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.

Frontiers: X-ray astronomy

One of the first x-ray telescopes, hurled above the atmosphere by a rocket, discovered the most famous of all the x-ray sources: Cygnus X-1, the best black-hole candidate. The *Uhuru* satellite of the early 1970s discovered many more x-ray sources in the Milky Way galaxy. In the late 1970s, a series of far more powerful x-ray telescopes, the HEAO's, was launched, and we are slowly developing an understanding of the types of objects that can produce large quantities of x rays. The x rays in most galactic x-ray sources come from accretion disks around small objects like neutron stars of black holes. Interpretation of the x-ray observations can produce a deeper understanding of black-hole candidates like Cygnus X-1, and perhaps can lead to the discovery of other strange ways that stars can end their lives.

X- and gamma-ray bursts

In late November 1975, Jonathan Grindlay, a research associate at the Harvard Observatory, noticed some strange numbers in a page of computer printout of data. These numbers came from x-ray telescopes on board the Astronomical Netherlands Satellite (ANS). In one particular one-minute interval, the telescope picked up twice as many x rays as it did at other times. This blast of x rays was not merely a celestial hiccup; at its peak, an x-ray burster like this one is 100,000 times as powerful as the sun.

Grindlay's reaction to his discovery of these numbers was not "Eureka!" but surprise and disbelief.[1] Had these numbers been garbled as many, many millions of bits of data were fed through the tortuous path that information from a satellite telescope must take? Data from a satellite are transmitted to earth as a series of pulses, the zeroes and ones of the binary-number system. These millions of bits are radioed from the satellite, picked up by a NASA ground station, in this case a radio telescope in Santiago, Chile, and sent over telephone lines through various computers before they reached Harvard. Checking revealed that the numbers were real, and that most of the powerful blast of x rays was produced in the first few seconds of that one-minute period. Subsequent checking revealed more bursting x-ray sources. Grindlay and John Heise of Utrecht in the Netherlands announced their discovery. Shortly thereafter George Clark and Garrett Jernigan of MIT confirmed the existence of these bursts with another satellite. And at least one other group had independently discovered this phenomenon.

Satellite astronomy has also revealed other sudden blasts of high-energy radiation from the cosmos. Bursts of gamma rays, different from the x-ray bursts, were discovered by a satellite that was not launched with astronomy in mind. After a nuclear-test-ban treaty was signed in 1963, the United States launched satellites to monitor the extent to which the treaty was being observed. An exploding nuclear bomb emits a blast of gamma rays when nuclear particles rearrange themselves and release the energy that makes the bomb work. An orbiting satellite can detect this sudden eruption of gamma rays, telling us that someone has set off an atomic bomb.

The American monitoring satellites, called Velas, worked very well. Mountains of data, enormous collections of numbers, piled up at Los Alamos. Trained investigators soon fell behind in their efforts to make sense of it all. In 1969, scientists poring over the 1967 data detected a burst of gamma rays. Presumably the characteristics of this burst differed from the bursts expected from nuclear bombs, so it had not been noticed earlier when the data were analyzed for evidence of nuclear explosions. Later generations of satellites were modified so that approximate locations for the gamma-ray bursts could be determined, and it turned out that the gamma rays were coming from the sky.[2] No one knows just how far away the sources of the gamma-ray bursts are, so we don't know if they are feeble phenomena that we see because they are close by or powerful blasts coming from a great distance. But even if the gamma-ray bursters are no farther away than the nearest stars, at their peak they are ten times as luminous as the sun. Since they are probably much farther away, they are likely to be considerably more powerful.

The x- and gamma-ray bursts involve sudden surges of radiation from a particular object. There is another type of variable x-ray source called a *transient* x-ray source. The most dramatic of these appeared in August 1975, when a group from the University of Leicester, in England, using a satellite called Ariel 5, noticed the sudden appearance of an x-ray source in the constellation of Monoceros (the Unicorn). Using an initial letter A for Ariel, this source was dubbed A 0620–00, where, as is often the case, the position of the object in the sky becomes part of its name. By mid-August this source was the brightest x-ray source in the sky, and it then declined. This behavior is reminiscent of the supernova phenomenon, described in Chapter 3. Other, less spectacular x-ray transients have appeared in recent years. What are these x-ray sources?

Globular-cluster x-ray sources

A type of x-ray source that might be an intriguing black-hole candidate is the globular-cluster x-ray source, first discovered in 1974. Globular star clusters are large collections of between 10^4 and 10^6 stars (see Figure 6-1). It is possible that the x rays from these star clusters come from an accretion disk surrounding a 1000-solar-mass black hole located in the center of the cluster. When the globular-cluster x-ray sources were first

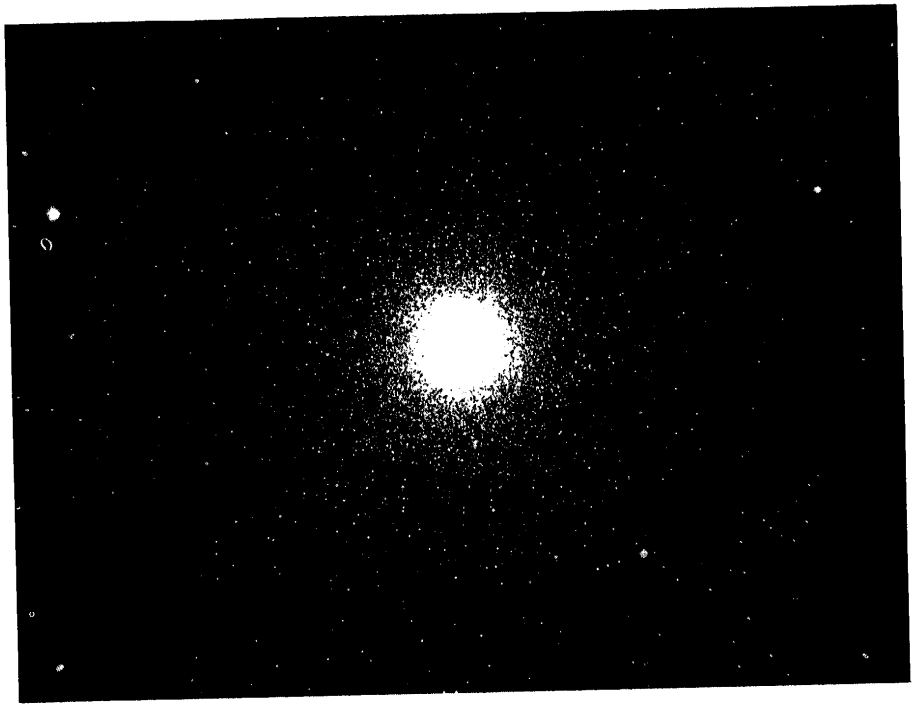

FIGURE 6-1 The globular cluster Messier 3. These star clusters contain more than 100,000 stars. Seven globular clusters are x-ray sources. Some theorists suspect that the x rays may come from an accretion disk surrounding a massive black hole in the center of the cluster. (Hale Observatories photograph)

discovered, this seemed like a very good possibility, but now there are other models, not involving giant black holes, that also explain the observations.

Analysis of the *Uhuru* catalog of x-ray sources indicates that seven of the hundred or so globular clusters in the Milky War galaxy are x-ray sources. This number is a bit high; if these clusters contained the same proportion of x-ray-emitting double stars as the Galaxy does, you would expect only one x-ray source, at most, in one of these star clusters. Clearly something about globular clusters causes them to produce more than the average number of x-ray sources. But what is it? Where are the x-ray sources?

Turning to possible theoretical interpretations, let us take the most obvious one first. At the center of a globular cluster, stars can no longer be considered as isolated, tiny gas spheres roaming the vast deeps of interstellar space. Rather, they would be very close to each other. When they go through their red-giant stages, globular-clusters, stars shed mass in the way that all stars do. This mass swirls in toward the cluster center, forms an accretion disk around the massive, central black hole, and emits x rays just before it takes the final plunge into the event horizon. A black hole of a few hundred solar masses would be big enough to do the job and produce the required x-ray luminosity. The idea that globular clusters contain such maxi-black holes seemed at first to be quite attractive, and it may still be the right interpretation.

However, another interpretation is possible. The globular-cluster x-ray sources are not drastically different from other x-ray sources in the Milky Way galaxy. Their main peculiarity is that there are so many of them in these star clusters. George Clark of MIT has proposed that there are special conditions in globular clusters that favor the formation of the type of binary system that tends to produce x rays when one star dumps mass onto a neutron star or black-hole companion.

How do we decide which interpretation is correct, or if some other interpretation is needed? Several questions can be asked, and the next generation of x-ray satellites, the HEAO's, can answer them. Are the x-ray sources at the cluster centers? They would have to be, if the black-hole model were to be the right one. The HEAO's can find out whether these x-ray sources are all, in fact, at the cluster centers.

There are other ways that a 1000-solar-mass black hole at the cluster center would show up, for it would act as a strong gravitational influence and a larger-than-normal number of stars would collect around it. Such a concentration of stars would appear as a bright peak of light in the cluster center. This peak of light has, in fact, been seen in one of the x-ray-emitting globular clusters, but it can be interpreted in other ways.[3] We can also ask whether the appearance of 1000-solar-mass black holes at the center of globular clusters is reasonable, given what we know about these star clusters. Calculations show that a massive black hole at the cluster center would not grow fast enough to reach its present size by swallowing stars in the 15 billion years since the cluster formed.[4]

Thus the interpretation of globular-cluster x-ray sources is ambiguous. As I read the technical literature, I have the impression that the majority view favors the binary-star interpretation of these x-ray sources. The case for maxi-black holes of 1000 solar masses in the center of these clusters is not compelling.

A tour of the x-ray zoo

X-ray telescopes in satellite observatories have discovered an enormous variety of x-ray sources. Some of these sources are related to normal processes of quiescent stellar evolution. For example, the surfaces of some very hot white-dwarf stars emit x rays just because they are hot. But the most powerful x-ray sources involve other types of phenomena, phenomena that play key roles in the search for black holes. It is worth reviewing x-ray astronomy to see how analysis of present observations, supplemented by new data, will improve our understanding of the way that stars die, and the possible presence of black holes in some x-ray sources.

What types of animals are in the cages of this zoo of x-ray sources? Some x-ray sources pulsate, and are identified with neutron stars in binary systems. (I discussed these in Chapter 3.) Others flicker; one of the flickering ones is our best black-hole candidate, Cygnus X-1. Eruptive x- and gamma-ray sources flare up to extremely high luminosities and then subside in periods ranging from seconds to weeks. Several x-ray sources, including many of the bursters, are identified with globular star clusters. What general patterns can be found in these phenomena?

Many x-ray sources involve dead stars—neutron stars or black holes—in double-star systems. Mass dumped onto the dead star swirls around it, forming an accretion disk, and emitting x-rays. A working hypothesis is that many if not all x-ray sources found in the Milky Way galaxy involve dead or dying stars, and so an extremely active area of research involves the violent and nonviolent ends to stellar life cycles. X rays tend to be produced in double-star systems, where mass is dumped onto a stellar corpse. Thus a related unifying thread of x-ray astronomy is the accretion disk.

So far, this chapter has concentrated on stellar black holes, the subject of Chapters 2, 3, and 5. Most research is directed toward these objects, since the chances for conclusively proving that black holes exist seem highest in this aspect of the search. But black holes come in all sizes, not just the 10-solar-mass regular size. Globular clusters may contain maxi-black holes, with masses of several hundred solar masses. Mini-black holes—black holes far smaller than stars—may also exist. A rather curious property of mini-black holes is that the classical theory of gravitation due to Einstein is insufficient to describe them completely. Consider the properties that quantum mechanics gives to these mini-black holes, and a surprising thing happens: They explode!

Frontiers: exploding mini-black holes

Prior to the mid-1970s, all exploration of black holes involved the use of Einstein's theory of gravitation in its pure, unmodified form. The singularity was treated like a point mass, but even if it were a tiny glob of matter, like an enormously dense billiard ball, the classical properties of matter would not be different. The large-scale properties of black holes would not be different. The large-scale properties of black holes were the focus of attention, and the changes to the picture that the small-scale nature of matter produces were not considered (largely because no one knew how to calculate what they were).

Yet matter does not consist of tiny, billiard-ball-like particles. Electrons, protons, and neutrons, the constituents of matter at the atomic level, are not little tiny marbles. Electrons in atoms are more correctly visualized as clouds of charge. Recall the photograph of a molecule in Figure P-2; here the electrons are seen to be a few angstrom units across, not tiny points.

It was in the 1920s that physicists, seeking to understand atoms, developed quantum theory in order to explain the behavior of matter on a microscopic scale. It is not possible to locate a subatomic particle—an electron, for example—precisely. You cannot say that *now* it's on one side of a nucleus, and that at some subsequent moment it's on the other side of a nucleus. All you can say is that over a period of time, there is a certain probability of that electron's being in a particular place. To understand exploding mini-black holes, you don't need to understand all the details of quantum theory. The key concept is the concept of *uncertainty*—that you cannot precisely locate a very small particle, but can only specify probabilities that it is in one particular place. Readers interested in exploring quantum theory somewhat further will find Banesh Hoffman's book, *The Strange Story of the Quantum,*[5] a book written at the same level as this one, quite fascinating.

What makes black holes evaporate?

But this book is about black holes, not quantum theory. So let's see what happens when you apply quantum theory to black holes, exploring the discovery of the evaporation of tiny black holes by Stephen Hawking, a British physicist. There are two ways to visualize the way that this evaporation takes place, illustrated in Figures 6-2 and 6-3. Take Figure 6-2 first. Quantum theory states that on a small scale, particles are smeared out, looking like tiny clouds. From this viewpoint, the singularity at the middle of a black hole cannot be seen as an infinitely tiny marble, but must be seen as a cloud of matter. You can make statements only about the probability of where the singularity is at some instant in time.

For a 10-solar-mass black hole, the difference between the quantum and classical picture is relatively unimportant. The smeared-out singularity is deep within the event horizon, and the difference between this smeared-out singularity and the pointlike singularity of classical black-hole theory seems not to matter much. But for a mini-black hole, the smeared-out singularity is larger relative to the size of the black hole.

The shaded regions in Figure 6-2 do not show the full extent of the smeared-out singularity. The probability of finding it near the center of the hole, in the dark shading, is quite high. However, there is still a small—but nonzero—probability of finding some of the stuff in the singularity far away from the center of the hole. Someone taking a series of snapshots of the black hole might, once in the age of the universe, find some of the black-hole stuff far away from the center, even outside the event horizon. At such a time, this material might be able to head away from the black hole, tunneling out of the event horizon.

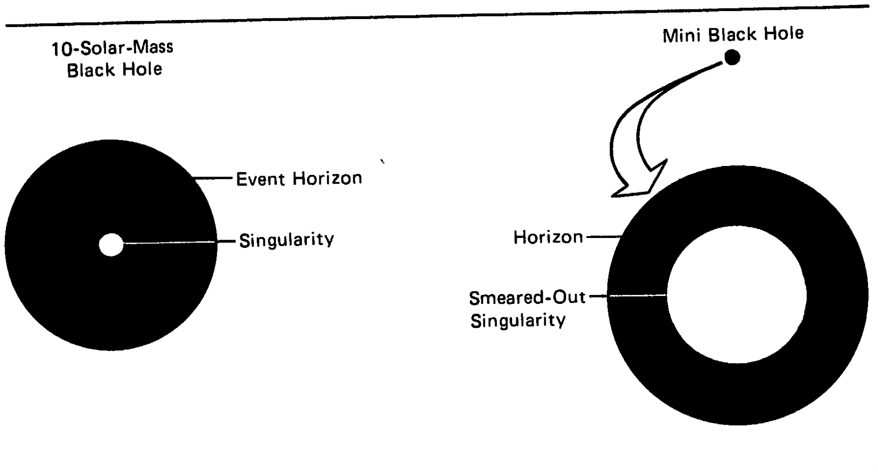

FIGURE 6-2 Quantum effects cause mini-black holes to evaporate. In a large, 10-solar-mass black hole (left), the smeared-out singularity is well within the event horizon. But in a mini-black hole (enlarged view at right), the singularity is reasonably large compared to the size of the event horizon, and there is a finite probability that some of the mass in the singularity will be found outside the horizon.

This process of evaporation would accelerate, for it is the small black holes that have event horizons closest to the singularity. Once a mini-black hole lost a little matter, it would become smaller and more susceptible to losing more. This process would accelerate until nothing was left.

It is possible to view the evaporation or explosion of mini-black holes in another way, a way that is a little harder to visualize but a little closer to the way that contemporary physicists conceive of the miscroscopic world. This view, shown in Figure 6-3, translates the somewhat vague concept of a "smeared-out singularity" into a cloud of *virtual particles* that surround any object that produces a strong force. These virtual particles are identical to real particles, save for the fact that they appear and disappear in very short periods of time. Objects interact with each other by the interaction of their attendant clouds of virtual particles.

What then happens to an evaporating black hole is not too hard to visualize, once you have made the conceptual leap (a leap that I find is not easy!) of viewing every particle in the universe as carrying along its escort of virtual particles. Again, it is the smallness of the event horizon in a mini-black hole that makes them evaporate in reasonable periods of time. There is a small probability that one of the virtual particles surrounding a mini-singularity will find itself outside the event horizon, on a path that will carry it far, far away from the black hole. Again, in this process the mini-hole loses mass, and the evaporation process accelerates. Eventually the mini-hole disappears in a cloud of high-energy particles, virtual particles that managed to find themselves outside the protective cloak of the event horizon.

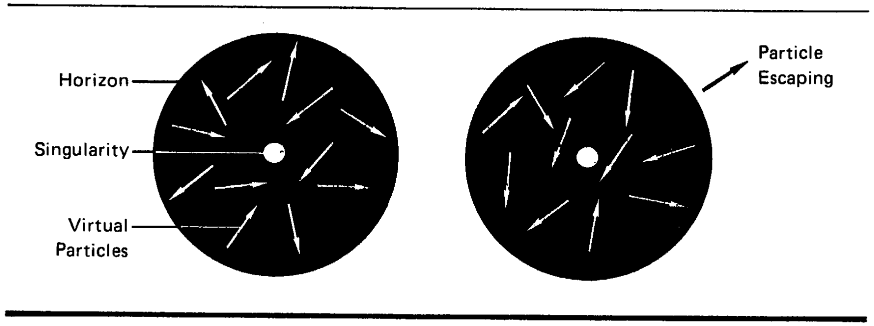

FIGURE 6-3 The particle viewpoint of the evaporation of black holes. Any mass is accompanied by a cloud of virtual particles (arrows). These particles are called virtual because they appear and then disappear so fast that they don't live long enough to be observed. It is possible that a virtual particle near the singularity of a mini-black hole will end up outside the event horizon of the hole. The hole will lose a bit of mass, and start to evaporate (right).

The concept of evaporating, or exploding, black holes would be nothing more than good fun for theoretical physicists were it not for the impact that Hawking's discovery had on our interpretations of the real world. An intriguing area of somewhat speculative research deals with the possibility of confirming the picture of exploding mini-holes by some kind of observations. In addition, this analysis has produced some radical revisions in our thinking about the conceptual impact of the idea of black holes on an overall, almost metaphysical view of the universe.

A search for mini-black holes

So what? So black holes evaporate, and the small ones evaporate more readily. Is this not yet another version of the Pygmalion syndrome, theory for the sake of theory? A skeptic might ask these questions. But it turns out that it is possible to observe mini-black holes evaporating, and that even a failure to observe such events could produce some insight into the early stages of the Big Bang, the explosion that marked the beginning of cosmic evolution.

What kinds of black holes might evaporate? The larger a black hole is, the slower the evaporation process is. The universe has been around for 10–20 billion years, and any black holes larger than 10^{15} grams would not have evaporated yet. Thus the search for evaporating holes must be confined to these tiny ones. The event horizon of a 10^{15}-gram black hole is 10^{-28} cm in radius—a very, very small distance. Now that we have specified the kinds of black holes that might evaporate now, let us ask the two questions involved in any search: How do you make them? and How do you find them?

Mini-black holes are made—if they are made at all—in the early stages of the exploding universe. 10^{15}-gram objects currently found in the universe have made their peace with gravity, since they are rigid enough to support themselves against gravitational forces. In the Big Bang, the matter that at present makes up the universe expanded and cooled. Did it expand smoothly, uniformly, like a high-speed version of the slow, languid flow of the Mississippi River? Or was the early expansion like a turbulent, white-water mountain stream, with small condensations of hot gas colliding, annihilating, and colliding again? Bernard Carr[6] has shown that unless the expansion was reasonably smooth, primordial black holes might well form. In fact, a very turbulent early universe might produce lots of them.

So now we go and look for them. An evaporating black hole produces a horde of particles tunneling out through its event horizon as it shrinks to nothingness. Calculations[7] show that many of these particles are gamma rays, so observers seek to find bursts of gamma rays in the universe. You are probably thinking that the gamma-ray bursts discussed earlier in this chapter might be just the gamma rays that are sought. However, the observed gamma-ray bursts are not rapid enough, nor are the gamma rays of high enough energy. Searches for the higher-energy, rapid-fire gamma-ray bursts from exploding black holes have been unsuccessful, and limits show that there must be fewer than a few thousand mini-black holes per cubic parsec. Under some circumstances, the limit might be reduced even further.

Another, far more speculative attempt to find mini-black holes was made by two theoretical astrophysicists who postulated that one of these objects collided with the earth in 1908. In June of that year, the Yenisei Valley in Siberia was devastated by a collision with some object from space—something that killed hundreds of reindeer (no humans) and scorched the forest for miles around. Because Russia was preoccupied with events that had a different kind of violent impact (the beginning rumblings of the Russian Revolution), the site, named Tunguska, was not scientifically explored until 1927.

Various people have proposed a number of possible objects as the source of this explosion. The theories range from the commonplace to the bizarre, and the commonplace theory is probably correct. It was probably a small comet, a chunk of ice a few hundred yards across, that collided with the earth in 1908. This model explains what happened. A small comet would evaporate in the atmosphere, leaving no remnant (as was observed); would have produced most of the damage from above (as was observed); and would have left some dust in the atmosphere (as was observed). Yet the success of the comet model has not deterred other speculations.[8]

In 1972, two theorists from the Center for Relativity Theory at the University of Texas speculated that a mini-black hole collided with the earth, sliced through it like a hot knife slices through soft butter, and came out the other side of the planet (conveniently, in the Atlantic Ocean where there were no trees, reindeer, or other objects to record the devastation). But the exit of this tiny object would have produced atmospheric shock

waves, which were not observed. Further, its passage through the earth would have produced earthquakes, which again were not observed. But the strongest argument against the black-hole interpretation of the Tunguska event is that it is extraneous. There is no need to invoke a black hole to explain what happened. (Further, there is no need to invoke antimatter or alien spaceships either.)

To summarize: There is no observational evidence that mini-black holes exist. Searches for gamma-ray blasts from exploding mini-black holes have been unsuccessful. Even stranger proposals involving collisions between such objects and the earth have not withstood scientific scrutiny. The lack of abundance of these objects has allowed us to rule out some of the Big Bang models in which the early stages of the expansion were exceedingly turbulent. But you should keep in mind that these mini-black holes don't have to exist at all, for there are Big Bang models in which they never form.

Frontiers: testing general relativity

So far I have been assuming that the general theory of relativity, proposed by Einstein in 1915, is the correct description of the way that gravity works. This theory has not gone unchallenged; close to a hundred competing theories have appeared in the scientific literature since then. These theories have all been tested, and most (some believe all) have failed to withstand the scientific test of agreement with experiment. There are various types of tests that a theory must pass: It must be complete and self-consistent. It must produce effects on orbiting planets that agree with recent observations. It must agree with a number of other ways in which the nature of gravity has been probed by experiments.

The first requirement that any theory of gravitation must meet is that it be complete and self-consistent. A theorist must be able to predict the results of a well-defined experiment or observation from a clearly stated set of first principles. As new experiments are done, you cannot just keep making up new physical laws to account for the experimental results. The set of first principles, basic physical laws, must be so complete that any experimental situation involving the forces that the theory explains (in this case gravity) can be modeled. The results of the model calculation must agree with experiment, within the limitations of each. Self-consistency requires that various mathematical approaches to the model calculation produce the same result. An example of an incomplete theory is Milne's kinematical relativity, proposed in 1937. This theory is unable to make any statements about gravitational redshifts. Although you could postulate gravitational redshifts as an additional physical law, the need to make such an extension of the theory shows that it is incomplete.

A surprising number of theories turn out to be incomplete or inconsistent. Many laymen have ideas that appear to be original, at least in the sense that these ideas have not migrated to the nontechnical literature. These ideas sometimes are written up as "theories" and are then sent to scientific journals or scientific societies. But an idea by itself, whether original or not, is not a theory. These "theories" generally start and end in thin air, since they are often just isolated ideas. A theorist must be able to show how an idea can be interwoven with all the other physical laws that apply to that particular field of science. A theory must be able to produce models that can then be experimentally tested.

Yet completeness and self-consistency, the ability to model experimental situations, are not the only tests that a theory must pass. General relativity and other modern theories of gravitation agree with the laws of Newton as long as the forces of gravity are extremely weak. Thanks to centuries of observation of planetary positions, we know that where gravity is weak, Newton's laws describe the motion of objects to a high degree of precision. Any new theory must agree with Newtonian theory in situations in which gravitational fields are extremely weak. And if a new theory of gravitation appeals to a connection with some other forces, like electromagnetism, it must agree with the classical descriptions of electromagnetism in situations in which those classical descriptions have been tested.

Yet even if a theory is complete, self-consistent, and in agreement with Newtonian theory in situations in which gravity is weak, it has to agree with a number of additional experimental tests. Einstein's theory of gravitation does differ from Newton's in several important ways. Many of the critical differences have been tested by experiment. For example, Einstein's theory states that any small object, no matter what its nature, falls under the influence of gravity. Such an assertion can be tested inexactly by dropping hammers and feathers in the lunar vacuum and seeing them hit the ground at the same time. Or it can be tested more precisely by carefully designed experiments that confirm this assertion to one part in a trillion.

In addition, there are a variety of fairly subtle effects of general relativity on the motions of planets. For example, the long axis of Mercury's egg-shaped orbit moves about 43 seconds of arc more per century (two parts in ten thousand) in Einstein's theory than it does in Newton's. Experiments in the 1970s showed that these subtle effects agree with models based on Einstein's theory within a percent or so. The high precision of these experiments has ruled out a number of competing theories of gravitation.[9] Some readers may have heard of the Brans-Dicke theory of gravitation, for example. The Brans-Dicke theory (also proposed by Jordan) enjoyed a fair degree of popularity in the late 1960s. Now, however, it is out of favor, since it does not agree with experiment.

Experimental tests based on the motion of planets in the solar system and on various terrestrial experiments share the weakness that in all cases the gravitational fields are quite feeble. There are a few theories of gravitation that produce the same results as Einstein's in such situations. These theories cannot be tested by solar-system experiments because in such experiments they agree with general relativity. Many of these theories have been proposed as mere foils to Einstein, as simple demonstrations of the existence of such theories. Such theories are conceptually equivalent to Einstein's.

Another theory that agrees with Einstein's in solar-system experiments, one proposed by Nathan Rosen in the 1930s, has the virtue that it was proposed before solar-system tests became quite accurate. Rosen's theory does not permit the existence of black holes, but it does permit supermassive neutron stars. Were Rosen's theory correct, the companion to Cygnus X-1 would be a large neutron star rather than a black hole.

A test of a theory like Rosen's requires a situation in the real world in which gravitational fields are quite strong, not weak, as they are in the solar system. It would be tempting to appeal to black holes as a test of such a theory, but it is very difficult to observe them, and very hard to imagine a situation in which an observation of a black hole would test a theory of gravitation rather than somebody's model of the structure of an accretion disk.

A cleaner test of gravitation theories comes from observations of very close double-star systems, where the strong gravitational interaction between two closely orbiting, massive objects produces some unusual effects. The changing gravitational forces in such a system produce *gravitational radiation,* fluctuating gravity fields that travel through space and carry energy away from the system. Consideration of this radiation can rule out Rosen's theory of gravitation on the basis of observations of a double star, consisting of a pulsar and a non-pulsating neutron star, the binary pulsar PSR 1913+16.

Frontiers: gravitational radiation

Many of the astronomical phenomena described in this book were discovered because astronomers developed new ways of looking at the universe. You have already seen the key role that x-ray astronomy has played in the search for black holes. The centerpiece of Part 2 of this book, the quasar, was discovered largely because radio astronomers picked up and analyzed radio waves emitted by celestial objects. Thanks to this history, astronomers have a keen interest in detecting new forms of radiation from the cosmos. By the beginning of the 1980s, we have exhausted the electromagnetic spectrum; all wavelengths of electromagnetic radiation have been detected from objects outside the solar system. Gravitational radiation may be one of the next frontiers, though at the present time the direct detection of this form of radiation appears to be quite difficult.

The generation of gravity waves

How might gravitational radiation, *gravity waves,* be produced? Consider a collection of massive objects, objects the size of stars or larger. These objects could be individual stars or parts of one larger star about to evolve violently. Put these objects very close together. Now let these objects fly about madly, rapidly orbiting each other or chaotically collapsing toward each other. Such a violently evolving object or collection of objects would be a source of gravitational radiation.

What produces the gravitational radiation? Imagine standing very close to this event, and measuring the gravitational fields from this collection of madly collapsing or circling matter. The gravitational field you measured would change rapidly in both intensity and direction as the massive objects, each a source of gravity, moved around. Someone standing close to a radio transmitter would see a similar changing electrical field because electrons in the transmitting antenna are accelerated by electrical forces.

The scenario of the last two paragraphs does not involve any particular theory of gravitation. Such an event could occur in Newton's theory. However, in Einstein's theory of gravitation, the changing gravitational fields seen by someone close to the rapidly accelerating masses propagate through space at the speed of light in the same way that electrical disturbances propagate in the form of electromagnetic radiation. Someone anywhere in the universe could detect this gravitational radiation by measuring small changes in the gravitational field at a particular location.

Thus, in principle, gravitational radiation can exist. But as scientists we are interested in real, observable phenomena, not phenomena that exist only "in principle." Black holes and neutron stars remained in limbo for decades as objects that might, in principle, exist, but could not be observed with the techniques available in the first half of the twentieth century. Gravitational radiation has had a similar history, with a long dormant period that separated the theoretical discovery of its existence and the first searches for it. The development of the first pioneering gravity-wave telescopes and the realization that violent astrophysical events could produce detectable amounts of this radiation produced a resurgence of interest in this field.

The detection of gravitational radiation is a difficult job. Consider two masses separated by some distance, as shown in Figure 6-4. When a gravity wave passes by, the gravitational field in the vicinity of these two masses fluctuates slightly, and the masses start moving back and forth. You can detect a gravity wave by observing the tiny motions of these masses. It sounds simple, but in practice it is extremely difficult. Were a 10-solar-mass star to collapse to form a black hole at a distance of ten parsecs, and were gravitational radiation to be generated by this event at the maximum conceivable rate, the separation between two masses would change by one part in 10^{14}, ten parts per quadrillion. Detecting gravity waves is a difficult job.

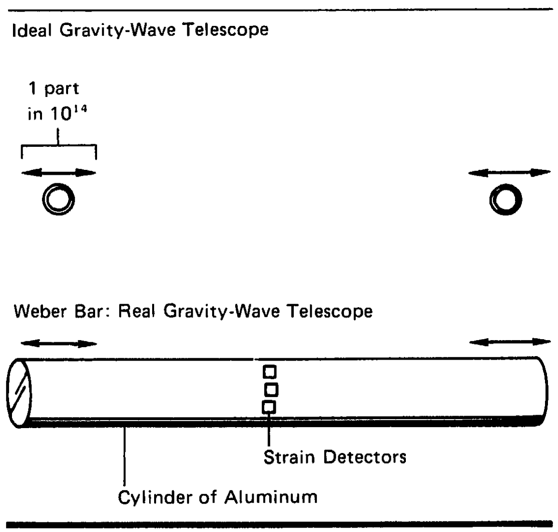

FIGURE 6-4 Detectors of gravitational radiation. An idealized telescope consists of two masses some distance apart. A gravity wave causes these masses to oscillate. Because it is very difficult to measure the separations of masses with the required accuracy (one part in 10^{14} for the strongest conceivable gravity wave), most gravity-wave telescopes are long bars with strain detectors to measure the strain on the bar produced when the ends oscillate.

Large amounts of gravitational radiation might be produced in situations in which large masses move around each other or otherwise accelerate quite rapidly. Many of the events discussed in Part 1 of this book are good candidates as sources of gravity waves. Were a massive black hole at the center of a star cluster to eat a star, the final stages of this process would produce a rapid acceleration of the star, considerable distortion of the gravitational fields from it, and a detectable burst of gravitational radiation. A collision between two black holes—a very improbable event—would produce enormous gravity waves. The most plausible violent event that would produce gravitational radiation would be the final collapse of a massive star to the neutron-star or black-hole state. It is possible, but not certain, that this final collapse would occur chaotically, producing the violent motions needed to make gravitational radiation. Rapidly orbiting double stars are less violent forms of sources of this radiation, and radiation from one such system may have been detected indirectly.

Possible observation of gravity waves: the binary pulsar

In the late 1950s and early 1960s, several astronomers added some numerical estimates as flesh to the skeletal picture of gravity waves outlined above. These calculations showed that it would be extremely difficult to detect gravity waves from any reasonable source of them. A stroke of luck, such as a supernova explosion within a parsec or so of the sun, would be needed to produce enough radiation to be observable. Joseph Weber, pioneer of gravity-wave research, proceeded on undaunted and built the first gravity wave telescopes. Astronomers and physicists involved in the field give Weber enormous credit for his pioneering work, in spite of the fact that his claim to have actually detected gravity waves has been discredited because no one else has been able to duplicate his observations.

Weber's detector is the prototype of the advanced gravity-wave telescopes that are currently under construction. An idealized gravity-wave detector (Figure 6-4) would consist of two masses, which would oscillate with respect to each other when a ripple in the gravitational field passed by. Currently, real detectors are long bars of aluminum. Each end of the bar moves when a gravity wave passes by, and since the two ends are separated, they oscillate differently. The different motions of the two ends of the bar produce strains that are detected by detectors mounted around the belly of the bar. The most powerful astronomical source imaginable, a very chaotically forming 10-solar-mass black hole collapsing 10 parsecs away, produces a strain on the bar of one part in 10^{14}, or 10 parts in a quadrillion.

In the early 1970s, pioneer Joseph Weber startled astronomers with his claim that his detectors had actually seen gravity waves. Were his observations correct, an unbelievably powerful source of gravitational radiation would have had to be located at the galactic center, since that was where the radiation seemed to be coming from. As soon as his results were published many other investigators set up their own radiation detectors, but no one was able to confirm Weber's results, in spite of doing experiments that were far more sensitive. At this time, the consensus is that Weber's data-analysis procedures were at fault; few astronomers believe that he actually found gravity waves.

Despite the false alarm, gravity-wave astronomers have not given up. Current experimental efforts are all based on Weber's original idea. More sensitive telescopes use better materials and cool the bars so that thermal vibrations do not set off the strain detectors, mimicking gravity waves. Yet the prospects for immediate positive results are not good. Even the detectors of the early 1980s cannot see the gravitational radiation from the collapse of a massive star unless the star is within a dozen parsecs or so, and such an event is rather unlikely. Gravity-wave astronomy is not even in its infancy; it is in a stage of gestation.

Although direct detection of gravity waves is still in the future, gravity waves may have been indirectly detected by radio astronomers. Double stars can be good gravity-wave sources; the fluctuating gravitational fields produced by the rapid motion of two stars around each other can carry away energy. But for most stars, observations of the orbit are so imprecise and the motions are so slow that the tiny amounts of energy carried away by gravity waves could not be detected for centuries. But as soon as the binary pulsar, PSR 1913+16, was discovered in 1975, a spate of theoretical papers appeared that showed that gravitational radiation would carry away a detectable amount of energy from the system. And, in late 1978, a team of radio astronomers announced that they had seen an energy change that was equal to the change that would be expected as a result of gravity waves.

PSR 1913+16 consists of a pair of neutron stars, each with a mass of roughly 1.4 solar masses, orbiting each other in an elliptical orbit. On the average these stars are 2.8 solar radii apart, and it takes them 7¾ hours to complete their orbit. Their average orbital speed is about 0.001 of the speed of light. This rapid motion produces gravity waves that decrease their orbital period by 0.0001 second per year. Joseph Taylor, Peter McCulloch, and Lee Fowler of the University of Massachusetts announced their discovery of such an orbital decrease in late 1978, at a "Texas" symposium on relativistic astrophysics that was held in Munich, Germany.[10] (These "Texas" symposiums were originally held in Texas, but now they are held in various places; their proceedings are published by the New York Academy of Sciences.) Although this detection of gravitational radiation is only indirect, if it stands up to critical scientific scrutiny, it does represent an important confirmation of Einstein's theory of gravitation. Further, if gravity waves exist, Rosen's theory of gravitation would be shown to be wrong, since the binary pulsar would produce far too much gravitational radiation to be compatible with observations of its orbital change.[11]

Gravity waves represent a speculative research frontier. Einstein's general theory of relativity predicts that they do exist. However, they are very weak and difficult to detect. Direct searches for gravity waves have not been successful. The only real detection of this radiation has been an indirect one, based on careful observations of the orbit of a binary pulsar. But even if you believe that gravity waves have not yet been seen, they are still within the mainstream of scientific research. Their existence is firmly founded in theory and they can, in principle and quite possibly in practice, be observed. Fringe areas of black-hole research involve work that is less well founded in theory and is impossible to verify by observation, since these fringe areas involve the unknown and so far unknowable lower depths of the black hole, the region of space inside the event horizon.

Fringes

Papers dealing with speculative areas of research occasionally appear in the scientific literature. Any paper published in a scientific journal is generally critically examined by other scientists, who determine whether it has scientific value. Scientific referees and journal editors hesitate to reject all speculative papers, since something that appears to be far out on the fringes of science today may well turn out to be important tomorrow. Anyone trying to make an accurate assessment of the correctness of these speculative ideas has to be aware of the ideas themselves and criticisms of the ideas that appear in the literature.

These speculative topics, called fringes in this book, have great appeal to people who seek strange phenomena. Several books at the nontechnical level have dealt with these fringe areas.[12] Unfortunately, authors of these books, when writing for their lay audience, present a rather one-sided view of the scientific research literature. This lay audience naturally has not read the papers in the scientific literature, including the more skeptical ones. Readers interested in more details on the topics in this section will find William Kaufmann's book, *The Cosmic Frontiers of General Relativity,*[13] interesting. Kaufmann does mention the skeptical viewpoint, but not as prominently as I do here.

An uncritical scan of the scientific literature can turn up a variety of strange beasts that are vaguely connected with the black-hole phenomenon. Two that are dear to the hearts of science-fiction enthusiasts are white holes and space warps, or wormholes. A *wormhole* is a tunnel through space: Fall into it, and you emerge somewhere else in the universe, or even in "another" universe (whatever that means). A *white hole* is a time-reversed black hole. A black hole forms when stuff falls inward through an event horizon; a white hole is the eruption of stuff outward through an event horizon. Wormholes and white holes are mathematical creatures, not real ones.

A proper appreciation of the distinction between mathematical models and the real world provides the foundation for understanding just how worm holes and white holes fit into the world of black holes and associated phenomena. Recall our discussion in Chapter 1 of how science works. People make observations of the real world and seek to interpret these observations by creating mathematical models, idealized mental pictures of what is going on. These models are essential tools in the development of an understanding of a natural phenomenon, since we can only observe or experiment with the results of natural forces, not observe the forces directly. A mathematical model consists of calculations of the structure and behavior of matter. One can do calculations to describe the behavior of a wide variety of objects. The calculations that are useful for scientific research are those that depict objects that do exist or could exist in the real world.

Survey the different ways in which solutions to the Einstein equations have appeared in the book so far. When the mathematical idea of a black hole was first developed by Karl Schwarzschild in 1916, black holes had not been discovered. Schwarzschild's calculations were interesting because black holes could exist, and we now believe that they do exist. Calculations of the structure of accretion disks are models of a real phenomenon, the phenomenon that produces x rays from sources in the Milky Way galaxy. People test various theories of gravitation by calculating the effects of these different laws of gravitation on orbiting objects like planets

and the binary pulsar; here again, the calculations represent models of real objects. Hawking's calculations of the behavior of tiny, evaporating black holes are calculations of phenomena that could exist and could be observed.

Calculations or mathematical concepts can be irrelevant to the real world. Consider negative numbers. There are some circumstances in which negative numbers are useful and do correspond to something real. Suppose you are overdrawn at the bank by, say, \$100. A useful way of stating this is to say that you have a negative balance, a balance of minus \$100. But consider another situation. Say you are counting the number of apples in an apple orchard. You can, in principle, come up with a negative number. "There are −400 apples in the apple orchard." It's easy to write such a statement, but it doesn't mean anything. It doesn't have anything to do with real apples. (On the other hand, it *could* be relevant to reality, if you were an apple grower and sold somebody 400 apples that you didn't own.)

Now focus on the world of black holes. All the theoretical statements here and in Chapter 4 are based on solutions to the Einstein equations. These solutions must be idealized ones; a collapsing star is such a complex system that an exact solution that is valid for all times is impossible. The idealizing simplification is the assumption that the object at the center of the black hole is a point mass. Such a solution will be a valid representation of space and time after a star has formed to create the black hole.

To describe a real black hole, then, you take the Schwarzschild calculations of the behavior of space and time around a point mass and examine the part of these calculations that corresponds to times after the point mass—the singularity—has formed.

Examine other parts of your mathematics and you will find strange objects—wormholes. These wormholes, or space warps, are passages that connect our universe with a region of space and time that looks very much like a region of space outside a black hole, possibly another part of our universe. They are found by examining parts of the Schwarzschild solution to the Einstein equations that correspond to times before the black hole had formed. Imagine, say, an observer inside an event horizon, and visualize what this observer would see at earlier and earlier times. Go back far enough, and this observer would see the star that made the black hole collapsing under the influence of its own gravity. Go back further, ignoring that in the real world this observer would be inside a star, not inside a black hole. Eventually this observer would reach the point when the singularity would open up, no longer being a point mass. In this mathematical solution, the singularity would be connected to not one but *two* outside regions of space, each of which looks like our universe. In the Schwarzschild solution for a nonrotating black hole, the connection would remain open for only a millisecond before it pinched off. In a rotating black hole, the situation becomes a bit more complex, but the essence of the solution is the same. Wormholes are found only in parts of space and time in which a mathematical solution to the Einstein equations does not correspond to the behavior of real collapsing stars. Because wormholes are mathematical creatures, you can't go out and say they exist in the real world.

White holes are another creature lurking on the fringes of the black-holier-than-thou school of astrophysics. A black hole forms when a star collapses through its event horizon and forms a singularity. The Einstein equations say nothing regarding the direction in which time goes. A solution to these equations can be transformed into another solution simply by letting time run backward. As an analogy, consider the sinking of an eight ball in the final stages of a pool game. The cue ball travels toward the eight ball, strikes it, and the eight ball falls into the pocket, striking molecules inside the pocket and setting them vibrating in random directions. It is also remotely possible that the molecules inside the pocket would all move in the same direction, striking the eight ball, and erupting it out of the pocket so that it travels toward the cue ball, strikes it, and moves the cue ball back to its initial position.

Similarly, a white hole corresponds to the event that would occur when matter erupted from a black hole, outward through the event horizon, and gushed into the universe. The probability of a white hole really existing in the universe has not, to my knowledge, been calculated, but it is probably considerably less than the probability of an eight ball erupting out of the pocket of a pool table.

So white holes, too, are only mathematical objects, unrelated to the black holes that form from collapsing stars. But even if they did exist, what would happen? Douglas Eardley, then at Caltech, published some calculations of the behavior of a white hole in 1974.[14] Eardley found that matter around a white hole would be compressed. Photons would be compressed too, becoming bluer. The compressed, high-energy state of matter in the vicinity of a white hole is termed a "blue sheet." This blue sheet would rapidly form its own event horizon, rapidly converting the white hole into a black hole. For a 10-solar-mass white hole, this conversion would take place within a few hundredths of a second. It would be only under very, very special conditions that a white hole could avoid being swallowed by its own blue sheet and immediately converted into a black hole.

To summarize, then, white holes and wormholes (or space warps) are theoretical creatures that emerge from one particular solution of Einstein's equations. They are found by looking at the region of space and time in these equations which does not correspond to anything that we know of in the real world. In addition, white holes, even if they were to arise, would be immediately transformed into black holes. At the present time, these objects are theoretical speculation on the fringes of black-hole research. The status of these objects 10 or 20 years from now is anybody's guess. I find it extremely unlikely that they will be discovered in the real world. But I could be wrong: Some of today's speculation becomes tomorrow's fact. Much of it remains speculation forever.

Black holes and the universe

Another area of speculative current research deals with the significance of black holes in relation to the evolution of the entire universe. Here, too, theorists are dealing with speculations that are certainly difficult and probably impossible to test experimentally. Yet these speculations are more interesting than white holes and wormholes, from a theoretical viewpoint, because they help develop a deeper understanding of the meaning of Einstein's theory of gravitation. The peculiar nature of the event horizon and of the singularity within it focuses some questions regarding the one-way nature of cosmic evolution, the direction of the arrow of time.

The peculiar nature of the event horizon stems from its one-way character. Things can go into a black hole; they don't come out again. For a long time, this one-way property seemed to contradict a general tendency in the direction of energy dissipation that is noticed in all other cosmic processes. Sunlight, once a concentrated form of energy in hydrogen nuclei at the solar center, flows out and is dissipated into interstellar space. Drop this book onto the floor: Energy initially concentrated in your muscles ends up in the random, disordered motion of molecules on the floor and in the sound waves that die away. (These phenomena are both examples of the application of the second law of thermodynamics.) But when something forms a black hole, energy is concentrated in the singularity. The random motions of an enormously large number of molecules in a massive star are all hidden beneath the event horizon and end up in the singularity.

The singularity itself presents some potential problems. All the mass that falls into a black hole ends up there, in an object that has zero volume and infinite density, according to classical theory. Something traveling too close to a singularity would be subject to uncalculable forces. If a theory can't calculate something, it usually means that the theory needs help. So it is with classical general relativity; it breaks down near the singularity.

Hawking's work, showing that black holes evaporate eventually, provides some escape from the theoretical dilemmas involving the event horizon and the singularity. Energy falling down a black hole is eventually dissipated into the universe. It may take a while; a 10-solar-mass black hole like the one in Cygnus X-1 wouldn't evaporate for 10^{66} years. The singularity is no longer a point with zero volume. It has a finite size, or at least a cloud of virtual particles that make it look like it has finite size. The probabilistic nature of quantum theory is substituted for the absurdity of infinite, uncalculable forces that affect something passing too close to the singularity. The plight of a phantom astronaut—falling into a black hole, forever disappearing from sight, and subjected to unknown and unknowable forces near the singularity—is eased a bit. This resourceful rocket pilot will emerge to haunt us in the future—as a cloud of gamma rays! What happens near the singularity? Einstein never completely accepted the quantum theory because it never produced definitive calculations; as he put it, "God does not play dice." But here, as Hawking put it, "God not only plays dice but sometimes throws them where they cannot be seen."[15]

Can singularities be avoided? Roger Penrose, a British mathematician who has sometimes collaborated with Hawking, has asked this question. A large part of the answer is provided by a theorem the two proved in a jointly written paper, since known as the Penrose-Hawking theorem. The theorem states that—given some technical and apparently reasonable assumptions about the global properties of the universe—anything that ends up inside an event horizon must become part of the singularity that is inside the horizon. As long as Einstein's theory of gravitation holds, the trajectories of particles must end somewhere if they are ever inside the event horizon. Singularities must exist.

Singularities are rather uncomfortable places for a theorist to consider. Classical general relativity makes no predictions about what happens near them and we lack a quantum theory of gravitation which we need to produce an accurate description. But, fortunately, all these uncertainties are swept beneath the concealing carpet of the event horizon. The effects do not appear in the observable world outside.

Is this always true, even in black holes besides the standard ones discussed here? The "hypothesis of cosmic censorship," not yet proved but probably correct, says that a singularity is always hidden from the outside world, or clothed, by an event horizon. A singularity not inside an event horizon is called naked. A naked singularity is quite obscene, for a venturesome astronaut could go near it unaware and subject himself to unknown forces. If all singularities are clothed in event horizons, then the breakdown of Einstein's theory near one is unimportant to the theory of black holes. We encounter such a singularity only when we consider the evolution of the entire universe (Part 3).

A few caveats or warnings must be given in connection with the material of this last section. The relation between black holes and the universe is based on calculations involving Einstein's general theory of relativity. Einstein's theory has been tested only in the solar system, to some extent on the earth, and in the binary pulsar. It is possible (though unlikely) that it will be drastically different on a universal scale. Some of the technical, seemingly innocuous assumptions in theorems like the Penrose-Hawking theorem may invalidate the whole framework. Further, future progress on a quantum theory of gravitation may indicate that singularities behave in surprising and unexpected ways. Particle physicists—probers of the smallest constituents of subnuclear particles—have uncovered a set of fundamental particles that exhibit some striking symmetries. Consideration of these symmetries has produced a completely new approach toward unifying a theory of quantum gravity with theoretical descriptions of other forces of Nature. This new theory, called supergravity, is still at a very rudimentary stage, and it is unclear whether it will have any impact on the results discussed in this section.

The frontiers and fringes of research related to black holes cover a wide range. The launching of satellite x-ray observatories has stimulated the discovery and analysis of an enormous variety of x-ray sources. Most of these sources involve dying stars, and some may involve black holes. Theoretical work on the explosion or evaporation of black holes has prompted searches for these mini-black holes. General relativity has successfully stood up to a variety of experimental tests. Gravitational radiation is energetically sought, and may have been indirectly detected. On the fringe are speculations regarding the possible existence or nonexistence of white holes and wormholes. Another speculative area of thought involves contemplation and calculation of the relation between event horizons, singularities, and the entire universe.

Diverse as these frontier areas are, there are some common themes that unify them. One is the importance of observation, particularly the exploration of new types of radiation from the cosmos. In the 1950s, general relativity was an inactive field of research. The simple calculations had all been done, and there was no need for complex ones, since there were no observations to compare them with. X-ray astronomy has been a great stimulus to further work.The prospect of gravity-wave astronomy may play a similar role in the decades ahead. A second unifying theme is the role of cosmic violence in generating many of the phenomena that we observe. In particular, the violent end to the lives of massive stars, the catastrophic collapse to neutron-star or black-hole dimensions, produces sources of both x rays and gravitational radiation. There are places in the universe at which this type of violence occurs on a far larger scale. Huge galaxies, objects of 10^{11} solar masses rather than 10 solar masses, have cores that may also collapse catastrophically, producing a great deal of high-energy radiation. Those phenomena are the subject of Part 2.

Note added in proof. A bizarre object, discovered in early 1979, may be related to the topics discussed in this chapter. U.C.L.A. astronomer Bruce Margon and many of his California colleagues showed that this object, SS 433, contains two clouds of gas orbiting something at about 20 percent of the speed of light. These gas clouds may be high-velocity jets emerging from the neighborhood of a black hole.

SUMMARY OF PART 1

Three types of stellar corpses may exist: white dwarfs, neutron stars, and black holes. A star dies when its nuclear fires stop providing heat to maintain the star's internal pressure, which has kept the star from collapsing under the weight of its outer layers. White dwarfs and neutron stars substitute another kind of pressure for heat pressure: degeneracy pressure. Degeneracy pressure is independent of temperature, so that white dwarfs and neutron stars can cool without collapsing. White dwarfs and neutron stars are known to exist in the real world, the former as stars and the latter as pulsars.

Black holes, if they exist, would form from the collapse of very massive stars. Neutron stars and white dwarfs are certainly no more massive than three solar masses and probably a good deal smaller than that. The central feature of black holes is the event horizon, a spherical boundary that separates the inside of the hole from the outside world. The black-hole phenomena that we can see from out here occur just outside of the event horizon, where something falling toward the black hole is compressed by tidal gravitational forces and appears to freeze just short of the event horizon. Some double stars exist whose invisible companions may be black holes emitting x rays from gas compressed as it is pulled down toward the event horizon, forming an accretion disk. Cygnus X-1 is the strongest black-hole candidate. In a few other double-star systems, the x-ray source may be a black hole.

The genuine frontiers of black-hole research were described in Chapter 6. X-ray astronomy has provided many observations illustrating the violent deaths of some stars, some of which may involve the formation of black holes. In any frontier area of science, lively controversy makes it difficult to regard all the exciting results as definitive. The following display summarizes the results of Part 1 and classifies them according to what is fact, what is working model (accepted by many people but not completely proved), and what is controversy and speculation. Working models represent viewpoints that most people believe in, but would not be surprised to see proved wrong. This field moves so fast that "facts" may be shown to be wrong later, but I certainly believe that what is called fact here will stand the test of time.

FACT	White-dwarf stars exist Neutron stars are pulsars and exist Evolution of stars through the red-giant stage Theoretical model of a classical black hole (possibly including rotation) Black holes have no hair
PROBABLE FACT	Cygnus X-1 is a black hole Low-mass stars → planetary nebulae → white dwarfs
WORKING MODEL	Medium-mass stars → supernovae → neutron stars Massive stars may become black holes Black holes evaporate (very slowly) Gravitational radiation exists Einstein's theory of gravitation (general relativity)
CONTROVERSY	Is Epsilon Aurigae a black hole? Are globular-cluster x-ray sources giant black holes or neutron stars? Are most x-ray sources in the Milky Way galaxy related to dying stars? How do pulsars produce radio emission? How massive can a neutron star be?
SPECULATION	Wormholes, white holes, and space warps

SUMMARY OF PART 2

The completion of the 200-inch Hale reflector at the end of World War II marked the beginning of the intensive study of extragalactic objects that has paid great dividends for twentieth-century astronomy. Quasars, the most luminous objects in the universe, were discovered in 1963. Since then, we have realized that there are numerous objects similar to the quasars: the active galaxies. Many mysteries remain in our work on these objects.

The following display summarizes the essential results of this section, again differentiating among fact, concrete theory, informed opinion, and speculation. Here the observers are in the forefront of research, so that most theory consists of models that are very closely tied to the real world, in marked contrast to the black-hole business where we are not even sure black holes exist.

But some questions do remain. To a certain extent, these are questions of a more detailed nature, but some of them may be rather fundamental. The new generation of satellite observatories, to be launched in the 1980s, will provide a deeper view and perhaps some answers to these questions. And it is possible that some new physical laws will emerge from further research.

OBSERVATIONAL FACT	Quasars and active galaxies exist, with emission lines, radio-frequency radiation, infrared excesses, optical variations, and x rays Very-Long-Baseline observations of the radio structure of these objects show both compact and extended sources which are aligned with each other There is activity at the center of the Milky Way galaxy
CONCRETE THEORY	Radio-frequency radiation from quasars and active galaxies is synchrotron radiation The emission-line spectra of these objects come from clouds of gas subject to ultraviolet, ionizing radiation
WORKING MODEL	Variations in the intensity of quasar continuum radiation come from the production and expansion of clouds of high-speed electrons The infrared continuum comes from dust in some cases and synchrotron radiation in others The faster-than-light expansion of radio galaxies is an illusion BL Lac objects are quasars without emission lines Some quasars, BL Lac objects, and active galaxies are at the distances indicated by their redshifts; thus they have high luminosities Galactic activity—from the core of the Milky Way galaxy through the active galaxies, the BL Lac objects, and the quasars—is basically the same phenomenon
OPEN QUESTIONS	Are continuum x rays due to synchrotron radiation or to collisions between high-speed electrons and photons? Are high-speed electrons in radio sources produced by a beam of fast particles, by the slingshot ejection of a massive object from the core of a galaxy, or do they come from an expanding, turbulent cloud? Does the energy in quasars come from collisions of stars, from the rotation of a massive object, or from a black hole? Are all quasar redshifts cosmological?

SUMMARY OF PART 3

If cosmology is to be a branch of science instead of a philosophical recreation, there must be some data that enable the real world to enter. In the 1920s and 1930s, the discovery of the expansion of the universe gave us our first handle on the evolution of the universe as a whole. The logical interpretation of that expansion was the Big Bang theory. Until 1960, however, it was impossible to decide between the Big Bang and Steady State theories, because the expansion of the universe was the only piece of information that we had on its evolution. We could measure the expansion rate and determine the age of the universe, but we could not do so accurately.

Subsequent developments have greatly refined our knowledge of cosmology. The discovery of the primeval fireball, the background radiation filling the universe, which is a Big Bang relic, confirmed the Big Bang picture. The existence of a cosmic abundance of helium strengthens the Big Bang theory, but the interpretation of the helium data is still not certain. If the radio sources and quasars are very distant objects and we are seeing them as they were when the universe was still young, their abundance in the early universe rules out the Steady State theory in its original, strictly interpreted form. As a result we are fairly confident about our ideas of the past history of the universe.

We are much less certain of the future. Will the universe go on expanding forever? A search for the necessary mass to slow down the expansion did not succeed in uncovering it, but there are places that undetected mass could be hiding. Efforts to look to the past to detect changes in the expansion rate are clouded by problems of interpretation. Recent discoveries of deuterium seem to be pointing in the direction of an open universe, but it is not yet clear where this deuterium came from.

The Big Bang theory leaves one unanswered question. Who *created* the material that exploded as the Big Bang? For this, the astronomer has no answer. We may be able to look back to the early seconds of the evolution of the universe, but our vision stops there. This book ends by leaving the problems of creation to the philosopher and the theologian.

OBSERVATIONAL FACT	A microwave background with a blackbody spectrum exists Everywhere we have looked so far, the universe seems to be about 30 percent helium Deuterium exists in the universe The universe is expanding
CONCRETE THEORY	Big Bang universes make primeval fireball radiation and primordial helium; the Steady State universe contains neither
INFORMED OPINION	Because the microwave background is radiation from the primeval fireball and because helium was made in the first 20 minutes, the Steady State theory is wrong Other alternative cosmologies also conflict with observation The Hubble constant is 50 km/sec per megaparsec, so the universe is less than 20 billion years old Currently the evidence indicates that the universe is open, but all tests relative to this question are slightly ambiguous
UNANSWERED QUESTIONS	Did the deuterium come from the primeval fireball? (If it did, the universe is open.) Can we overcome the uncertainties due to the effects of evolution of galaxies and the effects of selection and measure changes in the expansion rate of the universe? Is there enough mass to close the universe? (We haven't found it so far.)
SPECULATION	What preceded the Big Bang? The cosmological singularity? Is there any connection between this singularity and black holes?