5

THE SEARCH FOR BLACK HOLES

Do black holes really exist? So far, we have examined a theoretical object, a component of the model world. Black holes are fascinating objects, but before you let yourself become too intrigued by the mysteries of the event horizon, you should try to ascertain the existence of some of these things in the real world. The search for black holes is somewhat more focused than the search for neutron stars because we have some ideas of what we should look for. In some respects, however, the stories are similar, in that it was first shown that black holes might exist (Schwarzschild, in 1916) and then it was shown that massive stars might actually become black holes (Oppenheimer and Snyder, in 1939). Now there is a good possibility that they might be observable.

Chapters 2 and 3, which provided a sketchy overview of the life cycles of stars, reached the conclusion that massive stars may end their lives as black holes. In summary, at the end of its life, a star has burned all of its nuclear fuel. It can no longer keep its inside hot enough to hold up its surface layers, so it shrinks. If a star leaves a small corpse, the dead star can prevent itself from totally collapsing because degeneracy pressure can hold the star up. Since degeneracy pressure does not arise from heat, it continues to operate even as the star cools. Stellar corpses with low masses thus end up as white dwarfs or neturon stars.

But if a dead star is more massive than some limiting, critical mass, degeneracy pressure is overpowered by the weight of the star. Degenerate matter is simply not strong enough to hold up a cold, dead star with a mass greater than a certain limit. The exact value of the limiting mass is a matter of some debate. As long as general relativity is valid, this limiting mass cannot exceed four solar masses, and is probably about two and a half solar masses. Many stars start their lives with more material than this limiting mass. To avoid becoming black holes they must shed mass in the red-giant stage. Although stars are known to shed mass as red giants, they probably don't shed enough to enable the largest stars to avoid the ultimate fate of the cosmic collapse—the black-hole stage. We astronomers cannot firmly argue that massive stars must become black holes, but they probably do.

Where are the black holes hiding?

Black holes come in all sizes, but in a limited variety of shapes. The properties of a black hole are mass, spin, and charge; we can therefore seek black holes of any mass. Yet the search for black holes is easier if we pick black holes that evolve from massive stars as the target. They are the ones whose origin we can understand reasonably well. Further, in double-star systems, stellar black holes can suck matter away from the companion star and emit x rays that we can see and analyze. It is the analysis of double-star systems that provides us with the best evidence that black holes exist.

Different sizes of black holes can also be looked for. Mini-black holes—black holes far smaller than stars—might have formed in the gravitational tangles of the Big Bang, the explosion that marked the beginning of the universe. A remarkable result of black-hole research in the 1970s is the theory that these mini-black holes evaporate eventually. But no one has yet found an evaporating mini-black hole. (Consideration on this exciting frontier area is deferred until Chapter 6.) Black holes larger than stars may also exist. These giant black holes may supply power to the x-ray sources seen in large star clusters. They may be the powerhouse that supplies energy to the quasars. If the expansion of the entire universe should ever come to a stop, then the universe would be one cosmic black hole.

But these Lilliputians and Gargantuans of the black-hole cast are hard to identify unambiguously. We understand stars and double-star systems far better than we understand mini-black holes, supermassive objects in the center of star clusters or galaxies, or the universe itself. We shall reserve mini-black holes and black holes in star clusters for the frontier areas treated in Chapter 6. The enigmatic quasars are the subject of Part 2, and I'll deal with the universe in Part 3. So, postponing these other topics until later, let us turn to the most promising place to search for black holes: double stars.

Spectroscopic double stars

If black holes are invisible, how can we find them? The simplest effect that a hole has on its surroundings is that it causes rockets, planets, other stars, or anything nearby to fall toward it or to orbit it. If the earlier illustration of a rocket ship orbiting a black hole is changed slightly, and we let a star be substituted for the rocket ship, then we have a black hole that can be detected. You can look and see the star orbiting something, and you cannot see the object it is orbiting. Therefore it is orbiting a black hole.

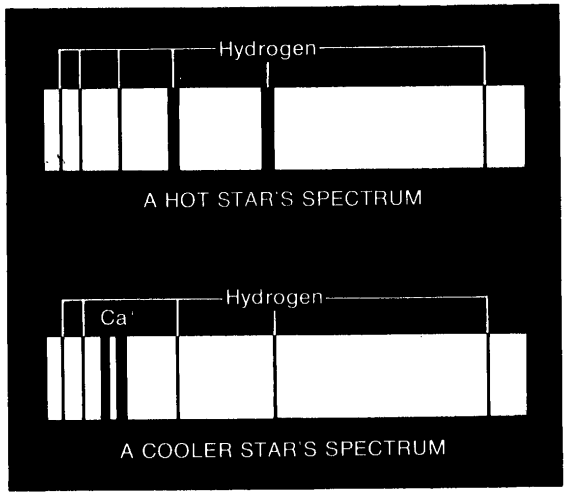

FIGURE 5-1
Stellar spectra
(schematic)

This picture is nice and simple when you have a close view. Unfortunately the stars are far away, and from a distance the situation is proportionately more ambiguous. How can you detect that a star is orbiting some invisible companion if the star is tens or hundreds of parsecs away? Close analysis of the message of starlight is required. There are two main questions: How do we know that the star is orbiting in the first place? and, How do we know that the companion is truly invisible and not just a dim star hidden by the light of the star we can see?

To answer both questions, we must analyze the star's spectrum. Starlight, like sunlight, is a mixture of all colors of the rainbow. To photograph a star's spectrum, we disperse the starlight into its different colors or wavelengths and photograph the result. Sketches of stellar spectra are shown in Figure 5-1. One can also, using varying techniques, determine the color of the star. All that we know about a star must be determined from its spectrum and its color, for the only messages that we receive from the star are the messages of radiation—light, radio waves, x rays, and other forms of radiation.

The most striking feature of the stellar spectra shown in Figure 5-1 are the dark lines crossing them. These dark lines indicate that less light is being emitted at that particular color, since in the spectrum the color of the light is changing from blue on the left to red on the right. Dark lines exist because particular atoms in the surface layers of the star are absorbing light and preventing it from reaching us. (The Preliminary section explains this phenomenon in more detail.)

What can we learn from these dark lines? From their pattern, we can learn what type of star is emitting light. We can classify the spectrum, and from this classification we can derive the star's temperature, size, and luminosity.

A star's temperature is the principal factor governing the appearance of its spectrum. Temperature classifications of stellar spectra are designated by letters, but the order is somewhat jumbled for historical reasons: O, B, A, F, G, K, M. For example, the bottom spectrum in Figure 5-1 is a G-type spectrum; the two very dark lines at the left come from ionized calcium atoms that are found mostly in stars with the same temperature as the sun, a G-type star. The top spectrum is that of a hotter A-type star; the calcium lines are absent.

Yet spectroscopists can tell more than just a star's temperature. The art of spectral classification has advanced to such a point that by examining a star's spectrum they can determine its size: supergiant, giant, or dwarf. If we can determine a star's temperature and size, we can also determine its luminosity.

We now have an idea of how to answer our second question about a star with an invisible companion. How do we know whether the invisible star is a dim companion star or a black hole—not a star at all? We classify the spectrum of the star that we see. From its spectral class, we can determine its luminosity. We then determine how faint its companion must be to remain invisible. We can then ask, Is it reasonable that the companion is so faint?

But how do we know that the companion is even there? We are not close enough to the star–black hole pair to see the star executing a beautiful elliptical orbit as it dances around the black hole. For some pairs of stars, you can actually see the stars move around each other. But none of the black-hole candidates is amenable to such an analysis. Once again, we must count on the spectrum to provide help. The exact color or wavelength of the dark lines tells us the answer. If the wavelength of these lines changes in time—if the lines appear to shift in wavelength and then shift back again—we know that the star is alternately moving toward and away from us. If it is moving in such a fashion, it is orbiting something. Figure 5-2 shows what the observing astronomer would see.

Doppler shifts

How does an observation like the one in Figure 5-2 tell us that there is a companion star? It is the changing color or wavelength of the dark lines in the star's spectrum that tells us that the visible star is moving in an orbit. This changing color arises from the Doppler effect. Light from a star moving toward the observer looks bluer than it did when it left the star, and light moving away from the observer looks redder. For example, if two astronomers on two planets watch a star move toward one of them and

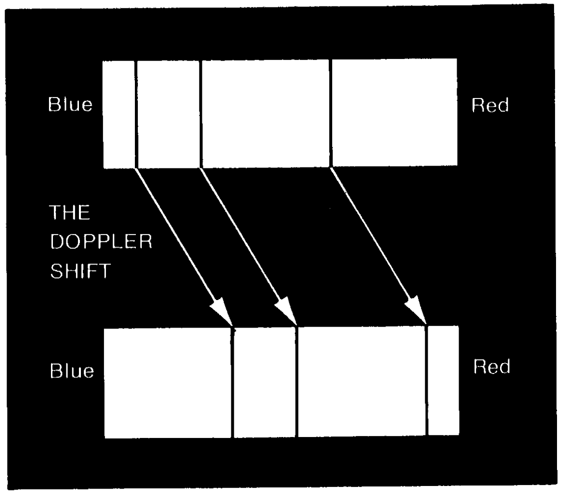

FIGURE 5-2 If the spectra of the same star taken at two different times show shifts in the wavelength (or color) of the spectrum lines, the star is alternately moving toward us and away as it orbits a companion.

away from the other, each will see a different spectrum (Figure 5-3). The astronomer on the right, seeing the star approach, will see a blueshifted spectrum. The one on the left will see a redshift. This shift connects the motion of a star to the colors or wavelengths of light in its spectrum.

What causes this Doppler shift? Consider a terrestrial analogy, shown in Figure 5-4. A police car moves down the street, like the star moving through space. This car is equipped with a siren tuned to middle C. Consider what two people on the sidewalk observe, as opposed to what a person inside the police car hears. As the car approaches the observer on the right, sound waves from the siren tend to pile up. The car is catching up with the sound waves it emits. As a result, the observer on the right senses that the length of the sound waves is shrinking, and hears a pitch higher than middle C. Similarly, the observer on the left, with the police car speeding away from him, experiences sound waves that appear stretched out, and perceives a wavelength that is longer and a sound that is lower-pitched. The person inside the car does not sense that the sound waves are either stretching out or shrinking, but simply hears middle C. (The pitch of a musical sound is related to its wavelength. Short-wavelength sounds are high-pitched; long-wavelength sounds are low-pitched.)

The extent of the Doppler shift is governed by the speed of the moving object, in this case the police car. The faster the car moves, the more the sound waves pile up (or stretch out), with consequent greater shift. In principle, a blind person with perfect pitch could determine how fast the police car was traveling. The blind person could recognize the pitch, and knowing what pitch the siren was tuned to, could thus determine

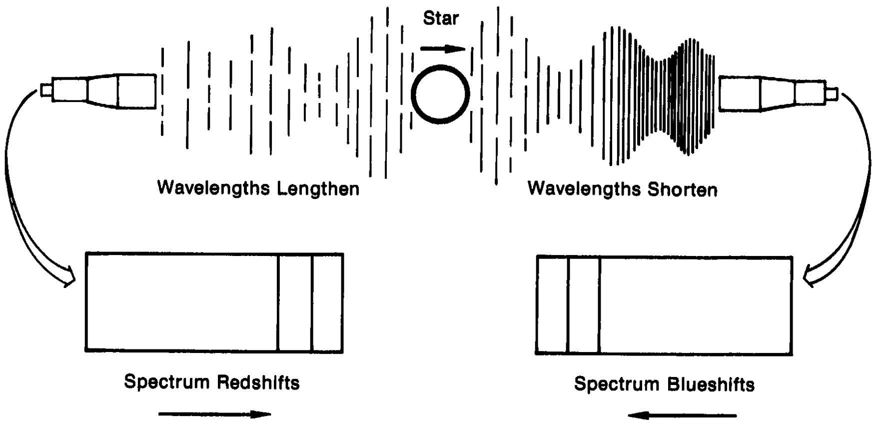

FIGURE 5-3 Astronomers see Doppler shifts in stellar spectra, as the colors (or wavelengths) of the dark lines change depending on the motion of the star. Compare with Figure 5-4.

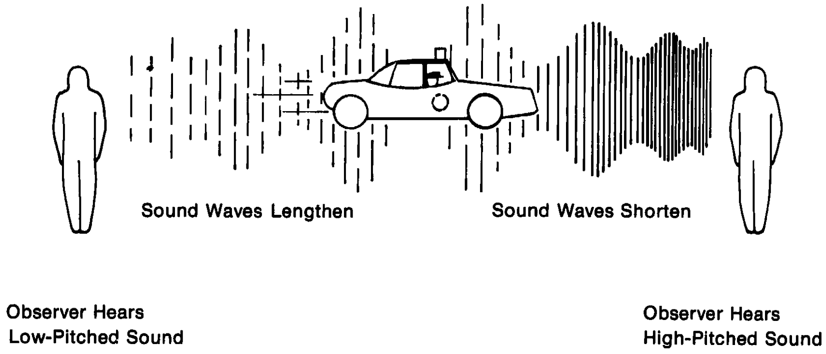

FIGURE 5-4 Pedestrians on a sidewalk can hear Doppler shifts from the siren of a passing police car.

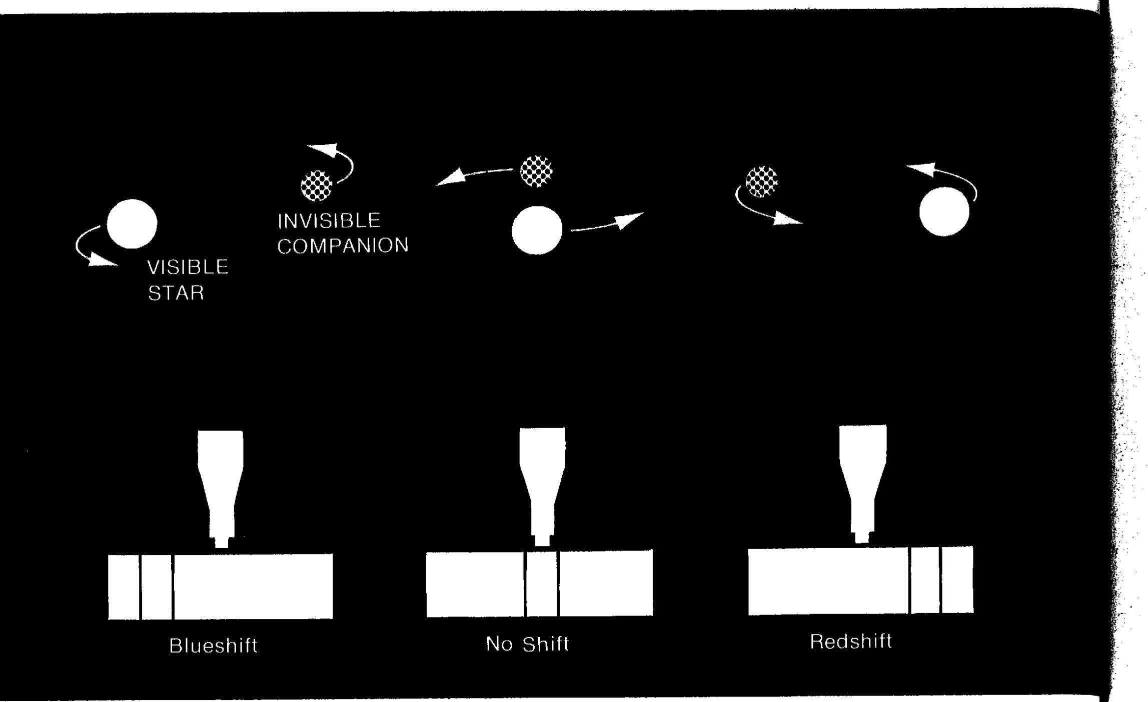

FIGURE 5-5 A single-lined spectroscopic binary, in which a star orbits a dark companion, will show a shift in its spectrum as the visible star moves toward and away from the observer in its orbit.

the car's velocity. You can hear the shift in pitch of a police car siren as one travels by you on the roadway. Try it sometime.

(To obtain a mathematical expression for the Doppler shift, express the shift in wavelength as $\Delta\lambda$, the wavelength as λ, the wave velocity as c, and the object velocity as v. The relation between these quantities is wavelength shift/wavelength = object velocity/wave velocity, or $\Delta\lambda/\lambda = v/c$. This relation holds only if v/c is small.)

In practice, the astronomer examines spectra of a star taken at various times. When the star is moving toward the earth as it orbits its companion, the lines in its spectrum are shifted toward the blue end of the spectrum, as the light waves are compressed by the star's motion. When the star passes between the earth and the companion, you observe no shift, and when the star is receding from the earth, you observe a redshift. The whole scheme is shown in Figure 5-5. (When you do work of this kind, you need to be able to measure the exact wavelength of the lines in the spectrum. You can do this by exposing the spectrum of a fixed source on the same photographic plate.) A star that shows changing shifts in its spectrum like those in Figure 5-5 is known as a single-lined spectroscopic binary: *single-lined,* because you observe only one spectrum, *spectroscopic,* because it takes a spectroscope to determine what is going on; and a *binary,* because the shifting pattern of spectrum lines indicates that there are two objects in the system, that the star whose spectrum you see is orbiting something.

A case history: Epsilon Aurigae

From this discussion, you might be tempted to conclude that all single-lined spectroscopic binaries are black holes. Such a conclusion would be premature. All that you know about a single-lined spectroscopic binary is that the system encompasses another object or other objects. Whether that object is in fact a black hole is a further question requiring thoughtful analysis. Each case must be considered individually. The investigator has to ask, Is there any way to explain what is observed in this system without involving a black hole? For each individual star, the arguments are slightly different.

The search for black holes in binary systems begins with one particular candidate, Epsilon Aurigae. I start here not because Epsilon Aurigae is the best black-hole candidate, for it is not the best. But it does illustrate some of the basic physical laws that underlie the quest. These basic laws are not just set forth abstractly, but are applied to a particular system. Further, this system may contain a black hole. However, the evidence is not so strong that astronomers believe that it *must* contain one.

Auriga is a constellation that is fairly easy to recognize. It is a pentagonal group of bright stars, north of Orion, and it passes almost directly overhead in the after-dinner sky of January (see Figure 5-6). Auriga contains the bright star Capella. Just south of Capella lies a group of three stars, and Epsilon is the northernmost, brightest star of the group. It is a very peculiar spectroscopic eclipsing binary. The lines of its spectrum shift in much the same way as described above. But in addition, every 27 years the bright star becomes dimmer as the *secondary* (as the companion is called) passed in front of the bright primary. All investigators agree that the secondary contains a cloud of dust that blocks out some of the light of the primary as the secondary passes between us and the primary, thus causing the eclipse. During the eclipse—and only during the eclipse—you see a second spectrum, quite similar to the spectrum of the primary star. Whether this second spectrum means that the secondary is actually emitting light of its own is unclear at present. The secondary is completely invisible outside of eclipse. Now one must attack the question, Is this invisible secondary, at the center of this immense dust cloud, a black hole?

To analyze this question, we must determine the properties of the secondary as best as we can from the information available. In particular,

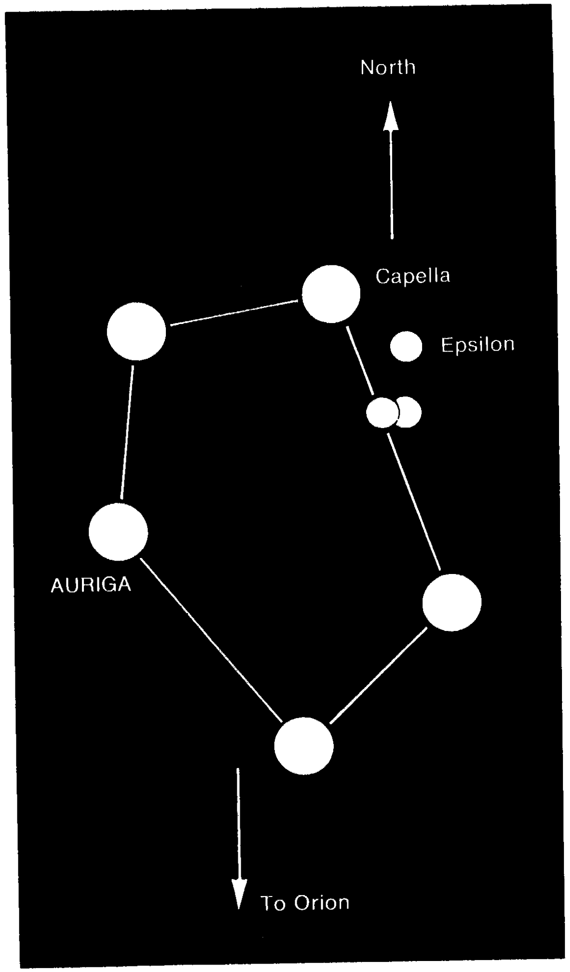

FIGURE 5-6
The constellation of Auriga and the location of the peculiar binary star Epsilon Aurigae

we need to know its mass. What do we know? We know that the primary, the star whose spectrum we see, is being pulled around by the secondary, for there are Doppler shifts in the spectrum of the primary. We can estimate the strength of the pull that the secondary is exerting. To go from the strength of this pull to the mass of the secondary, we need to know a little bit more about how double stars work.

Two stars orbiting each other are held together by gravity. The strength of the pull necessary to keep the stars from flying off in opposite directions depends on the speed of the stars in their orbit. Fast-moving stars need a strong gravitational force to hold them together, while slower-moving stars need less force. The strength of the force depends on the size of the orbit and the masses of the two stars, according to the laws of gravitation. The more massive the stars, the stronger the force; and the larger the separation between the stars, the weaker the gravitational force. Thus, if a pair of stars orbit each other rapidly at a great distance, we can deduce that they must be massive, since only massive stars can exert a strong gravitational force over a great distance.

(Mathematically, the relation described in the last paragraph is known as Kepler's Third Law, relating orbital period P in years, the distance between stars R in astronomical units, and the total mass M of the system in solar masses. This relation is $P^2M = R^3$. You need not understand the mathematical relation in order to understand what follows.)

Thus you can measure the mass of a double-star system if you know its orbital size and orbital period. Measuring the period is easy. Keep obtaining spectra and watch the lines shift back and forth. The amount of time it takes the lines to go through one full cycle is the period. The extent of the shifts tells you how fast the stars are moving toward and away from you. If you know whether the stars are moving directly at you or are moving on an angle, you can determine the orbital speed. You then know how fast the star travels in its orbit and how long it takes to get around, and you can calculate how big the orbit is.

Now you know the combined mass of the two stars. Sometimes you see both stars moving around each other, and you can tell which one has the greater mass, the greater inertia. But if you could *see* both stars in a double-star system, neither one would be a black hole. In a single-lined spectroscopic binary like Epsilon Aurigae or any other black-hole candidate, you need to estimate the mass of the visible star. You know the total mass of the system, and what's left over that you can't see is the mass of the invisible star, the black-hole candidate.

Because the analysis involves making some assumptions, different investigators obtain different models for the Epsilon Aurigae system. But the smallest mass anyone has found for the invisible companion is eight solar masses. An eight-solar-mass main-sequence star would be seen in mid-eclipse, so the companion isn't a normal main-sequence star. White-dwarf stars or neutron stars would be too dim to see in mid-eclipse, but neither can make up the needed mass of eight solar masses. At first glance, the only thing that would be massive enough to be the companion and still remain invisible is an eight-solar-mass black hole.

But wait. The eclipses of the visible star last two years, and eight-solar-mass black holes are too tiny to produce any visible eclipse—and certainly can't produce an eclipse that lasts that long. The companion is, presumably, surrounded by a cloud of dust that produces the eclipse. Models differ in detail. Is this cloud of dust a sphere? a disk? a ring? a rectangle? No one knows. But whatever it is, it could hide an eight-solar-mass main-sequence star from our eyes. The object at the center of this dust cloud could be a black hole, but it doesn't have to be. Is there any other, less ambiguous, fingerprint that we can use to identify a black hole in a double-star system? X-ray astronomy may provide the missing clue.

X-ray sources and black holes

The basic problem that Epsilon Aurigae presents as a black-hole candidate is the difficulty of distinguishing between a black hole and a normal star embedded in a dust cloud. We could tell, from the shift of lines in the spectrum of the visible primary star, that there was another star pushing the primary around. An estimate of the strength of this pull indicated that the companion was sufficiently massive to be a black hole rather than a white dwarf or neutron star. But is the companion an evolved star, so massive that it is certainly a black hole, or is it just a normal star hidden from our eyes by this vast dust cloud? Epsilon Aurigae does not provide any evidence bearing directly on this question. The answer may emerge eventually, but only after a series of detailed models have been made. In the search for black holes, attention now focuses on evidence that can prove that the star system of interest contains an evolved star. Neutron stars and black holes are evolved stars that are so small that in the literature they are often referred to as collapsed objects, although only a black hole is, strictly speaking, collapsed.

What does a collapsed object do that stars don't do? A collapsed object is very small—some tens of kilometers across, or maybe hundreds, at the utmost—while a massive star is quite large, millions of kilometers across. Remember the gruesome fate of an astronaut who ventures too close to a black hole. As the astronaut falls toward the hole, all body parts try to fall toward the same point. The astronaut is squashed by the straitjacket of gravity, as shoulders, head, feet, and the entire body fall inward toward the center. The whole astronaut is compressed. These compression forces are so strong that they would destroy any realistic space probe constructed with present-day technology that would explore a stellar-mass-sized black hole.

As gas and dust swirls toward a black hole they will be squashed in the same way that the astronaut would be. When gas is squeezed, it heats up. The more it is compressed, the hotter it gets, and the more rapid the swirling motion is as the gas falls toward the hole. This hot vortex of infalling gas eventually gets hot and dense enough that it emits x rays as it nears the collapsed object. Detailed theoretical models confirm this picture. If there is a black hole somewhere in space with a continuous supply of gas falling in on it, x rays come from the compressed, swirling gas just before it reaches the event horizon. X-ray astronomers can detect these high-energy signals that the black hole creates as it compresses the infalling gas stream.

X-ray astronomy

X-ray astronomy, which can provide a key step in the search for black holes, is now growing up. In the 1960s, all x-ray astronomy was done with instruments sent above the atmosphere in rockets or sometimes balloons. X rays cannot penetrate the earth's atmosphere, so it is necessary to go above the atmosphere with a rocket or satellite.

Rockets are advantageous instruments to use when you are just opening up a field and do not know whether you will find anything interesting or not. They are cheaper than satellites, both in dollars and in the amount of time it takes to put an experiment together. It takes only six months to set up a rocket experiment, if you have the instrumentation built, whereas five years often passes between the initial proposal and the launch of a satellite. However, rockets have a great disadvantage in that the observing time on a typical rocket flight is only about five minutes.

The rocket era of x-ray astronomy was extremely productive, considering that the total observing time amassed by various rocket flights was little over an hour. Think how little you would know about the sky if you had just an hour to look at it. In 1969, the rocket era came to a close with the launching of the *Uhuru* satellite. This first x-ray satellite observatory has probably been one of the most productive scientific ventures of all time. (Its name comes from the time and place of its launch: off the Kenyan coast on the fifth anniversary of Kenyan independence. *Uhuru* is the Swahili word for freedom.) Scanning the sky in the x-ray region, *Uhuru* has provided a comprehensive list of about 200 x-ray sources, half of which are located within the Milky Way galaxy. High Energy Astronomical Observatory satellites, along with others launched in the late 1970s, discovered many more x-ray sources, and provided much more information on those first seen by *Uhuru.* Yet it was *Uhuru* that first uncovered the wide variety of x-ray sources in the galaxy. Some of these x-ray sources may be black holes.

A few x-ray sources in the Milky Way galaxy are associated with other forms of dead stars. Some x-ray sources are gas clouds that are the expanding wisps of a star's outer envelope—the debris of a supernova. A few are very hot white-dwarf stars. Most are associated with binary stars, systems in which two stars orbit each other. Many of these binary systems contain neutron stars; the x-ray pulsars (see Chapter 3) are examples of these. A few of these binary systems may contain black holes, and these sources are worth examining in detail.

Flickering x-ray sources

A few x-ray sources are particularly interesting as far as the search for black holes is concerned. These x-ray sources flicker quite rapidly, varying in intensity within thousandths of a second. Of all the galactic x-ray sources, only a few fall into this category: Cygnus X-1 and Circinus X-1 are two of the best-investigated ones. The flickering nature of these sources provides evidence that the x-ray-emitting regions are very small, as small as the inner edge of a whirling vortex of gas surrounding a black hole. (I shall discuss the basis for this conclusion presently.) Recall that Epsilon Aurigae became an unpromising black-hole candidate because there was no reason that it couldn't be a large, evolving star rather than a tiny black hole.

Why does the flickering of the x rays provide information on the size of the x-ray-emitting region? Think about what happens when an object doubles in brightness. In order to double in brightness, a cloud of emitting material must either become twice as bright as it was, or another cloud of emitting material must start to radiate, in a short time interval—let us take 0.05 seconds as an example. Whatever caused the emitting region to suddenly turn on, information of some sort must travel from the stimulus to the responding gas, from the source of the energy to the gas that radiates it away as x rays. If the x-ray source is a little glob on the inner edge of the accretion disk, it must compress or heat up in that short time interval, and the sound waves that cause it to heat up or compress must cross the hunk of gas in that time of 0.05 second. These sound waves travel no faster than light; in fact, they probably travel much slower than light. Thus the gas cloud must be small enough so that light can cross it in 0.05 second—it must be less than 15,000 km across. (In fact, it is probably far smaller than that, but you would have to know how fast sound waves travel through this particular gas cloud to determine the size precisely.) Were this gas cloud larger than 15,000 km, it would be like the proverbial brontosaurus, which took several minutes to realize that its tail had been stepped on—it just couldn't respond in time to flare up quickly. Such a gas cloud is too small to be part of a main-sequence star like the sun, a star whose radius is 695,000 km. These x-ray sources are associated with tiny stellar objects: white-dwarf stars, neutron stars, or black holes. One particular star has been analyzed thoroughly enough so that the evidence favoring the black-hole interpretation is very strong. This object is Cygnus X-1.

Cygnus X-1: the first black hole

Discovery

Although it is not completely certain that Cygnus X-1 is a black hole, there is good evidence that it is. What follows is a cosmic detective story. The sky has presented astronomers with a puzzle. Where does the Cygnus X-1 piece fit in? One hesitates at first to put Cygnus X-1 in the black-hole slot, since invoking black holes to explain anything strange is not proving that they really exist. Although there is still some debate, it is difficult to explain Cygnus X-1 as anything but a black hole.

The story begins in 1965, when Cygnus X-1 was first discovered during a rocket flight. As its name indicates, it was one of the first x-ray sources to be discovered. Its nature was uncertain, since it could not be identified with any obviously peculiar optically observed object. It is located in the Milky Way (see Figures 5-7 and 5-8), and the first x-ray positions were not precisely determined. From the initial observations, all you could say was that it was somewhere in the region shown in Figure 5-8. There are a lot of stars in that picture, and it is impossible to check all of them for peculiarities, especially when you do not know exactly how the optical counterpart to an x-ray source will be peculiar. It might even be totally invisible optically, as some x-ray sources are. In the late 1960s, more data were accumulated. The x-ray intensity of the source varied. The nature of the source was still unknown.

In 1971 and 1972, the breakthrough occurred. In March and April 1971, the *Uhuru* satellite indicated a marked change in the x radiation from

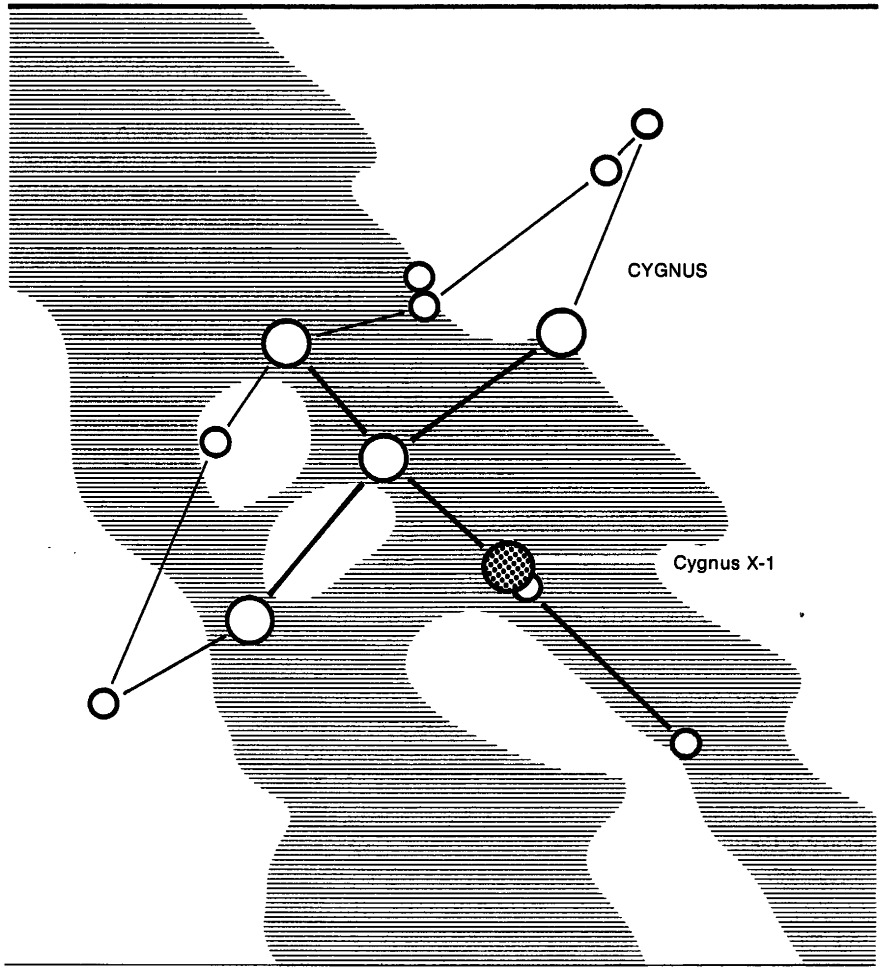

FIGURE 5-7 Cygnus, showing the location of Cygnus X-1. The heavy lines show the Northern Cross, one way of recognizing the constellation; you can make a swan out of it with the light lines. The Milky Way is also shown (lined area).

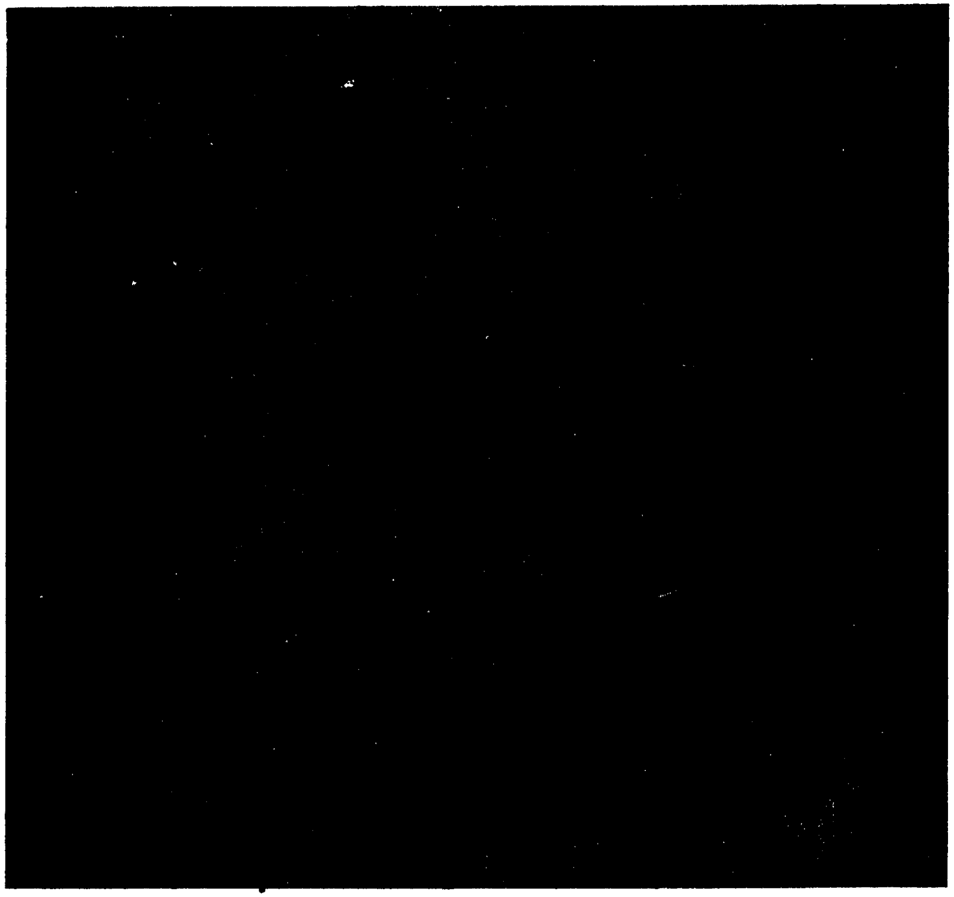

FIGURE 5-8 Enlargement of a Palomar Sky Survey print showing the location of Cygnus X-1, which is the bright star at the lower left of the ellipse. (From S. Rapaport et al., *Astrophysical Journal Letters*, vol. 168, plate L6, 1971, published by the University of Chicago Press. Copyright © by the University of Chicago. All rights reserved. The Palomar Sky Survey is copyright © by the National Geographic Society–Palomar Observatory Sky Survey.)

this source. Lower-energy x rays decreased in intensity to one-quarter of their former value, and high-energy x rays increased in intensity. But most important, a radio source appeared suddenly in the same part of the sky as the x-ray source. The 140-foot telescope of the National Radio Astronomy Observatory had been used to search for a radio counterpart to Cygnus X-1, but had not found one until this change occurred.

It seemed fairly clear that the radio source and the x-ray source were the same object. The importance of the discovery of the radio source was not that the radio noise provided much information about the nature of the source, but that the radio position could be measured much more accurately. At the same time, the x-ray position became more precise. (The ellipse in Figure 5-8 is the measured position of the source from an MIT rocket experiment; the experimenters said that the source was somewhere in that ellipse.) The bright star in that ellipse began to look much more intriguing, especially since the radio position was centered exactly on that star. The uncertainties in the radio position were about the same size as the image of the star in the photograph.

Thus the identification of Cygnus X-1 with a star was confirmed. Optical identification of x-ray sources is a critical step in determining their nature, as spectroscopy can tell you a lot about a star: how big it is, how hot it is, whether it is a double, and so forth. This star is called HDE 226868, Star No. 226,868 in the extension of the Henry Draper catalogue of spectral classifications. Its spectrum shows that it is a B-type supergiant, a large, hot, blue star.

A further discovery in 1971 was the finding, by a Japanese group, that the x-rays flickered very rapidly. This flickering is significant, you recall, because it shows that the x-ray source must be very compact. Cygnus X-1 began to look more and more like a black hole.

Now the optical astronomers started working. They looked for variable Doppler shifts in the star's spectrum. These would indicate that this massive B supergiant star, HDE 226868, was being pushed around by the gravitational forces of an invisible companion. It was crucial to measure the amplitude of these Doppler shifts, and it was also necessary to determine the properties of the visible star. During the 1972 observing season (an optical astronomer can observe stars only when they are in the night sky, and Cygnus is in the night sky only in the spring and summer), Cygnus X-1 was studied intensively. From these observations, a fairly good model emerged that several investigators agreed on. Although each individual adopted slightly different numbers, the basic model was the same. See Figure 5-9.

The star system is a double one, containing a B-type supergiant star and a black-hole companion. Mass flows away from the supergiant star in a stellar wind, produced by the high temperatures in the outer layer of the star. Were the supergiant star isolated in space, the stellar wind would just flow out into the depths of interstellar space, becoming part of the wispy gas between the stars. But the nearby companion gobbles up some of the outflowing mass. This gas swirls around the companion, forming a circular disk of matter around it. Gas in this accretion disk swirls down toward the black hole, is compressed, and emits x rays before it is swallowed up by the black hole. These x rays are one of the key links in the logical chain of reasoning that makes the black-hole interpretation of this stellar system the most favored one.

This gas stream shows up in other ways, too. Characteristic emission lines of hydrogen and helium come from parts of this stream. It is certain that these emission lines do not come from the star, as the Doppler shifts of these lines indicate that the gas producing them is not moving with either star.

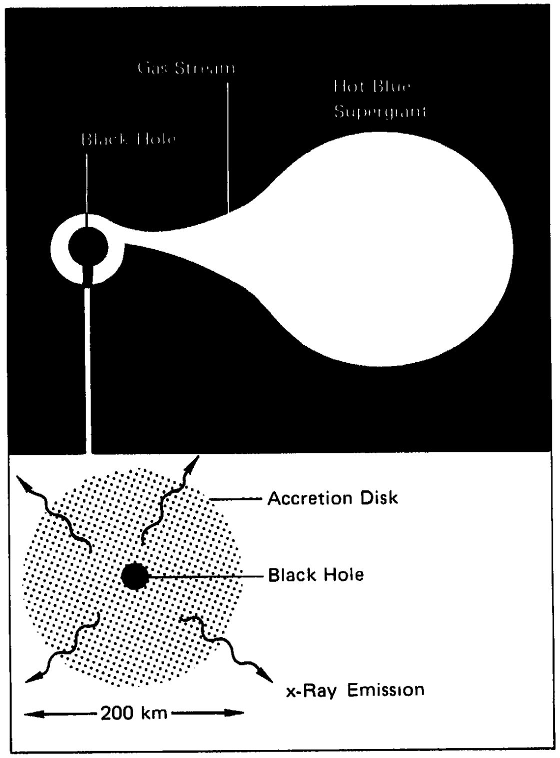

FIGURE 5-9
Model of Cygnus X-1

The model for Cygnus X-1 described above and depicted in Figure 5-9 manages to explain all the phenomena. But an astronomer must be skeptical and ask, “Is there any other believable model that can explain all the observations?” The most important observation here is the existence of the x rays, for the only reasonable way that a star can produce lots of x rays is for the star system to contain a neutron star or a black hole. Which is it? Neutron star or black hole? We have managed to find a source for the x rays, but have we really found a black hole? Remember that neutron stars can have at most three solar masses. To settle the question, we must determine the mass of the companion. The binary-star techniques described earlier were used to answer this question.

The general consensus at the end of 1972 was that the companion was so massive that it must be a black hole. Hot supergiants are generally massive stars, since stars that are not massive, it is believed are cooler and never pass through the blue supergiant stage, at least in normal stellar evolution. Typically, B-type supergiants like HDE 226868, the visible star, have masses of about 30 solar masses. With this large mass assigned to the primary, analysis indicates that the secondary must have a mass of at least five, and probably about eight, solar masses. Neutron stars certainly contain no more than three solar masses, and probably considerably less than that. Therefore the companion is a black hole.

Current research

The black-hole model for Cygnus X-1, illustrated in Figure 5-9, is quite a persuasive one. When all the pieces were more or less in place, in mid-1973, it was definitely time to take this news out of the scientific journals and tell the world that a black hole had been discovered. Enough evidence was in hand that this conclusion was more than mere conjecture or speculation.

But did the completion of the initial stage of analysis of Cygnus X-1 mean that it was time to stop, remain content that we had discovered a black hole, and work on other research problems? Science does not work that way. The model of Cygnus X-1 outlined so far, is deceptively complete. All the observations fit into place, but the explanations are quite generalized. Details remain to be worked out. Observations need to be verified. The analysis of this system continues. The next few pages describe the major topics of concern at the beginning of the 1980s.

How did the Cygnus X-1 system come to be the way it is? Astronomers hardly ever see stars evolve before their very eyes, so they need to use the tools of inference. Is it reasonable that the processes of stellar evolution could produce a system like Cygnus X-1? The discovery of Cygnus X-1 and other systems like it has spurred a revival of interest in theoretical calculations of the late stages of evolution of binary stars.

Right now, there are two stars in the system: a 25-solar-mass star that we see, and another object, the black hole, with a smaller mass—let's call it eight solar masses. In the beginning, the star that is now the black hole had most of the mass of the system. It became a red-giant star, and its envelope expanded just the way that red-giant envelopes normally do, to a point. But eventually the envelope got so big that the second star in the system, the one that we now see, started capturing some of the mass in the system. Streams of gas flowed from the bloated, distorted red-giant star toward the companion. Eventually all the envelope was dumped on the other star, and the core of this first red giant in the system collapsed to become the black hole that we see now. Subsequently this second star started dumping mass on the black hole, producing an accretion disk and the x rays that we see now.

Calculations that provide numbers describing the scenario of the last paragraph[1] indicate that systems like Cygnus X-1 don't last very long. In about 10,000 years, the rate of mass flow will increase because the 25-solar-mass star will get too big. This increased flow will probably choke off the x rays from the accretion disk. What happens then? It's anybody's guess.

So we can understand how Cygnus X-1 came to be the way that it is now. The short duration of the present phase, 10,000 years (short compared to the millions and billions of years it normally takes stars to evolve) explains why we don't see many more of these objects. When we observe the sky, we pick up only a few stars passing through this fleeting evolutionary phase. Most such systems are not yet x-ray sources, or were x-ray sources in the past.

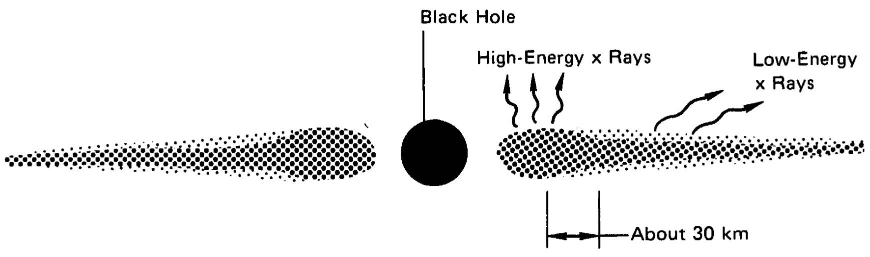

FIGURE 5-10 Sketch of the inner part of the accretion disk of Cygnus X-1. The two shaded regions show the shape of the accretion disk at two stages. In one state (dark shading), the disk is very flat, except in the extreme inner regions, which emit the high-energy x rays. In the other state, the thick part of the disk is larger. It is the transition from one state to the other that is responsible for the changing character of the x-ray spectrum. [Freely sketched from the models of Thorne and Price, *Astrophysical Journal Letters* 195 (1975), L101-L106, and Eardley, Lightman, and Shapiro, *Astrophysical Journal Letters* 199 (1975), L153-L156.]

Another active area of research involves modeling the accretion disk of the system, trying to understand exactly where the x rays come from. Theorists here seek to produce a model for the accretion disk that produces an x-ray system that resembles the real x-ray system. Some generalized understanding has emerged, but detailed agreement of theory and observation is still in the future. As an example, consider the changes in the x-ray behavior of the system. Sometimes the system emits radio waves and a few low-energy x rays. At other times, after an abrupt change, it emits no radio waves and larger quantitites of low-energy x rays. Alan Lightman and Douglas Eardley have shown that accretion disks are unstable. An accretion disk can be either thick or thin, and the transition from a thick disk to a thin disk is quite abrupt. Lightman, Eardley, and Stuart Shapiro showed that the thick-disk spectrum does resemble the observed x-ray spectrum in a general way, but Shapiro notes that "no details exist."[2] A rough sketch of this model is shown in Figure 5-10.

In the United States in the late 1970s, a new generation of x-ray telescopes called HEAO's (High Energy Astronomical Observatories) was launched. These telescopes provide additional information on the time variation of the x-ray emission. These x rays flicker, varying in intensity in milliseconds. These variations probably arise from the motion of lumps of gas in the accretion disk. A hot spot, a slightly denser gaseous glob, orbits the hole a few times before being sucked away from the inner edge of the disk into the cosmic garbage disposal—the black hole itself..

Suppose that the radiation from the hot spot was more or less beamed in a particular direction. This beam would circle the sky once for each orbit of the black hole, just as a pulsar beam sweeps around the sky once for each revolution of the spinning neutron star. X-ray observatories would see a short, quasiperiodic sequence of pulses of x-ray emission from this swirling hot spot. Observers have claimed to detect these quasiperiodic pulses with the *Uhuru* generation of x-ray satellite observatories, but none of these claims has been unambiguous. If such pulses are ever seen, analysis of them might provide further information about the structure of the accretion disk.

The last few paragraphs have provided a quick overview of one major area of current research on black holes and accretion disks. These projects are the work of "establishment" theoretical astrophysicists, people who subscribe to the majority view that the Cygnus X-1 system contains a black hole in the middle of the accretion disk. How are the black holes formed? How do the accretion disks produce x rays? Are hot spots in accretion disks observable? To progress, scientists must base their work on some paradigm, some underlying model of a particular star system. The black-hole paradigm for Cygnus X-1 seems to be a reasonable one.

Yet this conservative, establishment viewpoint is not the only one that can be taken. Another frontier of research in the black-hole business is pursued by devil's advocates. These people feel uncomfortable with the idea of a black hole as the central object of the accretion disk in the Cygnus X-1 system. Even if they are wrong, their research is useful, for it forces the establishment theorists to reexamine the foundations of the Cygnus X-1 model described above. And if the critics are right, the best candidate for a black hole vanishes, and we come back to square one: Do black holes really exist?

Is Cygnus X-1 really a black hole?

Alternative models

The devil's advocates have asked some probing, pertinent questions about the establishment model for Cygnus X-1. They have not yet engineered a coup, dethroning the black-hole model and consigning it to that remote prison that discredited scientific theories end up in—the prison of obscurity in the annals of science. In fact, at this time, the establishment model still prevails in the view of most astronomers. But even if the establishment model ultimately prevails, the questions asked by devil's advocates have deepened our understanding of double-star systems that contain accretion disks around black holes.

Must the x rays in the Cygnus X-1 system come from an accretion disk? The accretion disk surrounding the black hole is the centerpiece of the black-hole model for Cygnus X-1, for the accretion disk is the source of the x rays. One early proposal for avoiding the presence of a black hole in Cygnus X-1 argued that the massive companion in the system was a normal, massive star, just as the massive companion to Epsilon Aurigae may be a normal star. In this model, the two stars were connected by tangled magnetic fields, which accelerated electrons to high speeds and thus produced x rays.

There are two principal problems with the model of Cygnus X-1 as two magnetized stars orbiting each other, twisting up their magnetic fields, and emitting x rays. One is that the proposed companion star has never been seen—a problem that also arises with some of the other alternative models we shall consider later. A second, more serious problem is that this model makes no specific statements regarding what should be observed in order to confirm it. Since no one has observed any other star system in which two normal stars orbiting at similar distances produce x rays, how is this model to be confirmed? Actually, the model has not been taken too seriously because the accretion-disk models provide a far more natural explanation for the x-ray emission. But who knows? Perhaps this model has been dismissed too easily.

A question that has received more attention recently is, Must the secondary be indeed as massive as the observations say it is? The Cygnus X-1 binary system is far, far away; we must use indirect arguments to find the masses of the two stars in it. The Doppler shifts observed from the visible companion show how much that star is being pulled around by the other object in the system. If the visible star were a lightweight star, a low-mass, invisible companion could pull it around and produce the Doppler shifts that are observed.

A serious competitor to the black-hole model postulates that the visible, blue star is a peculiar, low-mass blue star that is in a strange stage of evolution. A low-mass blue star that could be in a similar stage of evolution has been found elsewhere; its catalogue name was HZ (= Humason-Zwicky) 22.

Yet a star like HZ 22 would have to be very close to us in order to be as bright as the visible star in the Cygnus X-1 system. In 1973, two teams of astronomers indirectly measured the distance to the Cygnus X-1 system, finding it to be about 2.5 kiloparsecs (8,000 light years) away. At this distance, a low-mass blue star with a low-mass companion would be invisible. That particular model for Cygnus X-1, a model that did not involve a black hole, bit the dust. By the end of 1975, a number of investigators, pursuing the problem from many different angles, agreed that the mass of the companion is between 10 and 15 solar masses.

The next question asked by devil's advocates was, Must the accretion disk be around the 10-to-15-solar-mass companion, or could it be somewhere else in the system? Two independent groups of astronomers suggested that the accretion disk could surround a neutron star. A main-sequence star could be the 10-to-15-solar-mass companion that produced the Doppler shifts in the star that we see, and a lower-mass neutron star could be responsible for the x-ray emission.

These models are a little difficult to believe in, for two reasons. They both postulate a massive, 10-to-15-solar-mass star in the system. Such a star would normally be quite luminous, and no other star has been seen in the system. The observations are almost, but not quite, sensitive enough to allow us to conclude that a 10-to-15-solar-mass star in the system would have been detected and that therefore, since it has not been detected, it isn't there. Further, a slight decrease in the x-ray emission from the system has been observed when the supergiant star is between us and the massive companion. A natural way to produce these reductions in x-ray intensity is to have the x rays absorbed by the supergiant star or by the gas stream flowing from the star to the accretion disk. In addition, it is a little difficult to understand how a triple system with a supergiant, a massive main-sequence star, and a neutron star might have evolved. This triple-star alternative to the black-hole model is almost, but not quite, shot down.

Another question about the black-hole model has been asked before, in considering what types of stars would form black holes. "Must a 10-to-15-solar-mass object at the center of an accretion disk be a black hole? Could it be an overweight neutron star?" With a limiting mass of 10-to-15 solar masses, such an object could not exist on the basis of conventional ideas of how matter behaves at high densities and on the basis of Einstein's theory of general relativity. You have to abandon general relativity to make overweight (or "obese") neutron stars that are as massive as Cygnus X-1. (This issue was discussed at the end of Chapter 3.)

Cygnus X-1 as a black hole

The story is not yet finished. More challenges to the establishment black-hole model for Cygnus X-1 could be mounted. Yet the established model has so far stood the test of time. Some pointed questions have been asked, some viable alternatives proposed, and many of the questions answered. One cannot avoid the presence of a black hole in Cygnus X-1 without invoking some fairly complicated models. Cygnus X-1 is *probably* a black hole; astronomers and physicists have not proved that it *must* be one. It is worth reviewing the steps in this somewhat complicated logical chain:

1. HDE 226868, the blue supergiant star that we see, is part of a stellar system containing the x-ray source Cygnus X-1.
2. Analysis of the Doppler shifts in the spectrum of this single-lined spectroscopic binary indicate that there is a companion in the system with a mass of 10-to-15 solar masses.
3. The x rays come from an accretion disk surrounding a compact stellar object (neutron star or black hole).
4. The massive companion is at the center of the accretion disk; the massive companion is the compact stellar object.
5. A compact stellar object with a mass of 10-to-15 solar masses is a black hole.

If Cygnus X-1 is to be proved a stellar system containing a black hole, each link in this chain of reasoning must be sound. So far, the links have been tested and they ring true. The questioning is an important part of the scientific process. Later on you will see similar questions posed with regard to various models of various astronomical phenomena. Up to now, the black-hole model of Cygnus X-1 has withstood the test of being assaulted by alternative models constucted by devil's advocates. The black-hole model is the simplest way to explain the observations. Therefore Cygnus X-1 probably is a double-star system with a black hole in it.

Other black-hole candidates

Lurking behind the lingering doubts that Cygnus X-1 is indeed a black hole is a hesitation to place too much reliance on one particular object in concluding that black holes really exist. Cygnus X-1 may be a strange, peculiar system. Nature may be playing tricks on us. Cygnus X-1 could be something else disguised as a black hole. But it is unlikely that the same peculiar disguises, the same tricks of Nature, would be at work in two different stellar systems. One system, one object, can always eventually be dismissed as "peculiar." But several objects, all of which act in the same way, cannot be passed off so easily. Complex models may be able to avoid the need for a black hole in the Cygnus X-1 system. Yet they could not, in all probability, apply to several x-ray-emitting double stars. The discussion so far has concentrated on Cygnus X-1, since it is the best-studied of the massive x-ray binaries. Some star systems exist in which the compact object is massive enough so that it *might* be a black hole, but not so massive that it *must* be a black hole. Two stars in particular, Circinus X-1 and V 861 Scorpii, are the best black-hole candidates (other than Cygnus X-1) at the present time.

Circinus X-1

Circinus X-1 is an intriguing x-ray source, but at this time it is not the best black-hole candidate. It is in a binary-star system, for the x rays turn off at 16-day intervals, indicating that orbital motion is carrying the x-ray source behind some other star from our viewpoint. But, for a long time, no optical star could be identified with this system. It was only in late 1976 that a team of astronomers working at the Anglo-Australian telescope (located in the mountains in Australia) identified Circinus X-1 with a very red, very faint star. This star looks red because its light has passed through a forest of interstellar dust clouds that have absorbed most of the blue light from the system. It is barely visible in blue light, even in photographs taken with the most powerful optical telescopes. Yet it is intriguing because its x-ray intensity fluctuates rapidly, in the same way that the x-ray intensity of Cygnus X-1 flickers in time scales of milliseconds. Since the optical star is so faint, it is not yet known whether it is a single-lined spectroscopic binary star, or whether the star that we see has an invisible companion that could be a black hole. The status of Circinus X-1 as a black-hole candidate stems from its identification as a binary star and the flickering nature of the x-ray source.

V 861 Scorpii

In the summer of 1978, another—potentially more promising—black-hole candidate was discovered by a group of astronomers using the Copernicus satellite. This star had been discovered to be a single-lined spectroscopic binary. Analyses of its orbit completed in the early 1970s by E. N. Walker showed that the invisible companion had a mass between 7 and 11 solar masses, too much for a neutron star. R. S. Polidan, G. S. G. Pollard, P. W. Sanford, and M. C. Locke used the satellite to study mass transfer in binary-star systems. They observed V 861 Scorpii in April 1978 with the ultraviolet and x-ray telescopes on the satellite. They discovered that this star is also an x-ray source, and that the x rays are eclipsed once in each orbital period when the supergiant star or the gas stream prevents the x rays from reaching us.

V 861 Scorpii, then, seems to be an analogue of Cygnus X-1. All the ingredients for a black hole are there: a massive invisible companion, x rays that can come from an accretion disk, and a visible star to supply mass to the accretion disk. The observations so far lack the wealth of detail that is available about Cygnus X-1. Yet what we *do* know about the system certainly makes the case for a black hole in V 861 Scorpii a promising one.

Finding black holes is a tricky business. Since you cannot see a black hole, you can only hope to detect it through its gravitational effect on another star. Such a gravitational effect appears in the changing Doppler shifts in a visible star's spectrum, a phenomenon that indicates that the star is orbiting an invisible companion. Mass transferred from the visible star to an accretion disk around the companion eventually is heated by the swirling motions in the disk, and the accretion disk emits x rays. The case for a black hole in any particular system is built up on inference.

We discussed several black-hole candidates in this chapter. Two equivocal candidates are Epsilon Aurigae and Circinus X-1. Epsilon Aurigae has a massive, invisible companion, but the x rays that would demonstrate the presence of an accretion disk around a small object in the system are not there. Circinus X-1 has the x rays, but the star is so faint that spectroscopic evidence for a massive companion is very difficult to obtain. More promising candidates are Cygnus X-1 and the recently discovered V

861 Scorpii. Of these, far more evidence is available for Cygnus X-1. All the elements of the black-hole model come together in Cygnus X-1. There is a visible star that orbits an invisible companion, feeding matter to it. There is an accretion disk around the companion that emits x rays. And, apparently, the companion is too massive to be a neutron star. Models that attempt to explain the observations without involving a black hole run into difficulties which almost, but not quite, make them untenable. It is not easy to fit the pieces of this cosmic puzzle together unless you make the companion a black hole.

6 FRONTIERS AND FRINGES

The black hole described in Chapter 4 is a well-understood one, to take the viewpoint of the theoretician. As long as you go along with Einstein's theory of gravitation, that kind of black hole is the only kind of black hole there is in the universe. Yet our understanding of the phenomena described in Chapters 4 and 5 is not complete. We now know what black holes look like (for example, that black holes have no hair) but we have yet to figure out how they are produced in Nature. We think that Cygnus X-1 is a black hole, but we aren't sure; so observers and theorists obtain and analyze more data, and perform more calculations in order to better understand this enigmatic stellar system and other systems like it.

There is a component of current research on black holes and related phenomena that goes beyond re-exploration of the familiar territory opened up in Chapters 4 and 5. X-ray astronomers have discovered a veritable zoo of x-ray sources. The x-ray sources located within the Milky Way galaxy contain stellar corpses, neutron stars, possibly white-dwarf stars, and possibly black holes. Einstein's theory of general relativity—the basis for the black-hole picture developed so far—is being tested, and some of its consequences are being explored. The violent end to the lives of massive stars produces gravity waves that ripple across the cosmos, and these waves are currently being searched for.

There are a few frontier areas of black-hole studies that are properly called fringes, since they represent speculative ventures far beyond the boundaries of experimentally tested or even testable theory. These fringe areas are widely publicized. You see reports that black holes are space warps: You can fall into one and come out somewhere else in this universe or in another universe. Although these ideas *could* be true, they are, at our present level of sophistication, flights of fancy into the never-never land inside the event horizon. It is very easy to believe that black holes are such strange objects that, if you accept their existence, then anything weird, even space-warp stories, that is said about them is true. Do not fall into this trap. Black-hole research, like most of science, contains some results that are true, some that are probably true, and some that are speculation—published because they are interesting if fanciful ideas and just *might* be true. I have gathered all these ideas and put them in the latter part of this chapter so that you, the reader, will know what is fact and what is not.