massive enough or small enough, its escape velocity could be greater than the speed of light. Relativity says that nothing can travel faster than the speed of light, so even photons, which have no mass, would be unable to escape. Such a small, massive object could never be seen because light could not leave it.

Long before Einstein and relativity, the Reverend John Mitchell, a British gentleman astronomer, realized this particular consequence of Newton's laws of gravity and motion. In 1783, he pointed out that an object 500 times the radius of the sun but of the same density would have an escape velocity greater than the speed of light. Then, "all light emitted from such a body would be made to return towards it." Mitchell didn't know it, but he was talking about a black hole.

Schwarzschild Black Holes

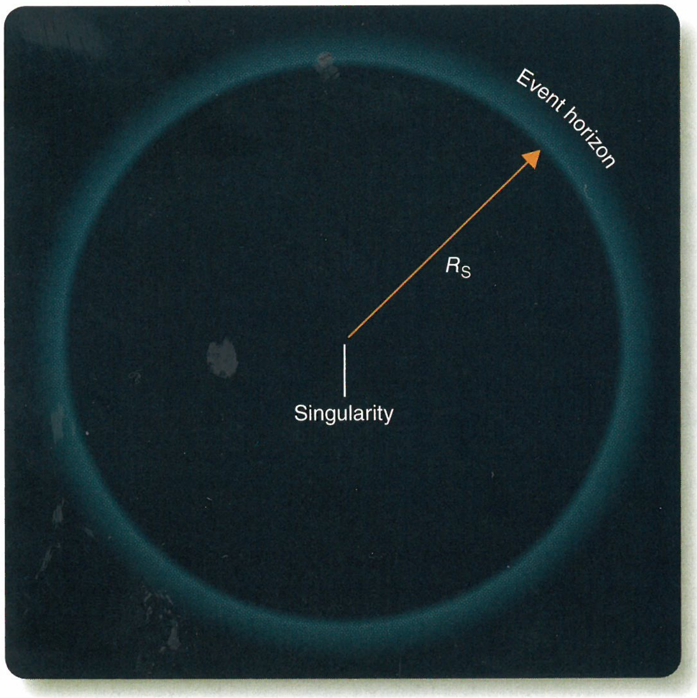
If the core of a star contains more than 3 solar masses when it collapses, no force can stop it. It cannot stop collapsing when it reaches the density of a white dwarf because degenerate electrons cannot support that weight, and it cannot stop when it reaches the density of a neutron star because not even degenerate neutrons can support that weight. No force remains to stop the object from collapsing to zero radius.

As an object collapses, its density and the strength of its surface gravity increase. If an object collapses to zero radius, its density and gravity become infinite. Mathematicians call such a point a **singularity,** but in physical terms it is difficult to imagine an object of zero radius. Some theorists believe that a singularity is impossible and that the laws of quantum physics must somehow halt the collapse at some subatomic radius roughly 10^{20} times smaller than a proton. Astronomically, it seems to make little difference.

If the contracting core of a star becomes small enough, the escape velocity in the region of space around it is so large that no light can escape. This means you can receive no information about the object or about the region of space near it. Because it emits no light, such a region is called a **black hole.** If the core of an exploding star collapsed into a black hole, the expanding outer layers of the star could produce a supernova remnant, but the core would vanish without a trace.

To understand black holes, you should consider relativity. In 1916, Albert Einstein published a mathematical theory of space and time that became known as the general theory of relativity. Einstein treated space and time as a single entity called space-time. His equations showed that gravity could be described as a curvature of space-time, and almost immediately the astronomer Karl Schwarzschild found a way to solve Einstein's equations to describe the gravitational field around a single, nonrotating, electrically neutral lump of matter. That solution contained the first general relativistic description of a black hole, and nonrotating, electrically neutral black holes are now known as Schwarzschild black holes. In recent decades, theorists such as Roy Kerr and Stephen Hawking have found ways to apply the sophisticated mathematical equations of the general theory of relativity and quantum mechanics to describe charged, rotating black holes. For this discussion, the differences are minor, and you may proceed as if all black holes were Schwarzschild black holes.

Schwarzschild's solution shows that if matter is packed into a small enough volume, then space-time curves back on itself. Objects can follow paths that lead into the black hole, but no path leads out, so nothing can escape. Because not even light can escape, the inside of the black hole is totally beyond the view of an outside observer. The **event horizon** is the boundary between the isolated volume of space-time and the rest of the universe, and the radius of the event horizon is called the **Schwarzschild radius, R_S**. A collapsing stellar core must shrink inside its Schwarzschild radius to become a black hole (■ Figure 11-13).



■ Figure 11-13

A black hole forms when an object collapses to a small size (perhaps to a singularity) and the escape velocity becomes so great light cannot escape. The boundary of the black hole is called the event horizon because any event that occurs inside is invisible to outside observers. The radius of the black hole R_S is the Schwarzschild radius.

Although Schwarzschild's work was highly mathematical, his conclusion is quite simple. The Schwarzschild radius depends only on the mass of the object:

$$R_S = \frac{2GM}{c^2}$$

In this simple formula, G is the gravitational constant, M is the mass (in kilograms), and c is the speed of light (in meters per second). A bit of arithmetic shows that a 1-solar-mass black hole has a Schwarzschild radius of 3 km, a 10-solar-mass black hole has a Schwarzschild radius of 30 km, and so on.

Every object has a Schwarzschild radius determined by its mass, but not every object is a black hole. For example, Earth has a Schwarzschild radius of about 1 cm, meaning that it could become a black hole if you squeezed it smaller than that radius. Fortunately, Earth will not collapse spontaneously to become a black hole because the strength of the rock and metal in its interior is sufficient to support its weight. Only extinguished stellar cores more massive than about 3 solar masses can form black holes under the sole influence of their own gravity.

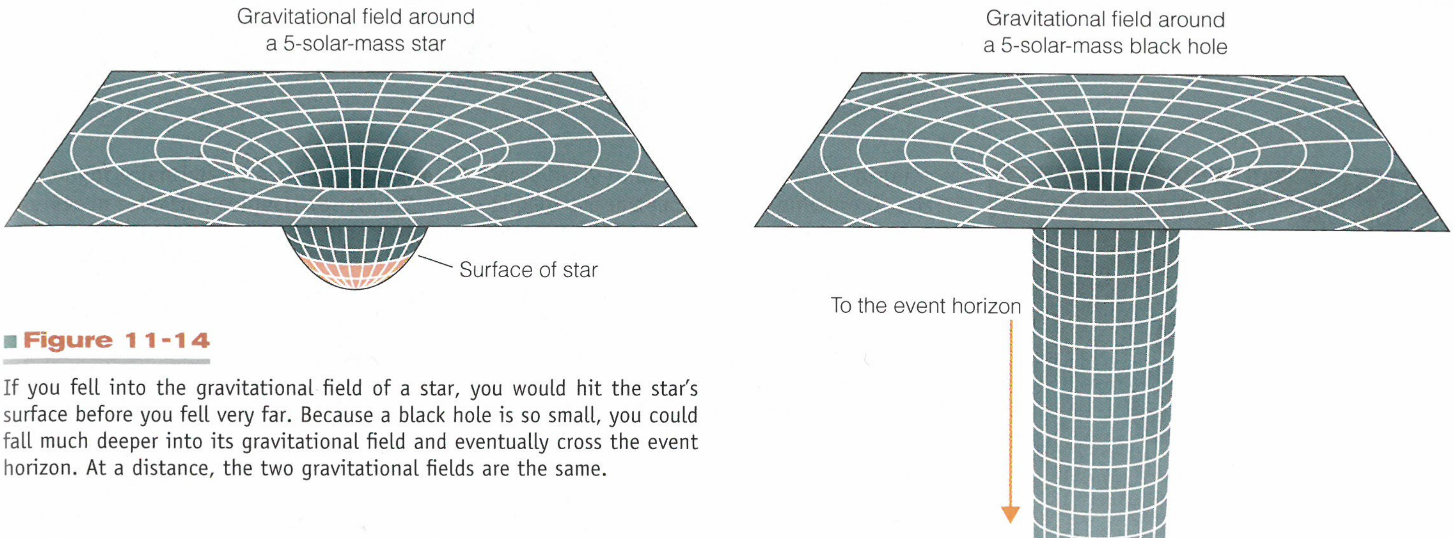
It is a **Common Misconception** to think of black holes as giant vacuum cleaners that will eventually suck in everything in the universe. A black hole is just a gravitational field, and at a reasonably large distance its gravity is no greater than that of a normal object of similar mass. If the sun were replaced by a 1-solar-mass black hole, the orbits of the planets would not change at all. ■ Figure 11-14 illustrates this by representing gravitational fields as curvature of the fabric of space-time. Normal uncurved space-time is represented by a flat plane, and the presence of a mass such as a star curves the plane to produce a depression. The extreme curvature around a black hole produces a deep funnel-shaped surface in this graphic representation. You can see from the graphs that the gravity of a black hole becomes extreme only when you approach close to it.

Now you can check off another **Common Misconception** that may strike you as silly. Because of special effects in movies and TV, some people think black holes should actually look like funnels. Of course, the graphs of the strength of gravity around black holes look like funnels, but black holes themselves are not shaped like funnels. If you could approach a black hole, you might be able to see hot gas swirling inward, but you wouldn't be able to see the black hole itself.

Leaping into a Black Hole

Before you can search for real black holes, you need to understand what theory predicts about a black hole. To explore that idea, you can imagine leaping, feet first, into a Schwarzschild black hole.

If you were to leap into a black hole of a few solar masses from a distance of 1 AU, the gravitational pull would not be very large, and you would fall slowly at first. Of course, the longer you fell and the closer you came to the center, the faster you would



■ Figure 11-14

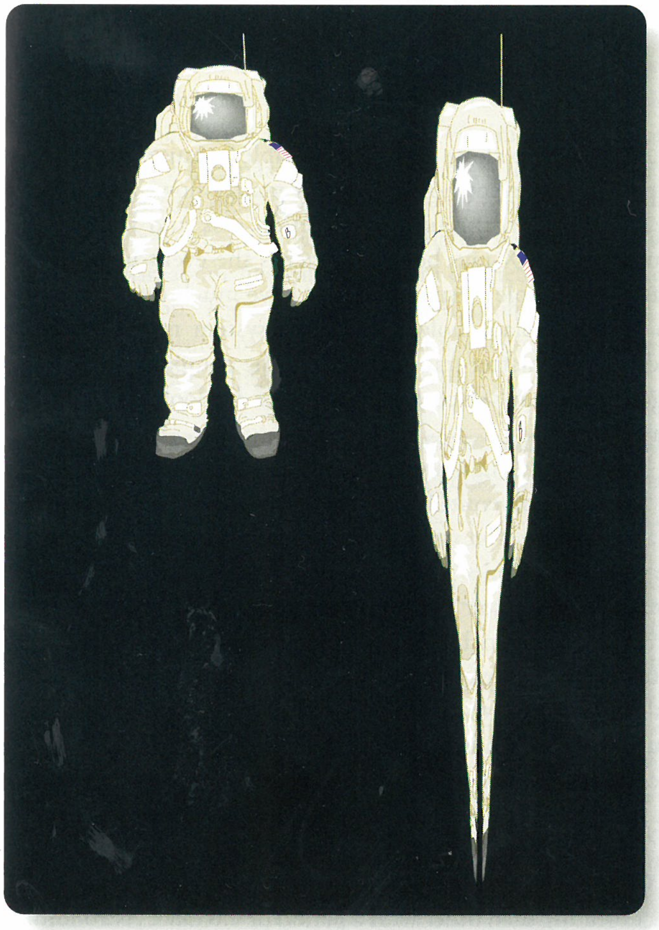
If you fell into the gravitational field of a star, you would hit the star's surface before you fell very far. Because a black hole is so small, you could fall much deeper into its gravitational field and eventually cross the event horizon. At a distance, the two gravitational fields are the same.

travel. Your wristwatch would tell you that you fell for about two months by the time you reached the event horizon.

Your friends who stayed behind would see something different. They would see you falling more and more slowly as you came closer to the event horizon because, as explained by general relativity, time slows down in curved space-time. This is known as **time dilation.** In fact, your friends would never actually see you cross the event horizon. To them you would fall more and more slowly until you seemed hardly to move. Generations later, your descendants could focus their telescopes on you and see you still inching closer to the event horizon. You, however, would have sensed no slowdown and would conclude that you had reached the event horizon after about two months.

Another relativistic effect would make it difficult to see you with normal telescopes. As light travels out of a gravitational field, it loses energy, and its wavelength grows longer. This is known as the **gravitational redshift.** Although you would notice no effect as you fell toward the black hole, your friends would need to observe at longer and longer wavelengths to detect you.

While these relativistic effects seem merely peculiar, other effects would be quite unpleasant. If you were falling feet first, you would feel your feet, which would be closer to the black hole, being pulled in more strongly than your head. This is a tidal force, and at first it would be minor. But as you got closer to the black hole, the tidal force would become very large. Another tidal force would compress you as both your left and your right side fell toward the center of the black hole. For any black hole with a mass like that of a star, the tidal forces would crush you sideways and stretch you lengthwise long before you reached the event horizon (■ Figure 11-15). The friction from



■ Figure 11-15

Leaping feet-first into a black hole. A person of normal proportions (left) would be distorted by tidal forces (right) long before reaching the event horizon around a typical black hole of stellar mass. Tidal forces would stretch the body lengthwise while compressing it laterally. Friction from this distortion would heat the body to high temperatures.

How Do We Know? 11-2

Checks on Fraud in Science

How do you know scientists aren't just making stuff up? The unwritten rules of science make fraud difficult, and the way scientists publish their research makes it almost impossible. Scientists depend on each other to be honest, but they also double-check everything.

For example, all across North America, black-capped chickadees sing the same quick song. Some people say it sounds like *Chick-a-dee-dee-dee,* but others say it sounds like *Hey-sweetie-sweetie-sweetie.* You could invent tables of data and publish a paper reporting that you had recorded chickadees around Ash Lake in northern Minnesota that sing a backward song: *Sweetie-sweetie-sweetie-hey.* Experts on brain development and animal learning would be amazed, and your research might secure you praise from your colleagues, a job offer at a prestigious university, or a generous grant—but only if you could get away with it.

The first step in your scheme would be to publish your results in a scientific journal. Because the journal's reputation rests on the accuracy of the papers it publishes, the editor sends all submitted papers to one or more experts for peer review. Those world experts on chickadees would almost certainly notice things wrong with your made-up data tables. On their recommendation, the editor would probably refuse to publish your paper.

Even if your faked data fooled the peer reviewers, you would probably be found out once the paper was published. Experts on bird song would read your paper and flock to Ash Lake to study the bird songs themselves. By the next spring, you would be found out—and the journal would be forced to publish an embarrassing retraction of your article.

One of the rules of science is that good results must be repeatable. Scientists routinely repeat the work of others, not only to check the results but as a way to start a new research topic. When someone calls a news conference and announces a new discovery, other scientists begin asking, "How does this fit with other observations? Has this been checked? Has this been peer-reviewed?" Until a result has been published in a peer-reviewed journal, scientists treat it with extra care.

Fraud isn't unheard of in science. But because of peer review and the requirement of repeatability in science, bad research, whether the result of carelessness or fraud, is usually exposed quickly.

Chickadees always sing the same song. Hey-Sweetie-Sweetie-Sweetie. (Steve and Dave Maslowski/ Photo Researchers, Inc.)

such severe distortions of your body would heat you to millions of degrees, and you would emit X-rays and gamma rays. (Needless to say, this would render you inoperative as a thoughtful observer.)

Some people have suggested that it is possible to travel through the universe by jumping into a black hole in one place and popping out of another somewhere far across space. That might make for good science fiction, but tidal forces would make it an unpopular form of transportation even if it worked. You would certainly lose your luggage.

Your imaginary leap into a black hole is not frivolous. You now know how to find a black hole: Look for a strong source of X-rays. It may be a black hole into which matter is falling and being heated.

The Search for Black Holes

Do black holes really exist? The first X-ray telescopes reached orbit in the 1970s, and that allowed astronomers to begin searching for evidence of black holes. They tried to find one or more objects that were obviously black holes. That very difficult search is a good illustration of how the unwritten rules of science help scientists understand nature (**How Do We Know? 11-2**).

A black hole alone is totally invisible because nothing can escape from its event horizon, but if matter flows into a black hole, it will whirl through an accretion disk and become hot enough to emit X-rays before it reaches the event horizon. An isolated black hole in space will not have much matter flowing into it, but a black hole in a binary system might receive a steady flow of matter transferred from the companion star. This suggests you can search for black holes by looking closely at X-ray binaries.

Some X-ray binaries such as Hercules X-1 contain a neutron star, and they will emit X-rays much as would a binary containing a black hole. You can tell the difference in two ways. If the compact object emits pulses, you know it is a neutron star because the neutron star has a solid surface on which hot spots and beam sources are anchored and sweep across Earth's view as the neutron star spins (page 231). With no solid surface, a black hole would not be able to emit an extended series of regular pulses. Another clue depends on the mass of the object. If the mass of the compact object is greater than about 3 solar masses, it cannot be a neutron star; it must be a black hole.

The first X-ray binary suspected of harboring a black hole was Cygnus X-1. It contains a supergiant B0 star and a compact object orbiting each other with a period of 5.6 days. Astronomers

■ **Figure 11-16**

The X-ray source Cygnus X-1 consists of a supergiant B0 star and a compact object orbiting each other. Gas from the B0 star's stellar wind flows into the hot accretion disk around the compact object, and the X-rays astronomers detect come from the disk. (Don Dixon)

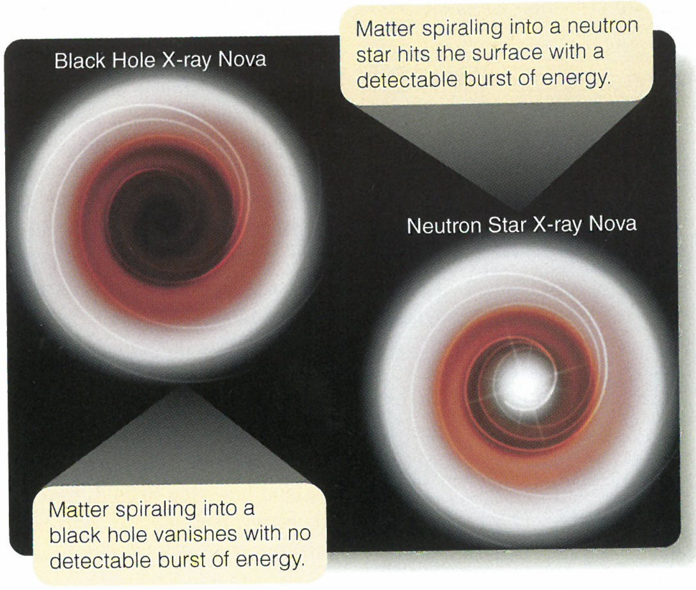
hypothesized that the X-rays are emitted by matter from the star flowing into the compact object. The object is invisible, but Doppler shifts in the spectrum reveal the motion of the B0 star around the center of mass of the binary. Years of observations and analysis show that the visible star has a mass of about 25 solar masses, and the compact object is about 10 times the mass of the sun, well above the maximum possible mass for a neutron star. Astronomers conclude that matter flows from the B0 star as a strong stellar wind, and much of that matter gets caught in a hot accretion disk about five times larger in diameter than the orbit of Earth's moon. The inner few hundred kilometers of the disk has a temperature of about 2 million degrees Kelvin—hot enough to radiate X-rays (■ Figure 11-16).

As X-ray telescopes have found many more X-ray-emitting objects, the list of black hole candidates has grown to dozens. A few of these objects are shown in ■ Table 11-1. Each candidate is a compact object surrounded by a hot accretion disk in a close X-ray binary system. Some of the binary systems are easier to analyze than others, but in the end, it has become clear that at least a few of these compact objects, including Cygnus X-1, are clearly too massive to be neutron stars and must be black holes. The evidence is now overwhelming: Black holes really do exist.

Another way to confirm that black holes are real is to search for evidence of their distinguishing characteristic—event horizons—and that search also has been successful. In one study, astronomers selected 12 X-ray binary systems, six of which seemed

■ **Table 11-1 | Nine Black Hole Candidates**

Object	Location	Companion Star	Orbital Period	Mass of Compact Object
Cygnus X-1	Cygnus	B0 supergiant	5.6 days	10 $M_\odot$
LMC X-3	Dorado	B3 main-sequence	1.7 days	~10 $M_\odot$
A0620-00	Monocerotis	K main-sequence	7.75 hours	10 ± 5 $M_\odot$
V404 Cygni	Cygnus	K main-sequence	6.47 days	12 ± 2 $M_\odot$
GRO J1655-40	Scorpius	F–G main-sequence	2.61 days	6.9 ± 1 $M_\odot$
QZ Vul	Vulpecula	K main-sequence	8 hours	10 ± 4 $M_\odot$
4U 1543-47	Lupus	A main-sequence	1.123 days	2.7–7.5 $M_\odot$
V4641 Sgr	Sagittarius	B supergiant	2.81678 days	8.7–11.7 $M_\odot$
XTE J1118+480	Ursa Major	K main-sequence	0.170113 days	>6 $M_\odot$



■ Figure 11-17

Gas spiraling into an accretion disk grows hot, and as it nears the central object, a strong gravitational redshift makes it appear redder and dimmer. Systems containing a neutron star emit bursts of energy when the gas hits the surface of the neutron star, but such bursts are not seen for systems containing black holes. In those systems, the matter vanishes as it approaches the event horizon. This is direct observational evidence of an event horizon around black holes. (NASA/CXC/M. Weiss)

to contain neutron stars and six of which were thought to contain black holes. Using X-ray telescopes, the astronomers monitored the systems, watching for telltale flares of energy as blobs of matter fell into the accretion disks and spiraled inward. In the six systems thought to contain neutron stars, the astronomers could detect final bursts of energy when the blobs of matter finally impacted the surfaces of the neutron stars. In the six systems suspected of containing black holes, however, the blobs of matter spiraled inward through the accretion disks and vanished without final bursts of energy. Evidently, those blobs of matter became undetectable as they approached the event horizons (■ Figure 11-17). This is dramatic evidence that event horizons are real.

The evidence shows that black holes really do exist. The problem now is to understand how these objects interact with the matter flowing into them through accretion disks to produce high-energy jets and outbursts.

SCIENTIFIC ARGUMENT

If relativistic effects slow time and prevent you from seeing matter cross the event horizon, how can infalling matter disappear without a trace?

This argument brings together observations and theory. Astronomers observed flares when matter hit the surfaces of neutron stars, but observed no flares when matter fell into a black hole. Although time slows near the event horizon, remember the gravitational red shift. Hot matter flowing into a black hole can emit X-rays, but as the matter nears the event horizon, the gravitational red shift lengthens the wavelengths dramatically. The matter vanishes, not because you see it cross the event horizon but because its photons are shifted to undetectably long wavelengths.

Now build a new argument to review a basic principle. **Why does matter become hot as it falls into a black hole?**

11-3 Compact Objects with Disks and Jets

MATTER FLOWING ONTO A NEUTRON STAR or onto a black hole forms an accretion disk, and that can produce some surprising phenomena. Astronomers are just beginning to understand these peculiar effects.

Jets of Energy from Compact Objects

Observations show that some compact objects are emitting jets of gas and radiation in opposite directions. These jets are similar to the bipolar outflows ejected by protostars but much more powerful. You have seen in the X-ray images on page 231 that some young pulsars, including the Crab Nebula pulsar, are ejecting jets of highly excited gas. The Vela pulsar does the same (Figure 11-4). Systems containing black holes can also eject jets. The black hole candidate GRO J1655-40 has been observed at radio wavelengths sporadically ejecting oppositely directed jets at 92 percent the speed of light.

One of the most powerful examples of this process is an X-ray binary called SS 433. Its optical spectrum shows sets of spectral lines that are Doppler shifted by about one fourth the speed of light, with one set shifted to the red and one set shifted to the blue. Furthermore, the two sets of lines shift back and forth across each other with a period of 164 days. Astronomers recognized the combination of red and blue Doppler shifts as evidence of oppositely directed jets.

Apparently, SS 433 is a binary system in which a compact object (probably a black hole) pulls matter from its companion star and forms an extremely hot accretion disk. Jets of high-temperature gas blast away from the disk in beams aimed in opposite directions. As the disk precesses, it sweeps these beams around the sky once every 164 days, and telescopes on Earth detect light from gas carried outward in both beams. One beam produces a redshift, and the other produces a blueshift.

It's not clear how an accretion disk can produce jets. Accretion disks around neutron stars and black holes are very small, spin very fast, and grow very hot. Somehow the hot gas in the disk can emit powerful beams of gas and radiation along the disk's axis of rotation. You can recognize the geometry of SS 433 in the cover illustration for this chapter (page 226). The exact process isn't well understood, but it seems to involve magnetic fields that get caught in the accretion disk and are twisted into tightly wound tubes that squirt gas and radiation out of the disk and confine it in narrow beams. Such pairs of jets are a prototype that illustrates how the gravitational field around a compact object can produce powerful beams of radiation and matter. You will meet this phenomenon again in a later chapter when you study active galaxies.

Gamma-Ray Bursts

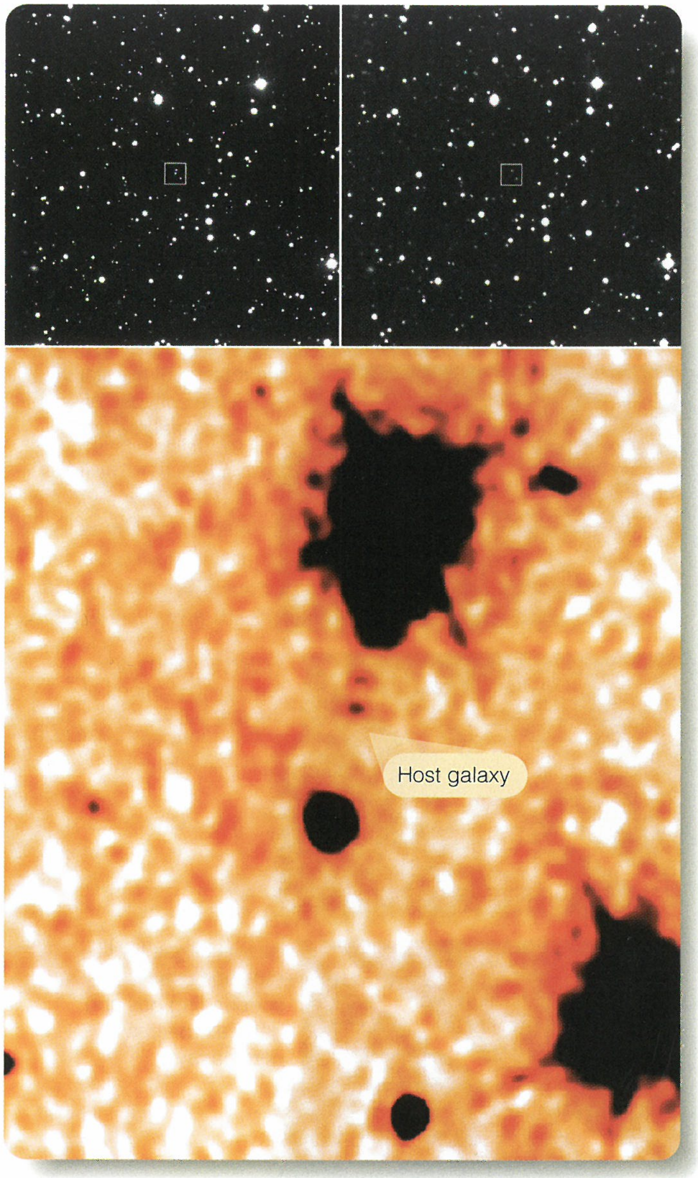
The Cold War played a minor part in the story of neutron stars and black holes. In 1963, a nuclear test ban treaty was signed, and by 1968, the United States was able to put a series of satellites in orbit to watch for nuclear tests that were violations of the treaty. A nuclear detonation emits gamma rays, so the satellites were designed to watch for bursts of gamma rays coming from Earth. The experts were startled when the satellites detected about one gamma-ray burst a day coming from space. When those data were finally declassified in 1973, astronomers realized that the bursts might be coming from neutron stars and black holes. These bursts are now known as **gamma-ray bursts** (abbreviated **GRBs**).

The Compton Gamma Ray Observatory (CGRO) reached orbit in 1991 and immediately began detecting gamma-ray bursts at the rate of a few a day. Its observations showed that the intensity of the gamma rays rises to a maximum in seconds and then fades away quickly; a burst is usually over in a few seconds to a minute.

Data from the CGRO also showed that the gamma-ray bursts were coming from all over the sky and not from any particular region. This helped astronomers eliminate some hypotheses. For example, there was a hypothesis that the gamma-ray bursts were being produced by relatively common events involving the stars in our galaxy, but these results eliminated that possibility. If the gamma-ray bursts were produced among stars in our galaxy, you would expect to see them most often along the Milky Way where there are lots of stars. That the bursts occurred all over the sky meant that they were being produced by rare events in distant galaxies.

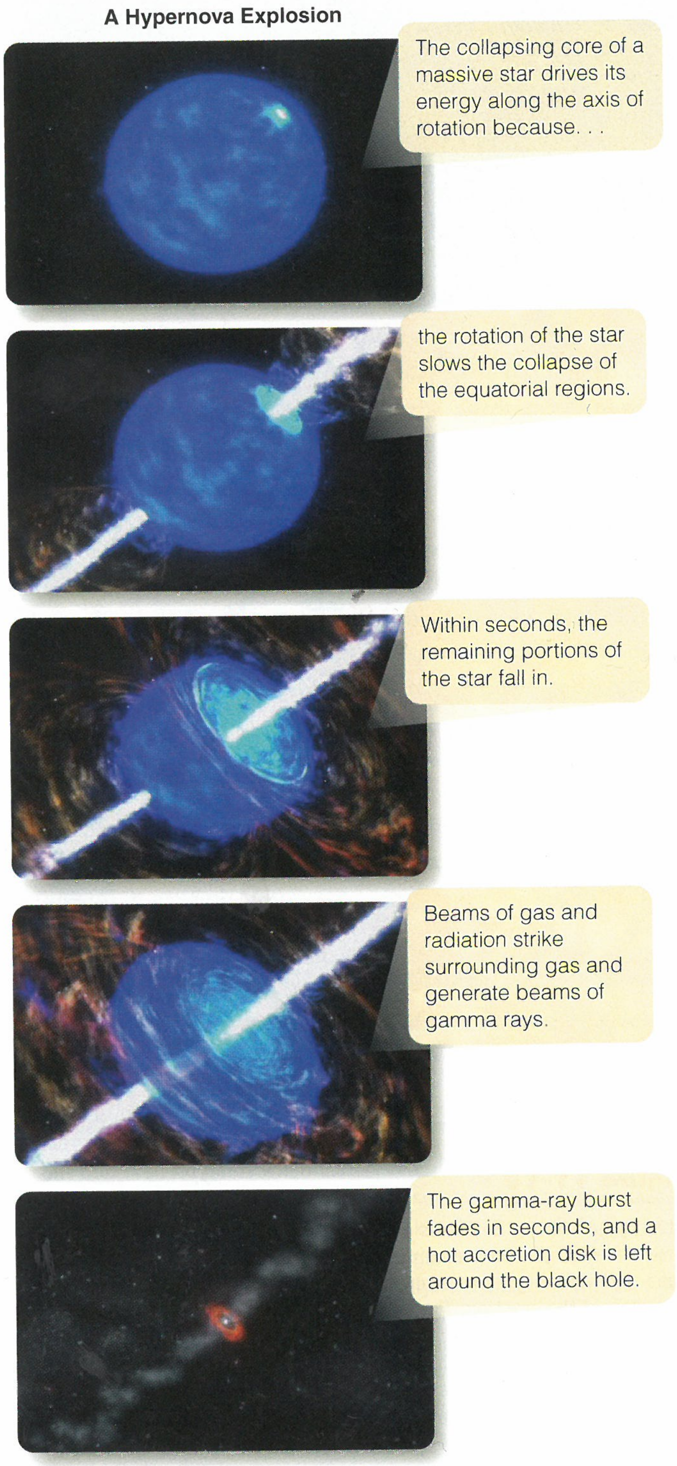
Gamma-ray bursts are hard to study because they occur without warning and fade so quickly, but starting in 1997, new satellites were put into orbit to detect gamma-ray bursts. Their data show that there are two kinds of gamma-ray bursts. Short bursts last less than 2 seconds, but longer bursts can go on for many seconds. Specialized space observatories now can detect bursts, quickly determine their location in the sky, and immediately alert astronomers on the ground. When telescopes on Earth swiveled to image the locations of the bursts, they detected fading glows that resembled supernovae (■ Figure 11-18), suggesting that long gamma-ray bursts are produced by a certain kind of supernova explosion.

Stellar interior models indicate that a star more massive than some upper limit of about 20 solar masses can exhaust its



■ **Figure 11-18**

Alerted by gamma-ray detectors on satellites, observers used one of the VLT 8.2-meter telescopes on a mountaintop in Chile to image the location of a gamma-ray burst only hours after the burst. The image at top left shows the fading glow of the eruption. The image at top right, recorded 13 years before, reveals no trace of an object at the location of the gamma-ray burst. (Top left and right: NASA/JPL-Caltech/P. Garnavich [Notre Dame]) The Hubble Space Telescope image at bottom was recorded a year later and reveals a very faint, distant galaxy at the location of the gamma-ray burst. (ESO and NASA) nuclear fuel and collapse directly into a black hole. Models show that the collapsing star would conserve angular momentum and spin very rapidly, slowing the collapse of the equatorial parts of the star. The poles of the star would fall in quickly, and that would focus beams of intense radiation and ejected gas that would blast out along the axis of rotation. Such an eruption has been called a **hypernova** (■ Figure 11-19). If one of those beams were pointed at Earth, it could produce a powerful gamma-ray burst. Evidently the long gamma-ray bursts are produced by hypernovae.


A Hypernova Explosion

The collapsing core of a massive star drives its energy along the axis of rotation because. . .

the rotation of the star slows the collapse of the equatorial regions.

Within seconds, the remaining portions of the star fall in.

Beams of gas and radiation strike surrounding gas and generate beams of gamma rays.

The gamma-ray burst fades in seconds, and a hot accretion disk is left around the black hole.

Short gamma-ray bursts, on the other hand, don't seem to be associated with hypernovae. Some repeat, and these repeating bursts seem to be produced by neutron stars with magnetic fields 100 times stronger than that in a normal neutron star. Dubbed **magnetars,** these objects can produce bursts of gamma rays when shifts in the magnetic field break the crust of the neutron stars—causing "starquakes"—and release large amounts of energy (■ Figure 11-20). The *Fermi Gamma-Ray Space Telescope,* launched in 2008, has detected a neutron star that has eruptions as often as 100 times in 20 minutes. Another magnetar produced a burst of gamma rays that reached Earth in 1998 and was strong enough to increase the ionization of Earth's upper atmosphere noticeably, disrupting radio communication worldwide.

Not all short gamma-ray bursts are produced by magnetars. Some bursts have occurred in parts of distant galaxies where you would not expect to find the young, massive stars that produce magnetars or hypernovae, and the afterglows don't resemble fading supernovae. These bursts may be produced by the merger of two neutron stars or a neutron star and a black hole that orbited each other, radiated orbital energy as gravitational radiation, and spiraled into each other. Such a collision would cause a violent explosion as the two objects merged to form a new, or larger, black hole. The gamma-ray burst and fading afterglow from a neutron star plus black hole merger should be different from that produced by the merger of two neutron stars. Astronomers are now working to distinguish between these two kinds of short gamma-ray bursts.

In 2008 the Swift orbiting telescope detected an intense gamma-ray burst that originated in a galaxy 7.5 billion light years from Earth. The burst was so powerful that for about one minute, its visual-wavelength component was bright enough to see with the unaided eye. If you had been looking directly at it, you would have seen it appear as a star slightly brighter than those in the Little Dipper. Another powerful gamma-ray burst detected by *Swift* in 2008 originated in a galaxy 12.2 billion light-years away. In spite of the distance, it was one of the brightest gamma-ray bursts ever detected. Astronomers suspect that these bursts were produced by hypernova collapses of massive stars in which one of the jets was aimed directly at Earth.

■ Figure 11-19

The collapse of the cores of extremely massive stars can produce hypernova explosions, which are thought to be the source of gamma-ray bursts longer than 2 seconds. (NASA/Skyworks Digital)

Figure 11-20

Some neutron stars appear to have magnetic fields up to 1000 times stronger than those in a normal neutron star. These magnetars can produce bursts of gamma rays when shifts in the magnetic field rupture the rigid crust of the neutron star. (NASA/CXC/M. Weiss)

Could a gamma-ray burst occur near Earth? The nearest known binary pulsar is only about 2000 ly from Earth. If a gamma-ray burst occurred at that distance, the gamma rays would shower Earth with radiation equivalent to a 10,000-megaton nuclear blast, comparable to a full-scale nuclear war between superpowers. (The largest single bombs ever made released less than a hundred megatons of energy.) The gamma rays could create enough nitric oxide in the atmosphere to produce intense acid rain and also would destroy the ozone layer, exposing life on Earth to deadly levels of solar ultraviolet radiation. Gamma-ray bursts can occur relatively near the Earth as often as every few hundred million years and could be one of the causes of the mass extinctions that show up in the fossil record.

Does it surprise you that such astonishing events as merging neutron stars and hypernovae produce something so common that gamma-ray telescopes observe one or more every day? Remember that these events are so powerful they can be detected over very great distances. There may be 30,000 neutron star binaries in each galaxy, and there are billions of galaxies within range of gamma-ray telescopes. Earthlings are treated to the entire observable universe's display of these cosmic catastrophes.

What Are We? Abnormal

Look around. What do you see? A table, a chair, a tree? It's all normal stuff. The world we live in is familiar and comfortable, but astronomy reveals that "normal" isn't normal at all. The universe is, for the most part, utterly unlike anything you have ever experienced.

Throughout the universe, gravity makes clouds of gas form stars, and in turn the stars generate energy through nuclear fusion in their cores, which delays gravity's final victory. But gravity always wins. You have learned that stars of different masses die in different ways, but you have also discovered that they always reach one of three end states: white dwarfs, neutron stars, or black holes. However strange these compact objects may seem, they are common in the universe. They are normal.

The physics of compact objects is extreme and violent. You are not accustomed to objects as hot as the surface of a neutron star, and you have never experienced the environment near a black hole, where gravity is so strong it would pull you to pieces.

The universe is filled with things that are so violent and so peculiar they are almost unimaginable, but they are so common they deserve the label "normal." Next time you are out for a walk, look around and notice how beautiful Earth is and recall how unusual it is compared to the rest of the universe.