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PREFACE

In the last decade, astronomers have discovered that violent, explosive phenomena play a vital role in cosmic evolution. For example, the end of a star's life cycle often results in violent collapse of the core. Some stellar cores become so compact that nothing, not even light, can escape from them, and they become black holes. The nuclei of galaxies contain explosive phenomena as well. The exploding nuclei of some galaxies are the most luminous objects in the universe: the quasars. In the last few years, as observations have provided confidence in our picture of cosmic evolution, there has been renewed interest in cosmology, the study of the evolution of the entire universe.

This book covers a dynamic field; the fast pace of the research frontier has called for a second edition. I am happy to report that there is little in the first edition that can be regarded as downright wrong, but there are many places in which it is now quite incomplete. I have updated all chapters and have essentially rewritten some of them in order to keep this book current.

I believe this book can fill three needs. First, many interested non-astronomers read magazine articles on black holes, cosmology, or other topics treated here and want to know more. Next, more colleges offer a course on modern astronomy, addressed to the non-science major, that goes beyond or supplements the traditional one-semester survey courses. Third, the survey courses can use this book as an enriching addition to the standard introductory texts which generally devote relatively little space to the topics treated here.

In revising the first edition, I left no chapter untouched. The treatment of pulsars in Chapter 3 is considerably expanded. Chapter 5 introduces the new black-hole candidates V 861 Scorpii and Circinus X-1, and presents recently uncovered facts regarding the prima donna of all black-hole candidates, Cygnus X-1. Chapter 6 has been completely rewritten. Most of what were classified as the frontiers of black-hole research in the first edition are now facts, and have been moved to Chapter 4. A host of *new* frontier areas have appeared: globular cluster x-ray sources, x- and gamma-ray burst sources, evaporating black holes, and the detection of possible gravitational radiation from a pulsar in a double star system.

Part 2 talks about many new phenomena related to quasars: the discovery that BL Lacerta objects are definitely active galaxies, the association of some quasars with galaxies of similar redshifts, clarification of the source of infrared emission in many objects, the discovery of radio jets, and the increasing prominence of black-hole models for the energy source. I rewrote Chapter 12, which deals with the nature of quasar redshifts, in

Yet another complication is introduced when we consider that many stars exist in binary systems. One possible scenario for the making of a black hole is to postulate a neutron star in a binary system and then imagining the companion to the neutron star dumping enough mass onto it to make a black hole. Alternatively, a white-dwarf star in a binary system could gain mass by stealing it from its companion and becoming a neutron star—or even a black hole, if it ate enough extra mass.

Thus our only firm conclusion connecting stellar corpses with the red-giant stage is the statement that low-mass stars produce white-dwarf stars. Larger stars may make white-dwarf stars, neutron stars, and black holes in some proportion. The masses of the heaviest known stars exceed 40 solar masses. These stars must lose a great deal of mass to become stable neutron stars. Stars tend to form cores that contain a third of their mass, and it seems reasonable to state that these stars form cores that cannot become neutron stars. They should become black holes. But we can't say that they *must* become black holes.

After all this academic hedging, you are probably thinking, "Get out of the computer center and into the real world. Go find black holes in the sky, not in computer models of the late stages of evolution of massive stars." That is where we are headed next. It is comforting to know that massive stars could make black holes. But first, another chapter from theory. You have to know what a black hole looks like before you try to go out and find one.

White-dwarf stars and neutron stars exist. These stars have managed to win the battle with gravity and stop collapsing, thanks to degeneracy pressure. White-dwarf stars can be seen in the sky; neutron stars have been observed as pulsars. Observations of radio and x-ray pulses from neutron stars have provided some information about the structure of these objects.

But neutron stars must evolve from stars that, at the end of their lives, are fairly small, no more massive than three or four times as massive as the sun. The only firm evolutionary connection between living stars and dead stars is the connection between low-mass stars and white-dwarf stars. One can reasonably suppose that a third type of stellar corpse—the black hole—exists, but we need to know more about stellar evolution before this line of attack can provide us with definitive evidence that black holes do exist.

A better answer to the question, Do black holes exist? would come from the real world with the discovery of one. Let's go and look. First we have to know what we're looking for.

4 JOURNEY INTO A BLACK HOLE

A black hole is the area of space surrounding an object that has shrunk to such small dimensions that its gravity becomes overwhelming. Once anything—even light—is inside the black hole, it cannot escape from the gravitational influence. Hence the name *black hole*. In principle, black holes of any size can exist, but it is difficult to see how a black hole containing less than 1.4 solar masses would form, for such small objects would form white dwarfs or neutron stars when they collapsed. A 1.4-solar-mass black hole would be just five kilometers across.

But a capsule definition of a black hole does not provide enough information to enable us to discover one. We want to bring black holes from the status of theoretical objects in the model world to the status of real objects in the real world. The search for a black hole must begin with a description of what one looks like and how it interacts with the outside world. What black-hole phenomena would render a black hole detectable? Exploration of the properties of a black hole also affects the world of physics, because physicists would like to use black holes as the ultimate testing ground for Einstein's theory of gravitation. Holes are the only places in the universe where gravity is stronger than all other forces. Some black-hole characteristics are quite odd. The theory states that there should be a singularity in the hole's center, a point at which matter is crushed to infinite density and zero volume. Does this singularity really exist? The idea sounds physically absurd. Can a theory that predicts such crazy things be correct?

The structure of black holes can be examined from two points of view. The centerpiece is a thought experiment, in which we follow the adventures of a courageous, suicidal, and indestructible astronaut who undertakes to explore a black hole by falling in to see what is there. One point of view is taken by the outside world, here represented by a rocket ship orbiting the hole at a safe distance. The other point of view is taken by the astronaut. This second approach is purely theoretical, for the astronaut could never return from the hole's interior to tell us whether our ideas are correct or not.

The standard black hole described in this chapter is a product of Einstein's theory of gravitation. This black hole is one that forms after the collapse of a nonrotating star; it obeys Einstein's theory. Adding spin to the black hole complicates the details, but does not affect the essential properties. Extending the black-hole idea to hypothetical holes that do not form from collapsing stars, or trying to modify Einstein's theory so that various uncomfortable aspects of black-hole phenomena go away, opens up new landscapes that lie at the frontiers and fringes of black-hole research (more on this in Chapter 6). The phenomena described in this chapter are based on well-understood theoretical results drawn from Einstein's theory of gravitation.

Black holes are, so far, entirely theoretical objects. Since it is plausible to expect that they exist, their properties are worth exploring. No black hole has yet been found, although there is one object that certainly looks very much like one. Black holes exist primarily in the model world. It is very tempting, especially for people who like science fiction, to succumb to the Pygmalion syndrome and endow these model black holes with a reality that they do not yet possess. Beware of this.

History of the black-hole idea

Pierre Simon, Marquis de Laplace, first thought of black holes in 1796. His initial musings were based on Newtonian gravity and Newton's now discredited corpuscular theory of light. Newton thought of light as little pellets or corpuscles, having properties like very small billiard balls. Laplace realized that such corpuscles could not escape from the surface of a sufficiently massive body. He wondered whether space would be full of these *corps obscurs,* as he called them. Maybe they would be as numerous as stars? However, there was no way to test his idea, and it disappeared into the libraries, never quoted or explored by others.

Shortly after Einstein's theory of gravitation appeared, the German physicist Karl Schwarzschild calculated what space would look like surrounding a point-mass. He thus discovered the standard black hole as an inhabitant of the model world, but he, like Laplace before him, had no idea whether such a body could really exist. This was not determined until 1939, when J. Robert Oppenheimer and a student, Hartland Snyder, showed that a cold and sufficiently massive star must collapse indefinitely, becoming a black hole. The Oppenheimer-Snyder work, appearing about the same time as the Oppenheimer-Volkoff paper on neutron stars, reached much the same conclusion: Black holes could exist. They might be real objects, not just mathematical games that people played with Einstein's theory. In the 1960s, with a revival of interest in Einstein's general theory of relativity, black holes were intensively investigated and their detailed properties were elucidated.

This history bears some resemblance to the early history of neutron stars. Both types of stellar corpse were first known as theoretical objects. Very little research was done on them until the 1960s, when advances in astronomical instrumentation and a revival of interest led them to be investigated more intensively. Unfortunately, black holes are somewhat more difficult to find than pulsars, as will become evident shortly.

Black holes and Einstein's theory of gravitation are very closely tied together. You cannot describe a black hole even remotely well with Newton's theory of gravity because Newton's theory works only when gravity is weak or speeds are small. Newton's theory may work when you try to calculate the trajectory of a thrown baseball, but close to the surface of a black hole, the effects of general relativity are overwhelming.

If black holes are so closely connected to Einstein's theory, you might well ask, What happens to them if Einstein is wrong? But Einstein's theory is almost certainly the correct theory of gravitation; it is accepted by almost all working physicists. Furthermore, most rivals of Einstein's theory are really modifications of it, descriptions of gravity that differ in detail but not in spirit from Einstein's original theory of general relativity. Experiments have ruled out almost all alternative theories of gravitation. (Chapter 6 will describe these experiments.) Those alternative theories that add a small additional effect to the basic framework of Einstein's theory amount to slight variations on a theme, and they produce black holes that are, for all intents and purposes, identical to those described in this chapter. There is one theory that is almost ruled out by the observations: Rosen's "bimetric" theory of gravitation. It is quite different from Einstein's in that it does not produce black holes.

The centerpiece of any of these theories of gravitation is the idea that gravity when it is near a strong source of gravitation, like a black hole, modifies the way that time flows and the way that distances are measured.The next few pages follow the journeys of several hypothetical astronauts who venture forth into these strange parts of the universe.

The view from a distance

One way to approach the understanding of what happens near a black hole is to suppose that you are a spaceship pilot of the future who happens to come upon one. The spaceship scenario is not necessary for our thought experiment, but it is true that you have to be quite near a black hole to really see what is going on. Furthermore, when you want to explore the black hole's immediate surroundings, you have to be close enough to drop probes into it and see what happens to them.

You can only sense the existence of the black hole through its gravity. You cannot see a black hole. No light escapes from it—that is why it is called a black hole. The first noticeable effect sensed by a spaceship would be a weak but relentless gravitational pull. The spaceship would begin to fall toward the black hole. There would be nothing very unusual about this pull, though. Gravity is ubiquitous in the universe, and any massive object would deflect the path of a spaceship.

If you wanted to explore the black hole, you might well choose to go into orbit around it. The spaceship's motion past the hole would prevent it from falling into the hole. The ship would fall around the hole in the same way that the moon falls around the earth, following an orbit. You could measure the mass of the hole by determining exactly how much the hole was pulling you off the straight-line path you were on before you encountered the object. If you were in orbit, you could measure how long it took to complete one circuit of the hole. The more massive the hole, the faster the orbiting. (A bigger hole pulls on you harder, and you have to travel faster to stay in orbit around it.) If, for example, it took 3.7947 months to make a complete circle one astronomical unit away from the hole, you could deduce that the hole had ten times as much pulling power, or ten times as much mass, as the sun. (One astronomical unit is the distance from the earth to the sun, 1.495985×10^8 km.) This is just Kepler's third law, used by astronomers to deduce the masses of double stars (described in more detail in Chapter 5). Nothing new here.

It is only when you look toward the hole that you see something a little odd. Most ten-solar-mass objects in the universe are visible. You would expect to see some sort of star at the center of your orbit; a ten-solar-mass star is generally a bright blue one. You would see nothing. You would be in orbit around an invisible object. The hole itself would be 0.08 second of arc across, or as big as a dime 15 miles away. It would take a 400-inch telescope to see the hole as a disk, even if there were anything there to see.

If you were lucky, you might be able to detect the hole in another way, since you would see light rays from stars on the other side of the hole bend as they passed by the hole (Figure 4-1). You could do this only if there happened to be stars in the right places. According to Einstein, the paths of all particles, even photons, are affected by gravity. Thus the path of a photon or light ray is bent by a gravitational field in the same way that the earth bends the path of a thrown baseball and causes it to fall. Since the paths of light rays from distant stars would be bent as they passed by the hole, these stars would seem to be out of position. The light would have to fall around the hole to reach the spaceship. This bending of light has been observed near the sun as a shift of star positions during a solar eclipse. Thus there is nothing very new about this effect; it is just that near a black hole the effect would be considerably larger.

Unfortunately neither of these two methods that a spaceship pilot near a black hole could use to detect the hole's presence would work from the surface of the earth, far away from the hole. Obviously you need to be near the hole to go into orbit around it. The bending of light by the hole, if seen from the earth, would be minuscule. No equipment now available could detect it. Observations of holes must be based on phenomena arising from the interaction of holes with the material around them.

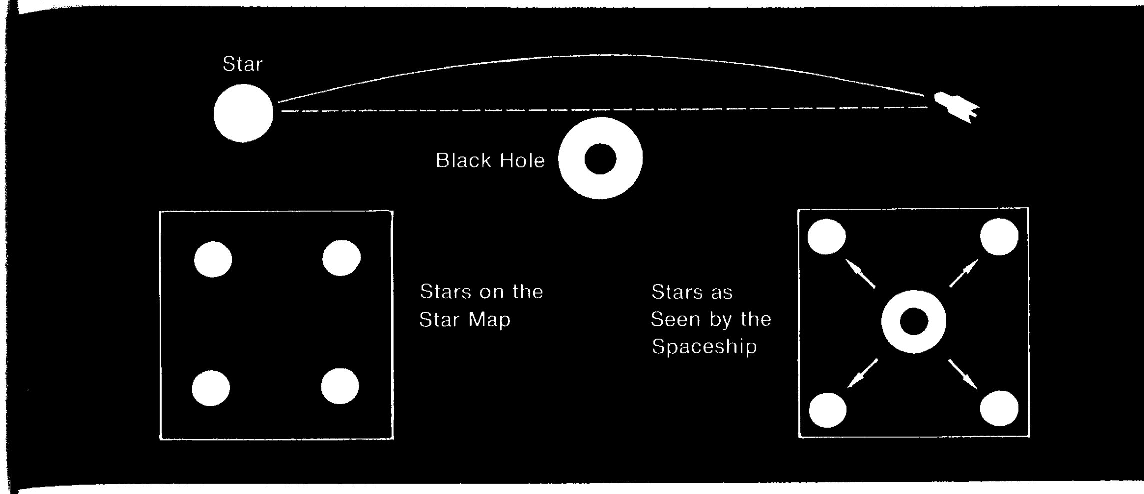


FIGURE 4-1 If you look toward a black hole from a distance, light must fall around the hole to reach your eyes. Stars near the hole would appear to be out of position.

Thus our exploration of the hole will have to be extended to the depths of the hole. Furthermore, it is impossible to find out very much about the nature of a black hole simply by looking at it, since there is nothing much to see. Our spaceship will have to send a probe toward the hole and see what happens to it.

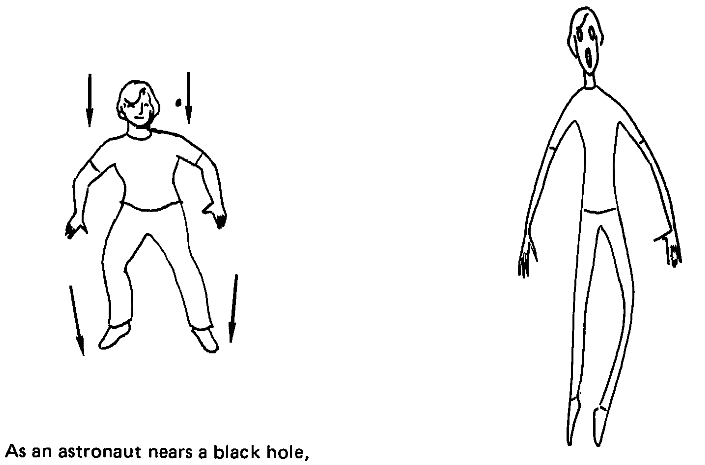
In the next few pages, for the sake of definiteness, I shall present the numerical details as they would apply to an astronaut exploring a hole of ten solar masses. Black holes forming from stellar collapse would be roughly this size. It is unlikely that any significantly smaller holes exist in the real universe; no one has figured out a way to make a hole of less-than stellar-mass. Large holes with upwards of 10^6 solar masses may exist at the center of active galaxies and quasars as the energy source of these objects, according to one idea. Events around a large hole would be qualitatively the same as events around a smaller hole, except for the strength of the tidal forces, which would be the first phenomenon encountered by a probe that was dropped into the hole.

Tides near a black hole

As the probe approaches the black hole, nothing unusual happens for a long time. Since the peculiar effects of a black hole are evident only close to the hole, this is not surprising. The first uncomfortable effect is noticed long before the neighborhood of the hole is reached, but like the bending of light, this effect is only a familiar force amplified to uncomfortable proportions; that is, tides.

Consider the effects of gravity on a person, perhaps our heroic astronaut falling to his doom, as he falls feet first toward the black hole (Figure 4-2). His legs are nearer the hole than his head, and the gravitational force pulling on his legs is stronger than the force on his head. The difference between these two forces is the tidal gravitational force, which, if unopposed, stretches the astronaut out into a long cylinder. The force arises because the closer you are to a massive object, the stronger the gravitational force is. These tides are a common feature of the interaction between two bodies, such as the moon and the earth. This tidal effect produces the ocean tides that are a familiar fact of life along the coast. They act on our bodies all the time, since our feet are nearer the center of the earth than our heads. On the earth, however, they do not present any serious threat, as they are very weak. Near a black hole they are much stronger.

Another tidal force acts as a straitjacket, squeezing the astronaut's shoulders together. All parts of the astronaut fall toward the center of the black hole. In particular his two shoulders fall on converging paths. Gravity draws them together. It is a somewhat gruesome fate for our hero, being stretched out as though on a rack and compressed by this gravitational straitjacket. Bones and muscles must resist these forces if the body is to survive. How close can anyone get to the black hole and put up with this sort of treatment?



As an astronaut nears a black hole, the difference in the gravitational force on different parts of his body will exert a force on him.

When he can no longer resist these forces, he is stretched vertically and compressed horizontally.

FIGURE 4-2 Tidal forces would distort an astronaut's body near a black hole. (The difference between the forces on different parts of the astronaut's body is exaggerated.)

Optimistically, the human body can withstand a strain of ten times the earth's gravity without breaking. Our astronaut would be 3000 kilometers from the ten-solar-mass black hole when the tidal forces became this strong. He would be killed by them before he ventured any closer. It is not easy for a live astronaut to investigate the properties of a ten-solar-mass hole.

A very large black hole would be a more favorable candidate for investigation, since you can get closer to it before the tidal stresses become severe. If you were investigating a hole larger than 10^4 solar masses, you could reach the inside of the hole before the tidal forces pulled you apart. Holes this big may exist at the centers of galaxies, but as the smaller holes are likely to be more common and are certainly more detectable from the earth, I shall stick with them.

These tidal forces are the black-hole phenomenon that gives us a chance to observe real black holes. As gas falls toward a black hole, it is compressed by these same tidal forces that make life unpleasant for our imaginary astronaut. As this gas is compressed, it heats up. Hot gas emits high-energy radiation like x rays, and it is these rays that are the sign of a black hole. Not all x-ray sources are black holes; you must closely investigate any black-hole candidate to rule out other possible sources for these x rays. (I shall return to this subject in Chapter 5.)

But these horrendous tides are not the phenomenon that makes the black hole one of the strangest concoctions that has been extracted from Einstein's theory of gravitation. The essence of a black hole is the *event horizon,* the point of no return. At the event horizon, you would have to travel at the speed of light to escape from the black hole. Since no material object can travel that fast, nothing can return to the outside world once it has stepped over this invisible boundary. As we watch our probe fall deeper into the hole, we explore the neighborhood of the event horizon.

Approach to the event horizon

The black hole affects space and time around it in two ways. Its gravity distorts and hinders the passage of signals from objects near it as they try to communicate with the outside world, and greatly distorts the passage of time. The event horizon is the edge of a black hole. Once past it, you are inside the hole, caught in its grip forever. You cannot return to the outside world. The horizon is a spherical boundary whose radius depends on the mass of the black hole. Fortunately, this radius is quite small, so the hole is small too. The radius, also called the *Schwarzschild radius* in honor of the discoverer of black holes, is numerically equal to 2.95 kilometers times the mass of the hole in solar masses. Our ten-solar-mass hole is thus 30 kilometers in radius or 60 kilometers across; an object this small is very difficult to see in interstellar space, much less run into. Because black holes are so small, the chances of a collision between the earth and a black hole are extremely remote.

The essence of Einstein's theory of gravitation is that gravity acts on particles by distorting space and time. Thus our exploration of the ten-solar-mass hole will proceed mostly by dropping clocks in the vicinity of the hole and seeing what happens to them. The behavior of falling clocks and signals from them are affected by the motion of the clocks themselves. For instance, the clocks slow down because they are moving. (This is one result from Einstein's *special* relativity theory, which has nothing to do with gravity.)

Thus our thought-experiment scenario for exploring the hole will have to be a bit more complex. Our exploring probe, manned by an indestructible astronaut, sets forth on its journey into the interior with a large collection of clocks—reliable and accurate clocks, strong enough to withstand the great tidal forces near the hole. Every once in a while, the astronaut releases a clock, tossing it into orbit around the hole. When it is in orbit, it is not moving very fast relative to the distant observer, so we can watch it from our distant vantage point and see how the black hole's gravity affects space and time, entirely apart from the way that the motion of the probe hurtling to its doom affects the way that its clocks and meter sticks work. Simultaneously, we ask what our own clocks read during the progress of the journey.

The events we see as we follow the black-hole adventure are summarized in Table 4-1.[1] The astronaut puts the first clock into orbit when he is 300 kilometers, or 10 Schwarzschild radii, away from the hole. What odd phenomena do we observe?

The first odd effect is that light from this clock, in orbit around the hole at a distance of 10 Schwarzschild radii, is redshifted. The photons from this clock lose energy as they struggle out of the intense gravitational field near the hole. They are transformed from energetic short-wavelength photons into tired long-wavelength photons, just as a person loses energy climbing a flight of stairs, doing work against the earth's gravity. A loss of energy is a loss of frequency, or an increase in wavelength. Red photons are long-wavelength photons. Therefore this phenomenon is called a *gravitational redshift.*

The column labeled Redshift lists the quantity, conventionally noted by the letter z, equal to the fractional change in the wavelength of light emitted by the clocks. (Mathematically, if the wavelength emitted by the clocks is λ and the change is $\Delta\lambda$, then $z = \Delta\lambda/\lambda$.) Thus, if the clocks are illuminated with green light with a wavelength of 5000 angstroms, that light will be shifted by 250 angstroms as it travels to the distant rocket ship ($0.05 = 250/5000$). Such effects would be observable. A shift of 250 angstroms moves green light into the yellow part of the spectrum, toward the red.

TABLE 4-1 THE EVENTS WE SEE AS WE FOLLOW THE BLACK-HOLE ADVENTURE

DISTANCE FROM HOLE CENTER		REDSHIFT	RELATIVE CLOCK RATES	TIME	
In kilometers	In multiples of the Schwarzschild radius			As seen by the rocket ship	As seen by the probe falling in
1 A.U.	4.96×10^6	0	1	0	0
300	10	0.05	1.05	204 hr 33 min 50.1129 sec	204 hr 33 min 49.6681 sec
240	8	.07	1.07	50.1135*	49.6687*
180	6	.10	1.10	50.1141*	49.6692*
120	4	.15	1.15	50.1148*	49.669666*
90	3	.22	1.22	50.1150*	49.669854*
60	2	.41	1.41	50.1153*	49.670012*
45	1.5	.73	1.73	50.1155*	49.670078*
33	1.1	2.32	3.32	50.1157*	49.670091*
30.03	1.001	30.25	31.25	50.1162*	49.670123*
$30+(3\times10^{-8288})$	$1+10^{-8289}$	$10^{4144}-1$	10^{4144}	205 hr	49.670133*
30	1	∞	∞	∞	49.670133*
15	0.5	—	—	—	49.670177*
0	0	—	—	—	49.670200*

* All items marked with the asterisks refer to 204 hr, 33 min plus the tabulated number of seconds.

Along with the gravitational redshift, the clocks close to the hole seem to slow down, as is shown in the column Relative Rate. This column lists the number of seconds ticked off by the distant observer's clock in the time that it takes the clocks near the hole to tick off one second. Thus the rocket ship's clock would tick off 1.05 seconds for every second ticked off by the clock 300 kilometers away from the hole. Clocks near the hole seem to run slowly, and events will take place in slow motion.

Once again, the gravitational redshift and the slowing of clocks are nothing very new, but close to a black hole they become extremely large. The gravitational redshift has been observed elsewhere—in white dwarfs, in the sun, and in photons sent from the basement to the top floor of Jefferson Physics Laboratory at Harvard. These two effects are related; if you run your eye down the two columns you will notice that the relative clock rate is simply $1 + z$, where z is the gravitational redshift. A relation between the rates of two atomic clocks at different altitudes was one effect observed when atomic clocks were flown around the world in commercial

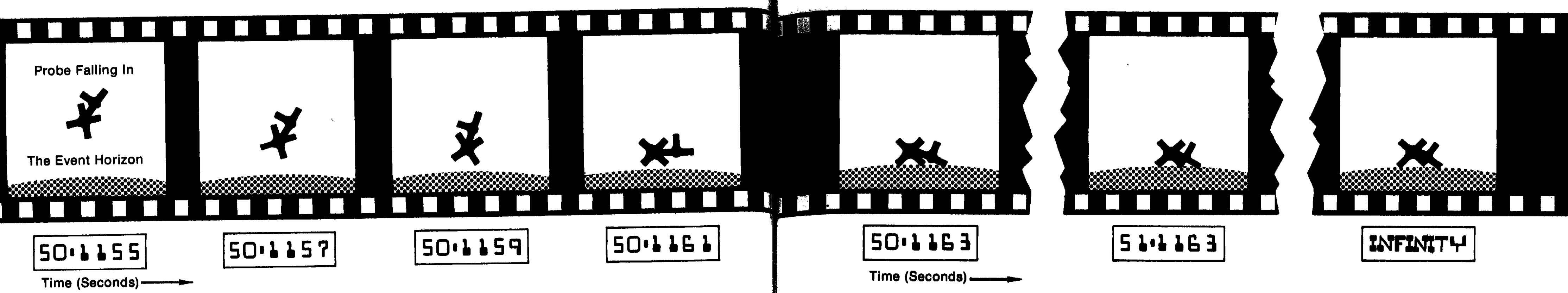


FIGURE 4-3 A movie showing how a distant observer would see a space probe approach a black hole. As the space probe falls in, its motion appears to freeze at the event horizon. (The numbers are meant to apply to the fall of a rocket ship toward a ten-solar-mass black hole as described in the text.)

airliners, but the principal effect observed in that experiment was not the effect of gravity. These peculiar effects near a black hole are just more dramatic versions of effects verified experimentally here on earth.

The astronaut's own clock and ours would disagree on how long it took him to reach the 300-kilometer checkpoint. He says that he deposited the first clock in orbit 204 hours, 33 minutes, and 49.6681 seconds after he left orbit. We should imagine his fall to that point to have taken a little longer, 204 hours, 33 minutes, 50.1129 seconds, a difference of 0.4448 second. This half-second difference between our clocks and the astronaut's clocks seems unimportant, for now. But wait. All these strange black-hole effects will become bigger as we probe closer to the event horizon.

The probe continues to fall downward as our astronaut comes closer to the event horizon, the goal of his mission. The gravitational redshifts become larger. At 120 kilometers the redshift is 0.15, and the light illuminating the orbiting clocks looks yellow to our eyes, with a wavelength of 5600 angstroms. The orbiting clocks have slowed down in proportion.They tick every 1.15 seconds according to our clocks, sitting in the orbiting rocket ship a safe distance from the black hole. That annoying half-second difference between our clock and the astronaut's is getting a little larger.

We must look fast at the orbiting clocks 120 kilometers away from the hole. Their orbits are unstable. They may be able to remain in orbit for a while, but any deviation from a circular orbit will cause them to be captured and eventually swallowed by the hole. As the astronaut approaches the hole, putting clocks into orbit as he travels, the redshift of the light from the clocks becomes larger and larger. At 90 kilometers, the

effect is truly a redshift as portrayed here. The green light illuminating the clocks will be red, with a wavelength of 6100 angstroms, by the time it reaches our eyes. At 60 kilometers, the clocks will have their light shifted beyond the red to 7000 angstroms, in the infrared part of the spectrum, by the hole's powerful gravity. We should have to look at them with an image tube, a device developed for use in Vietnam, which picks up infrared radiation. (This gadget has had many peaceful applications in astronomy, as it improves the effectiveness of telescopes.)

But the image tubes work well only up to a point, as the redshift becomes larger and larger the closer you get to the hole. When the astronaut is 30.03 kilometers from the hole's center, or 0.03 kilometers (30 meters) from the event horizon, the supposedly green light illuminating the clocks will have a wavelength of 150,000 angstroms, far in the infrared, beyond the range of an image tube. Is there no end? Will this redshift never stop increasing? No, there is not; the redshift of photons increases without limit as you approach the event horizon.

Along with the increase in redshift comes another, more bizarre effect. Clocks near the hole are slowing down along with the redshift, as the relative clock rate is $1 + z$. Events near the hole take much more time to occur. Thirty-three kilometers away from the hole, where the redshift is 2.32, the relative clock rate is 3.32. Events this close to the hole pass at roughly one-third their normal rate.

Nearer and nearer the horizon, the slowdown of clocks would increase. The orbiting clocks would tick slowly, slowly, more and more slowly—tick, tick, ... At the event horizon, what would happen? It would take an infinite time until the next clock tick. Events would be frozen. Time comes to a stop at the event horizon.

What about the falling astronaut? His clock and ours are shown in Figure 4-3, which depicts graphically the events shown in the table. That half-second difference between his clock and ours would become larger and larger as he approached the event horizon. If we were monitoring his heartbeat, it would be recorded as slowing down too, along with his clocks. He would seem to stop falling, as his fall would be frozen at the event horizon. It would be like watching a movie with someone slowing down the rate of the projector. The slowdown occurs very abruptly at the edge of the black hole. Our clock would not advance to 205 hours until the astronaut was within 3×10^{-8288} km of the event horizon. (To write out 3×10^{-8288}, I would have to put 8287 zeros between the decimal point and the 3. It would take three pages in this book to write out that small a number.) His clock would be frozen, and ours would tick on. We would never see his clock go beyond 204 hours, 33 minutes, 49.670133 seconds. We would never see him fall through the event horizon. He would inch closer and closer to it, ever more slowly, but he would never pass through.

The frozen star

If you happened to watch the formation of a black hole, you would see something similar (Figure 4-4). The collapse would proceed quite rapidly at first. The light from the star would be redshifted more and more as the star came closer and closer to the horizon. (Here the redshift of the star is rendered as a darkening.) Just short of the horizon, the collapse would slow down abruptly, because the star's own gravity would cause everything to seem to happen in slow motion to a distant observer. The collapse would be effectively frozen just short of the event horizon.

Remember, it is only exceedingly close to the event horizon that the collapse appears to freeze. The large redshifts at this point would cause the star to appear to be black. The freezing of the collapse occurs only when the redshift is extremely high. After 4.6×10^{-5} sec the redshift is 10, if you start counting from the time the star has a radius of 1.5 times the Schwarzschild radius. After another 4.6×10^{-5} sec, the redshift has increased tenfold again, to 100. Because the star is emitting its light in discrete photons, there is a time at which the star sends its last photon out to the outside world. Detailed calculations indicate that the last photon from a ten-solar-mass star would emerge less than 0.01 second after the star's surface passed the 1.5-Schwarzschild-radius, or 45-kilometer, point. The collpased star would be black, and its collapse would be frozen. Hence another name for black holes: frozen stars.

The event horizon as a limit

The preceding section points out that the event horizon is a limit. You cannot see anything happen *at* the event horizon, as no photons can reach you from there. As you look closer and closer to the event horizon, time slows down without bound. Closer, closer, closer the clocks go slowly, more and more slowly. Paradoxical place, the event horizon.

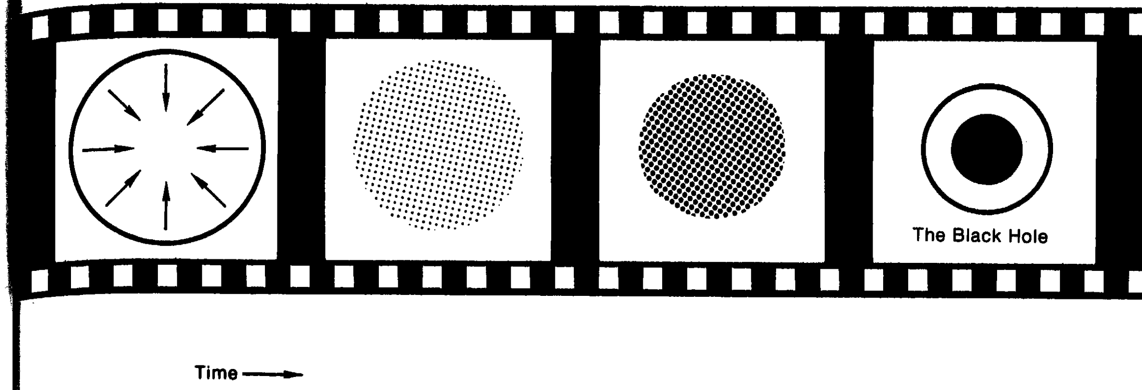


FIGURE 4-4 A movie showing the collapse of a star. As a star collapses to form a black hole, it dims very rapidly. It emits its last photon less than 0.01 second after it becomes smaller than 1.5 Schwarzschild radii. Compare with Figure 4-3.

The concept of the event horizon as a limit can perhaps be better illustrated by one of Zeno's paradoxes. Suppose you want to go through a door, and you are six feet away. For reasons best known to yourself, you decide to approach the door slowly, covering half of the remaining distance with each step. At first, this seems like a reasonable approach; your first step takes you three feet toward the door, and you have made progress. But you will never get through the door if you play the game according to the rules. The second step leaves you 1.5 feet away, the third 9 inches, the fourth 4.5 inches, the fifth 2.25 inches, and so on. No step will ever take you through the door, as you can only approach it with each step. The same thing happens as you look toward a black hole. If you try to watch someone enter the interior, it seems to take the person longer and longer to get there, as he or she travels more and more slowly.

Looked at from the outside, the event horizon seems to be a very strange place. Somehow the idea of time coming to a stop at the event horizon doesn't quite jibe with the way that the world is supposed to work. What sort of place is the event horizon, anyway? To explore the nature of the event horizon and the world inside it, the interior of the black hole, we shall have to succumb to the Pygmalion syndrome (recall Chapter 1) and leave the realm of the real world. Anyone who fell through the event horizon in an attempt to verify experimentally the theoretical results about to be presented could never return to tell us that we were right.

Yet there are good reasons for indulging in this theoretical exercise of imagining what a trip beyond the event horizon would be like. The idea that time comes to a stop there makes you think that maybe Einstein's theory breaks down at the event horizon. If this is true, then the very existence of black holes is open to question and the validity of Einstein's theory elsewhere in the universe is questionable. The theory is supposed to be valid anywhere in the universe, including in the vicinity of the event horizon.

It turns out that the peculiarity of space-time near the event horizon—the idea of time coming to a stop—is just a consequence of our point of view. If we follow our courageous astronaut through the event horizon, we find that the horizon is not such a strange place after all. Yet I repeat that what follows is theoretical only, as no one who fell into a black hole could come out again to tell us what was really there. (The speculation that in fact you *could* emerge from a black hole is dealt with in Chapter 6.)

Through the event horizon

Look at Figure 4-3 again, and at Table 4-1, this time paying attention to the astronaut's clocks. Unlike the external observer, he will not see his fall toward the hole freeze at the event horizon. 204 hours, 33 minutes, and 49.6681 seconds after he left the rocket ship, he would be 300 kilometers away from the hole, and his clocks would be in general agreement with the clocks back on the spaceship. Only a split second later, at 49.670133 seconds, he would fall through the event horizon. As he approached the hole, he would not notice any slowing down of clocks. He would not be able to see the surface of the frozen star, for it would be black. It would look like a hole. As he fell, he would see events around him (if there were anything happening) escape from their slow-motion mode as seen from the outside and proceed normally. When he fell through the horizon, he might have to endure some discomfort from the ever-increasing tidal forces. But the tidal forces would stay within bounds at the horizon, and a suitably built astronaut or probe would survive.

I cannot emphasize too strongly that at the event horizon, someone falling through would not experience any impossibly odd physical effects. There is no sign at the event horizon warning of the danger inside, no infinite tidal gravitational forces that would pull one apart before one got in. Look at the way the rocket ship sees the black-hole adventure in Table 4-1. See? The probe falls through the event horizon perfectly happily, in a reasonable amount of time, from its point of view.

The absence of any pathological effects at the event horizon means that Einstein's theory does not break down there. It is only our point of view from the outside that produces the odd effect of time's coming to a stop. If you adopt another point of view, the infinite redshifts and frozen clocks disappear. They are only ephemeral, a consequence of our point of view from the outside. Einstein's theory is still valid, and it is all right to use it to predict what happens up to and through the event horizon.

Why a black hole?

For a long time, the term used to describe the subject of our investigation was not *black hole* but *frozen star*, or *collapsar.* We see now that the term *black hole* is quite appropriate. The appropriateness of the term *black* was discussed before. From the outside, the star would fade to invisibility in one-hundredth of a second or less if you were watching it collapse. You could not even see its surface by shining a flashlight on it, as the light from the flashlight would catch up with the collapse on its way in—the collapse would be unfrozen from the point of view of the ingoing light. It would be swallowed up by the hole. No, you cannot see the frozen star. It is black.

A similar fate would befall any foolish astronaut who sought to prove that it was not a black hole, that it was only a frozen star there in space. If he tried to scoop up a piece of the frozen star, the collapse would always unfreeze just enough to stay ahead of the scoop. If he tried too hard to pick up a piece of the star, he would pass beyond the event horizon, and disappear from his friends in the world outside. Yes, this object is truly a hole, too. The accepted term now is *black hole.* If you fall into it, you fall, and you fall, and you fall, until . . . .

The interior of a black hole

There is one very serious problem with being inside the event horizon. You can never get out again once you are there. The event horizon is a cosmic turnstile. One way only. Anything, whether it is light, space probe, TV set, rock, rocking chair, or unfortunate astronaut, can go only in one direction: *inward* (Figure 4-5). Some serious frontiers or speculative fringes of black-hole research suggest that there may be possible exceptions to the one-way behavior of the event horizon. Work by Stephen Hawking indicates that any black hole will eventually evaporate—but, for a ten-solar-mass hole, 10^{66} years will pass before this happens. The fringe areas of black-hole research involve discussions of mirror images of black holes—white holes—in which material erupts. These white holes probably don't exist, however. See Chapter 6.

The one-way nature of the event horizon forces us to rely on theory in order to probe these lower depths of black holes. These theoretical calculations, although detached from the real world, are not totally meaningless, for they provide insight into the nature of the theoretical picture of a black hole and provide guides to the situations that Einstein's equations can be applied to. With these reservations, let us follow the probe as theory carries it toward the black hole's center. (I'll call it a probe now; the idea of subjecting a person to these hypothetical but nevertheless horrifying experiences is too lugubrious.)

The probe is pulled relentlessly toward the center of the black hole. As the probe approaches the center, the tidal forces become stronger and

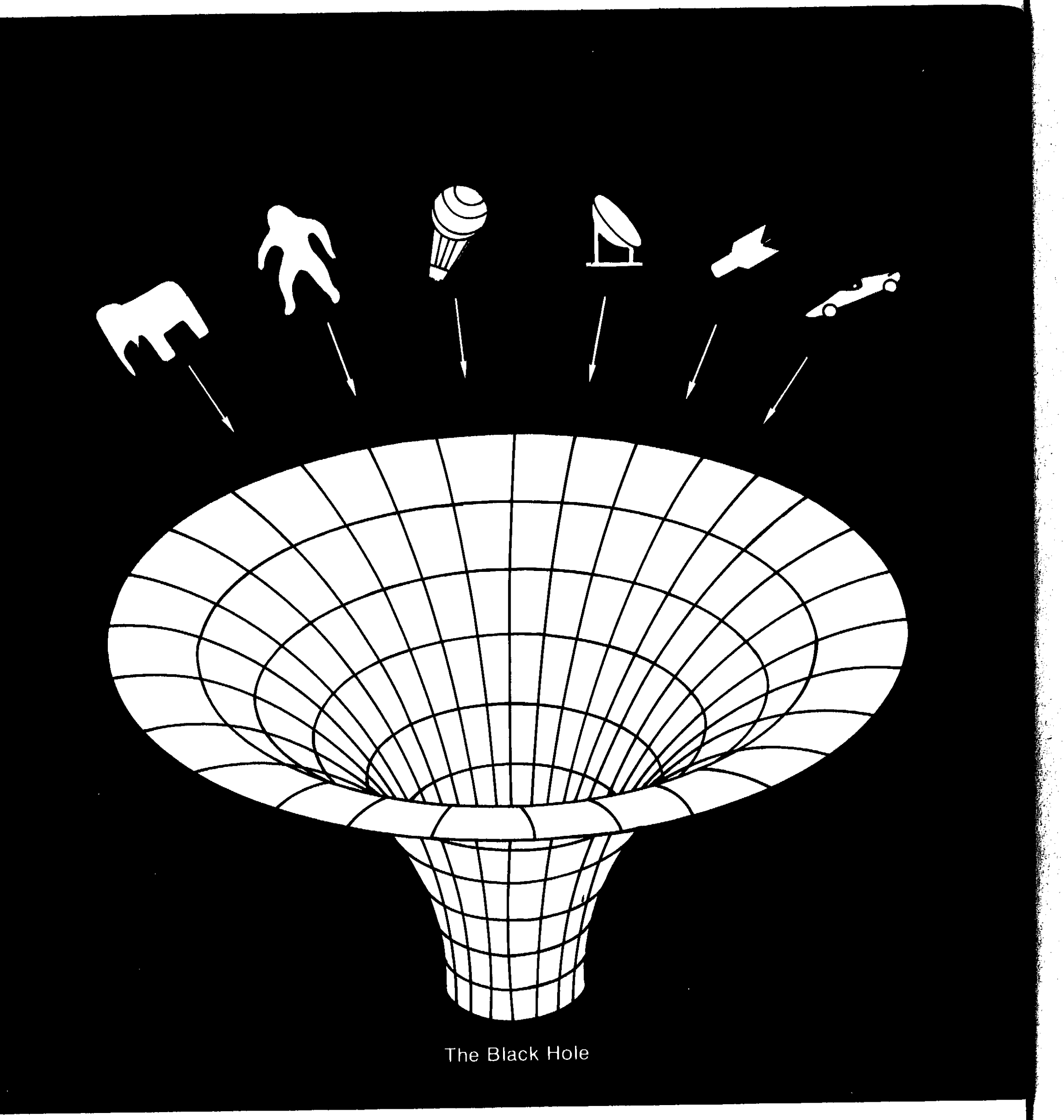


FIGURE 4-5 Everything falling into a black hole loses its identity. You do not know whether it was a space probe or a TV set that fell in. (Adapted from Remo Ruffini and John A. Wheeler, "Introducing the Black Hole," *Physics Today,* January 1970, p. 31, © American Institute of Physics.)

stronger. They increase indefinitely, so the probe will be destroyed by them before it actually reaches the center. The probe could struggle against gravity, trying to escape this fate by turning on its rocket engine and darting here and there, but it could only postpone the inevitable for a very short time. The tentacles of gravity have caught it, and it must fall to destruction at the center of the hole. In a ten-solar-mass hole, it would fall quite fast. If it did not start its engine in an attempt to escape, it would reach the center 67 millionths of a second after it passed the horizon.

What is at the center? Einstein's theory does in fact break down here. The theory presents us with a very bizarre object, a singularity. A singularity is an absurdity. It is a point containing all the mass of the hole. The singularity has zero volume, and the density of matter is infinite. The tidal forces are infinite. So the theory says, anyway.

The idea that there is a singularity at the center of a black hole makes many physicists feel uncomfortable. When a theory starts producing infinities in models derived from it, a reasonable feeling develops that the theory is wrong. Standard black-hole theory (the subject of this chapter) is based on Einstein's theory of gravitation, so a standard black hole has a singularity in the middle. Numerous people have tried to modify Einstein's theory of gravitation so that the singularity goes away.

To a certain extent, though, such modifications are beside the point. Remember the Pygmalion syndrome again. The whole purpose of this exercise of following an astronaut or probe into a hole was to see where inside the hole Einstein's theory breaks down, and in particular, whether it breaks down at the event horizon. What happens inside the event horizon has no effect on the outside world, since anything that falls in can never get out again. The interior of a black hole is cut off from our universe by the event horizon, so what happens there does not affect us.

Types of black holes

Rotating black holes

Real stars rotate, but the standard black hole described in the last few pages does not. One would expect a spinning star to produce a spinning black hole, but how would the spin of a black hole affect the hole's properties? Roy Kerr developed a mathematical description of a spinning black hole in 1963, and so spinning black holes are sometimes called "Kerr black holes," in contrast to the nonrotating Schwarzchild black holes, named for black-hole pioneer Karl Schwarzchild.

The event horizon of a rotating black hole would be found in the same place as the event horizon of a nonrotating black hole of similar mass.

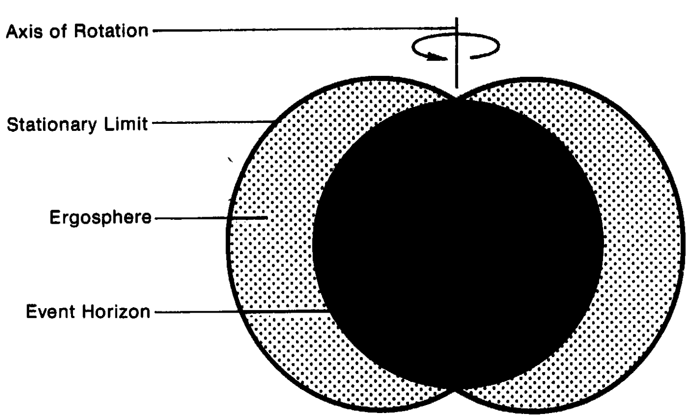


FIGURE 4-6 Cross section of a rotating black hole, showing the stationary limit, ergosphere, and event horizon.

The phenomena that occur near the event horizon, though, are a little different. Suppose you approached a rotating hole from the top, falling down the pole of rotation. The story described earlier in this chapter would be repeated in every detail: You would fall through the event horizon, never to be seen again. You would notice nothing peculiar near the horizon, given that you could survive the tidal gravitational forces and still see anything. The friends you left behind would see you fall more, more, and more slowly as you neared the limit of the event horizon.

But suppose you fell toward the black hole in a different direction, approaching it toward the equator, for example. Far away from the hole, the situation would be the same. Close to the hole, the hole's rotation tends to sweep objects around it, in the same direction that it spins. There are two consequences of this tendency. One—which might be able to be observed in real situations—is that small particles orbiting in the direction of the hole's spin could be closer to the hole and still stay in orbit than they could in the case of a nonrotating hole. The other difference involves a second boundary—the static limit. Before meeting the event horizon, an intrepid black-hole investigator would encounter this invisible boundary. Inside the static limit, it would be impossible to remain at rest, since the spin of the hole would carry you madly around in the direction that the hole is rotating. Yet you could still send signals to the outside world, and even escape from the hole's influence by turning on your rocket engine. This all presumes that you still *have* a rocket engine—and that it and you have not been destroyed by the tidal gravitational forces.

Investigators have explored various methods of extracting energy from a rotating black hole. Such explorations are motivated partly by curiosity and partly by the need to find sources of enormous energy to explain the powerful emissions of quasars and active galaxies, the subjects of Part 2 of this book. One proposal suggests that you drop a rocket engine inside the static limit, turn on the rocket, and watch the black hole's rotation shoot out the rocket at a high speed. Detailed calculations of this process show that the rocket would accelerate, but no more than it would if you did the same thing far from a black hole.

Another proposal deals with light waves focused into the space surrounding a rotating black hole. Given exactly the right conditions, these light waves could be amplified. The article announcing this mechanism is titled "The Black Hole Bomb." It talks about the possibility that a suitable mirror could be placed outside a rotating black hole to focus the light, and that eventually the amplified light waves would break the mirror. Realistically, more light would be lost down the hole than would be amplified, and this particular black-hole bomb would be a fizzle.

These investigations illustrate the strange phenomena that might occur near a rotating black hole. So far, many theories about black-hole powerhouses have turned out to be weak, but proposals for extracting energy from rotating black holes continue to appear. One of them may turn out to provide the powerhouse for the quasars.

In principle, electrically charged black holes could exist. Yet such objects are unlikely to form in the real world, for a charged black hole would repel objects of similar charge that tried to fall down it, and would attract oppositely charged objects, thus eventually neutralizing itself. Electrically charged black holes are, for the most part, similar to the neutral, uncharged ones.

Black holes have no hair

Mass, spin, and electrical charge—these are the three properties that we have considered so far. It is mass that governs the size of the event horizon and the scale of the black-hole phenomena that I have discussed. Spin and charge slightly modify the properties of the black hole. What other properties might a black hole have? Does it make any difference whether you make a black hole out of an iron stellar core or out of a carbon stellar core? Can you tell whether someone threw a cupful of white-dwarf stuff, a pinhead of neutron-star stuff, or 24 elephants down the hole? The somewhat surprising answer is no.

During the early 1970s, most theorists believed that mass, charge, and angular momentum were the only properties that a black hole could have, but no one had proved that this must be so. Some other property could perhaps remain after a black hole formed. Black-hole theorists Kip Thorne and John Wheeler referred to this other property as "hair," an attribute that could distinguish black holes of similar mass and spin from each other in the same way that the color, length, or style of hair distinguishes one human being from another. But in 1975, investigators proved the last of a series of theorems, showing that mass, spin, and possibly electrical charge are the only black-hole properties allowed by Einstein's theory of gravitation. These theorems are collectively (if informally) described by the short phrase "Black holes have no hair." Black holes can differ greatly in the amount of mass that they can have, and can differ in spin, but differ in no other ways—except possibly electrical charge. This completes our description of isolated black holes.

Isolated black holes are fascinating in many ways. The strange behavior of space and time near the event horizon is mind-expanding. The very existence of an event horizon, a point of no return, has stimulated many a science-fiction writer. Yet, in some other ways, isolated black holes are quite uninteresting. Black holes are black and the sky is black; black on black does not make for good observing. Present-day astrophysicists have probably discovered black holes by observing the interaction of holes with the world around them. We shall explore these interactions in Chapter 5, which deals with the search for black holes that form from stars.

* * *

You can look at a black hole from two points of view—the outside and the inside. The view from the outside is the only one that can be experimentally verified. Looking at a black hole, you see an event horizon, where time has come to a stop. Surrounding the event horizon, barely outside it, is the surface of the collapsing star that formed the black hole, from the collapse of this star that has been frozen. The frozen star emits no light, so it is black.

But time has not really come to a stop, since it is only your point of view, from the outside looking in, that makes you think it has. If you follow, theoretically, the adventures of a space probe dropped toward the hole, you will find out that the probe falls into the hole. Time has not stopped at the event horizon from the point of view of someone falling in. Outsiders cannot see the collapse go to completion, but someone falling in will pass straight through the event horizon, enduring discomfort only from the tidal forces. (A person would have to be pretty strong to endure those forces.) The person falls through the event horizon, into the speculative arena known as the interior of the black hole. No probe, rocket, astronaut, or anything else, once inside, can escape a standard black hole. The object is caught and pulled inexorably toward the central singularity, where Einstein's theory of gravitation breaks down as the forces of gravity take off toward infinity.

The inclusion of spin and electrical charge as black-hole properties does not fundamentally affect the nature of the event horizon or the singularity in black holes, although some details regarding the behavior of orbiting bodies near the event horizon are slightly modified by rotation. Recent work has shown that mass, spin, and electrical charge are the only properties that a black hole can have. Thus the description of a black hole in this chapter, suitably scaled to different masses, can be applied to any black hole in the universe.