Prologue: A Voyage among the Holes

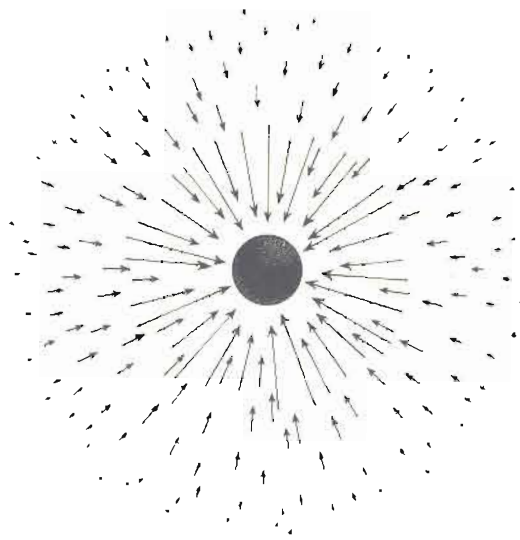
in which the reader,
in a science fiction tale,
encounters black holes
and all their strange properties
as best we understand them in the 1990s

Of all the conceptions of the human mind, from unicorns to gargoyles to the hydrogen bomb, the most fantastic, perhaps, is the black hole: a hole in space with a definite edge into which anything can fall and out of which nothing can escape; a hole with a gravitational force so strong that even light is caught and held in its grip; a hole that curves space and warps time.[1] Like unicorns and gargoyles, black holes seem more at home in the realms of science fiction and ancient myth than in the real Universe. Nonetheless, well-tested laws of physics predict firmly that black holes exist. In our galaxy alone there may be millions, but their darkness hides them from view. Astronomers have great difficulty finding them.[2]

Hades

Imagine yourself the owner and captain of a great spacecraft, with computers, robots, and a crew of hundreds to do your bidding. You

1. Chapters 3, 6, 7.
2. Chapter 8.

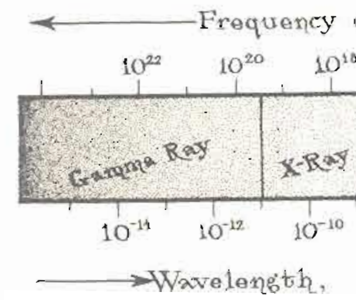


P.1 Atoms of gas, pulled by a black hole's gravity, stream toward the hole from all directions.

have been commissioned by the World Geographic Society to explore black holes in the distant reaches of interstellar space and radio back to Earth a description of your experiences. Six years into its voyage, your starship is now decelerating into the vicinity of the black hole closest to Earth, a hole called "Hades" near the star Vega.

On your ship's video screen you and your crew see evidence of the hole's presence: The atoms of gas that sparsely populate interstellar space, approximately one in each cubic centimeter, are being pulled by the hole's gravity (Figure P.1). They stream toward the hole from all directions, slowly at great distances where gravity pulls them weakly, faster nearer the hole where gravity is stronger, and extremely fast—almost as fast as light—close to the hole where gravity is strongest. If something isn't done, your starship too will be sucked in.

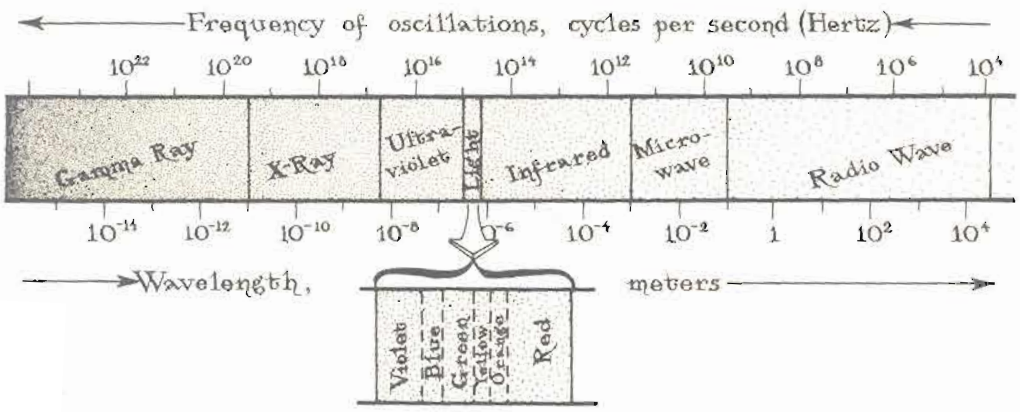
Quickly and carefully your first mate, Kares, maneuvers the ship out of its plunge and into a circular orbit, then shuts off the engines. As you coast around and around the hole, the centrifugal force of your circular motion holds your ship up against the hole's gravitational pull. Your ship is like a toy slingshot of your youth on the end of a whirling string, pushed out by its centrifugal force and held in by the string's tension, which is like the hole's gravity. As the starship



P.2 The spectrum of ele
long wavelengths (very l
lengths (very high freque
numbers (10^{21}, 10^{-12}, etc.

coasts, you and your c
At first you explore
study the electromagn
streams toward the ho
a few degrees above a
their slow vibrations p
which means waves w
long wavelengths. Th
hole, where gravity h
collide with each othe
heat makes them vibr
ing, shorter waveleng
varied hues: red, oran
closer to the hole, whe
faster, collisions heat
vibrate very fast, prod
length: X-rays. Seeing
are reminded that it
that astrophysicists, i
space: Cygnus X-1, 14

3. Chapter 8.



P.2 The spectrum of electromagnetic waves, running from radio waves at very long wavelengths (very low frequencies) to gamma rays at very short wavelengths (very high frequencies). For a discussion of the notation used here for numbers (10^{21}, 10^{-12}, etc.), see Box P.1 below.

coasts, you and your crew prepare to explore the hole.

At first you explore passively: You use instrumented telescopes to study the electromagnetic waves (the radiation) that the gas emits as it streams toward the hole. Far from the hole, the gas atoms are cool, just a few degrees above absolute zero. Being cool, they vibrate slowly; and their slow vibrations produce slowly oscillating electromagnetic waves, which means waves with long distances from one crest to the next—long wavelengths. These are radio waves; see Figure P.2. Nearer the hole, where gravity has pulled the atoms into a faster stream, they collide with each other and heat up to several thousand degrees. The heat makes them vibrate more rapidly and emit more rapidly oscillating, shorter wavelength waves, waves that you recognize as light of varied hues: red, orange, yellow, green, blue, violet (Figure P.2). Much closer to the hole, where gravity is much stronger and the stream much faster, collisions heat the atoms to several million degrees, and they vibrate very fast, producing electromagnetic waves of very short wavelength: X-rays. Seeing those X-rays pour out of the hole's vicinity, you are reminded that it was by discovering and studying just such X-rays that astrophysicists, in 1972, identified the first black hole in distant space: Cygnus X-1, 14,000 light-years from Earth.[3]

3. Chapter 8.

Turning your telescopes still closer to the hole, you see gamma rays from atoms heated to still higher temperatures. Then, looming up, at the center of this brilliant display, you see a large, round sphere, absolutely black; it is the black hole, blotting out all the light, X-rays, and gamma rays from the atoms behind it. You watch as superhot atoms stream into the black hole from all sides. Once inside the hole, hotter than ever, they must vibrate faster than ever and radiate more strongly than ever, but their radiation cannot escape the hole's intense gravity. Nothing can escape. That is why the hole looks black; pitch-black.[4]

With your telescope, you examine the black sphere closely. It has an absolutely sharp edge, the hole's surface, the location of "no escape." Anything just *above* this surface, with sufficient effort, can escape from gravity's grip: A rocket can blast its way free; particles, if fired upward fast enough, can escape; light can escape. But just *below* the surface, gravity's grip is inexorable; nothing can ever escape from there, regardless of how hard it tries: not rockets, not particles, not light, not radiation of any sort; they can never reach your orbiting starship. The hole's surface, therefore, is like the horizon on Earth, beyond which you cannot see. That is why it has been named *the horizon of the black hole.*[5]

Your first mate, Kares, measures carefully the circumference of your starship's orbit. It is 1 million kilometers, about half the circumference of the Moon's orbit around the Earth. She then looks out at the distant stars and watches them circle overhead as the ship moves. By timing their apparent motions, she infers that it takes 5 minutes and 46 seconds for the ship to encircle the hole once. This is the ship's *orbital period.*

From the orbital period and circumference you can now compute the mass of the hole. Your method of computation is the same as was used by Isaac Newton in 1685 to compute the mass of the Sun: The more massive the object (Sun or hole), the stronger its gravitational pull, and therefore the faster must an orbiting body (planet or starship) move to avoid being sucked in, and thus the shorter the body's orbital period must be. By applying Newton's mathematical version of this gravitational law[6] to your ship's orbit, you compute that the black hole Hades has a mass ten times larger than that of the sun ("10 solar masses").[7]

4. Chapters 3 and 6.
5. Chapter 6.
6. Chapter 2.
7. Readers who want to compute properties of black holes for themselves will find the relevant formulas in the notes at the end of the book.

You know that this h
a death in which the sta
own gravity, imploded
imploded, its mass did
mass today as its parent
mass must actually be a
thing that has fallen in
rocks, starships . . .

You know all this be
studied the fundamenta
an approximate form
revised into a more ac
learned that Einstein's
relativity, force black h
they force a dropped sto
to violate the laws of g
similarly it is impossib
laws: The hole must b
hole's mass, at birth, n
something falls into th
star is spinning as it im
and the hole's *angular*
spins) must be the same

Before your voyage,
standing about black ho
Hawking, Werner Israe
tic description[11] of the
be an exceedingly sim
strength of its gravitati
trajectories of starlight
mined by just three nu
the angular momentum
electrical charge. You a
space can contain much

8. Chapters 3–5.
9. Chapter 2.
10. For further discussion c
solar system, and the Univers
Chapter 1.
11. Chapter 2.
12. Chapter 7.

You know that this hole was created long ago by the death of a star, a death in which the star, no longer able to resist the inward pull of its own gravity, imploded upon itself.[8] You also know that, when the star imploded, its mass did not change; the black hole Hades has the same mass today as its parent star had long ago—or almost the same. Hades' mass must actually be a little larger, augmented by the mass of everything that has fallen into the hole since it was born: interstellar gas, rocks, starships . . .

You know all this because, before embarking on your voyage, you studied the fundamental laws of gravity: laws that were discovered in an approximate form by Isaac Newton in 1687, and were radically revised into a more accurate form by Albert Einstein in 1915.[9] You learned that Einstein's gravitational laws, which are called *general relativity*, force black holes to behave in these ways as inexorably as they force a dropped stone to fall to earth. It is impossible for the stone to violate the laws of gravity and fall upward or hover in the air, and similarly it is impossible for a black hole to evade the gravitational laws: The hole must be born when a star implodes upon itself; the hole's mass, at birth, must be the same as the star's; and each time something falls into the hole, its mass must grow.[10] Similarly, if the star is spinning as it implodes, then the newborn hole must also spin; and the hole's *angular momentum* (a precise measure of how fast it spins) must be the same as the star's.

Before your voyage, you also studied the history of human understanding about black holes. Back in the 1970s Brandon Carter, Stephen Hawking, Werner Israel, and others, using Einstein's general relativistic description[11] of the laws of gravity, deduced that a black hole must be an exceedingly simple beast[12]: All of the hole's properties—the strength of its gravitational pull, the amount by which it deflects the trajectories of starlight, the shape and size of its surface—are determined by just three numbers: the hole's mass, which you now know; the angular momentum of its spin, which you don't yet know; and its electrical charge. You are aware, moreover, that no hole in interstellar space can contain much electrical charge; if it did, it quickly would pull

8. Chapters 3–5.
9. Chapter 2.
10. For further discussion of the concept that the laws of physics *force* black holes, and the solar system, and the Universe, to behave in certain ways, see the last few paragraphs of Chapter 1.
11. Chapter 2.
12. Chapter 7.

opposite charges from the interstellar gas into itself, thereby neutralizing its own charge.

As it spins, the hole should drag the space near itself into a swirling, tornado-like motion relative to space far away, much as a spinning airplane propeller drags air near itself into motion; and the swirl of space should cause a swirl in the motion of anything near the hole.[13]

To learn the angular momentum of Hades, you therefore look for a tornado-like swirl in the stream of interstellar gas atoms as they fall into the hole. To your surprise, as they fall closer and closer to the hole, moving faster and faster, there is no sign at all of any swirl. Some atoms circle the hole clockwise as they fall; others circle it counterclockwise and occasionally collide with clockwise-circling atoms; but on average the atoms' fall is directly inward (directly downward) with no swirl. Your conclusion: This 10-solar-mass black hole is hardly spinning at all; its angular momentum is close to zero.

Knowing the mass and angular momentum of the hole and knowing that its electrical charge must be negligibly small, you can now compute, using general relativistic formulas, all of the properties that the hole should have: the strength of its gravitational pull, its corresponding power to deflect starlight, and of greatest interest, the shape and size of its horizon.

If the hole were spinning, its horizon would have well-delineated north and south poles, the poles about which it spins and about which infalling atoms swirl. It would have a well-delineated equator halfway between the poles, and the centrifugal force of the horizon's spin would make its equator bulge out,[14] just as the equator of the spinning Earth bulges a bit. But Hades spins hardly at all, and thus must have hardly any equatorial bulge. Its horizon must be forced by the laws of gravity into an almost precisely spherical shape. That is just how it looks through your telescope.

As for size, the laws of physics, as described by general relativity, insist that the more massive the hole is, the larger must be its horizon. The horizon's circumference, in fact, must be 18.5 kilometers multiplied by the mass of the hole in units of the Sun's mass.[15] Since your

13. Chapter 7.
14. Ibid.
15. Chapter 3. The quantity 18.5 kilometers, which will appear many times in this book, is 4π (that is, 12.5663706 . . .) times Newton's gravitation constant times the mass of the Sun divided by the square of the speed of light. For this and other useful formulas describing black holes, see the notes to this chapter.

orbital measurements have told you that the hole weighs ten times as much as the Sun, its horizon circumference must be 185 kilometers—about the same as Los Angeles. With your telescopes you carefully measure the circumference: 185 kilometers; perfect agreement with the general relativistic formula.

This horizon circumference is minuscule compared to your starship's 1-million-kilometer orbit; and squeezed into that tiny circumference is a mass ten times larger than that of the Sun! If the hole were a solid body squeezed into such a small circumference, its average density would be 200 million (2×10^8) tons per cubic centimeter—2×10^{14} times more dense than water; see Box P.1. But the hole is not a solid body. General relativity insists that the 10 solar masses of stellar matter, which created the hole by imploding long ago, are now concentrated at the hole's very center—concentrated into a minuscule region of space called a *singularity*.[16] That singularity, roughly 10^{-33} centimeter in size (a hundred billion billion times smaller than an atomic nucleus), should be surrounded by pure emptiness, aside from the tenuous interstellar gas that is falling inward now and the radiation the gas emits. There should be near emptiness from the singularity out to the horizon, and near emptiness from the horizon out to your starship.

16. Chapter 13.

Box P.1

Power Notation for Large and Small Numbers

In this book I occasionally will use "power notation" to describe very large or very small numbers. Examples are 5×10^6, which means five million, or 5,000,000, and 5×10^{-6}, which means five millionths, or 0.000005.

In general, the power to which 10 is raised is the number of digits through which one must move the decimal point in order to put the number into standard decimal notation. Thus 5×10^6 means take 5 (5.00000000) and move its decimal point rightward through six digits. The result is 5000000.00. Similarly, 5×10^{-6} means take 5 and move its decimal point leftward through six digits. The result is 0.000005.

The singularity and the stellar matter locked up in it are hidden by the hole's horizon. However long you may wait, the locked-up matter can never reemerge. The hole's gravity prevents it. Nor can the locked-up matter ever send you information, not by radio waves, or light, or X-rays. For all practical purposes, it is completely gone from our Universe. The only thing left behind is its intense gravitational pull, a pull that is the same on your 1-million-kilometer orbit today as before the star imploded to form the hole, but a pull so strong at and inside the horizon that nothing there can resist it.

"What is the distance from the horizon to the singularity?" you ask yourself. (You choose not to measure it, of course. Such a measurement would be suicidal; you could never escape back out of the horizon to report your result to the World Geographic Society.) Since the singularity is so small, 10^{-33} centimeter, and is at the precise center of the hole, the distance from singularity to horizon should be equal to the horizon's radius. You are tempted to calculate this radius by the standard method of dividing the circumference by 2π (6.283185307 . . .). However, in your studies on Earth you were warned not to believe such a calculation. The hole's enormous gravitational pull completely distorts the geometry of space inside and near the hole,[17] in much the same manner as an extremely heavy rock, placed on a sheet of rubber, distorts the sheet's geometry (Figure P.3), and as a result the horizon's radius is not equal to its circumference divided by 2π.

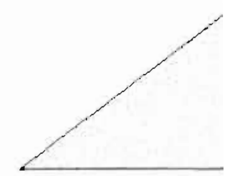
"Never mind," you say to yourself. "Lobachevsky, Riemann, and other great mathematicians have taught us how to calculate the properties of circles when space is curved, and Einstein has incorporated those calculations into his general relativistic description of the laws of gravity. I can use these curved-space formulas to compute the horizon's radius."

But then you remember from your studies on Earth that, although a black hole's mass and angular momentum determine all the properties of the hole's horizon and exterior, they do not determine its interior. General relativity insists that the interior, near the singularity, should be chaotic and violently nonspherical,[18] much like the tip of the rubber sheet in Figure P.3 if the heavy rock in it is jagged and is bouncing up and down wildly. Moreover, the chaotic nature of the hole's core will depend not only on the hole's mass and angular momentum, but also on the details of the stellar implosion by which the hole was born, and

17. Chapters 3 and 13.
18. Chapter 13.

the details of the subsequ
do not know.
"So what," you say to
chaotic core must have a
Thus, I will make only a
horizon's radius."
But then you remembe
the singularity that the c
in radius though only a f
as the rock in Figure P.3,
the rubber sheet exceedi
ference of the chaotic re

P.3 A heavy rock placed on
the sheet as shown. The she
tions of the geometry of spa
circumference of the thick
as the circumference of the
further detail, see Chapters

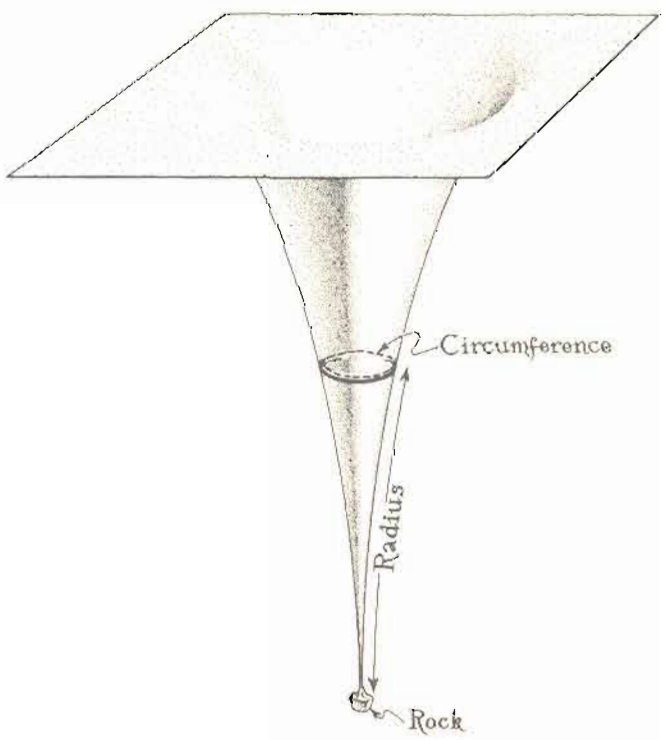


the details of the subsequent infall of interstellar gas—details that you do not know.

"So what," you say to yourself. "Whatever may be its structure, the chaotic core must have a circumference far smaller than a centimeter. Thus, I will make only a tiny error if I ignore it when computing the horizon's radius."

But then you remember that space can be so extremely warped near the singularity that the chaotic region might be millions of kilometers in radius though only a fraction of a centimeter in circumference, just as the rock in Figure P.3, if heavy enough, can drive the chaotic tip of the rubber sheet exceedingly far downward while leaving the circumference of the chaotic region extremely small. The errors in your cal-

P.3 A heavy rock placed on a rubber sheet (for example, a trampoline) distorts the sheet as shown. The sheet's distorted geometry is very similar to the distortions of the geometry of space around and inside a black hole. For example, the circumference of the thick black circle is far less than 2π times its radius, just as the circumference of the hole's horizon is far less than 2π times its radius. For further detail, see Chapters 3 and 13.



culated radius could thus be enormous. The horizon's radius is simply not computable from the meager information you possess: the hole's mass and its angular momentum.

Abandoning your musings about the hole's interior, you prepare to explore the vicinity of its horizon. Not wanting to risk human life, you ask a rocket-endowed, 10-centimeter-tall robot named Arnold to do the exploration for you and transmit the results back to your starship. Arnold has simple instructions: He must first blast his rocket engines just enough to halt the circular motion that he has shared with the starship, and then he must turn his engines off and let the hole's gravity pull him directly downward. As he falls, Arnold must transmit a brilliant green laser beam back to the starship, and on the beam's electromagnetic oscillations he must encode information about the distance he has fallen and the status of his electronic systems, much as a radio station encodes a newscast on the radio waves it transmits.

Back in the starship your crew will receive the laser beam, and Kares will decode it to get the distance and system information. She will also measure the beam's wavelength (or, equivalently, its color; see Figure P.2). The wavelength is important; it tells how fast Arnold is moving. As he moves faster and faster away from the starship, the green beam he transmits gets *Doppler-shifted,*[19] as received at the ship, to longer and longer wavelengths; that is, it gets more and more red. (There is an additional shift to the red caused by the beam's struggle against the hole's gravitational pull. When computing Arnold's speed, Kares must correct her calculations for this *gravitational redshift.*[20])

And so the experiment begins. Arnold blasts his way out of orbit and onto an infalling trajectory. As he begins to fall, Kares starts a clock to time the arrival of his laser signals. When 10 seconds have elapsed, the decoded laser signal reports that all his systems are functioning well, and that he has already fallen a distance of 2630 kilometers. From the color of the laser light, Kares computes that he is now moving inward with a speed of 530 kilometers per second. When the ticking clock has reached 20 seconds his speed has doubled to 1060 kilometers per second and his distance of fall has quadrupled to 10,500 kilometers. The clock ticks on. At 60 seconds his speed is 9700 kilometers per second, and he has fallen 135,000 kilometers, five-sixths of the way to the horizon.

19. See Box 2.3.
20. Chapters 2 and 3.

You now must pa
crucial, so Kares tu
details of the incom
still functioning nor
and he is falling to
seconds all is still w
meters per second,
beginning to chang
watch in amazemen
netic spectrum, fron
wave, to—. By 61.8
gone. Arnold has re
horizon. And in that
out, Arnold was ha
horizon approaching
As your exciteme
you find the full det
as Arnold fell, the w
at first, then faster a
had quadrupled, its r
the wavelength do
(0.0046 second) the
recording system's c
on doubling thereaft
for the wavelength t
long-wavelength sig
zon!
Does this mean t
never will? No, not
forever long to clim
through the horizon,
The weak remaining
time is so long. They
After many hours
long sleep to reinvig
exploration. This tim
but you will do it mu

21. Chapter 6.

You now must pay very close attention. The next few seconds will be crucial, so Kares turns on a high-speed recording system to collect all details of the incoming data. At 61 seconds Arnold reports all systems still functioning normally; the horizon is 14,000 kilometers below him and he is falling toward it at 13,000 kilometers per second. At 61.7 seconds all is still well, 1700 kilometers more to go, speed 39,000 kilometers per second, or about one-tenth the speed of light, laser color beginning to change rapidly. In the next one-tenth of one second you watch in amazement as the laser color zooms through the electromagnetic spectrum, from green to red, to infrared, to microwave, to radiowave, to—. By 61.8 seconds it is all over. The laser beam is completely gone. Arnold has reached the speed of light and disappeared into the horizon. And in that last tenth of a second, just before the beam winked out, Arnold was happily reporting, "All systems go, all systems go, horizon approaching, all systems go, all systems go . . ."

As your excitement subsides, you examine the recorded data. There you find the full details of the shifting laser wavelength. You see that as Arnold fell, the wavelength of the laser signal increased very slowly at first, then faster and faster. But, surprisingly, after the wavelength had quadrupled, its rate of doubling became nearly constant; thereafter the wavelength doubled every 0.00014 second. After 33 doublings (0.0046 second) the wavelength reached 4 kilometers, the limit of your recording system's capabilities. Presumably the wavelength kept right on doubling thereafter. Since it takes an infinite number of doublings for the wavelength to become infinite, exceedingly faint, exceedingly long-wavelength signals might still be emerging from near the horizon!

Does this mean that Arnold has not yet crossed the horizon and never will? No, not at all. Those last, forever-doubling signals take forever long to climb out of the hole's gravitational grip. Arnold flew through the horizon, moving at the speed of light, many minutes ago. The weak remaining signals keep coming out only because their travel time is so long. They are relics of the past.[21]

After many hours of studying the data from Arnold's fall, and after a long sleep to reinvigorate yourself, you embark on the next stage of exploration. This time you, yourself, will probe the horizon's vicinity; but you will do it much more cautiously than did Arnold.

21. Chapter 6.

Bidding farewell to your crew, you climb into a space capsule and drop out of the belly of the starship and into a circular orbit alongside it. You then blast your rocket engines ever so gently to slow your orbital motion a bit. This reduces slightly the centrifugal force that holds your capsule up, and the hole's gravity then pulls you into a slightly smaller, coasting, circular orbit. As you again gently blast your engines, your circular orbit again gently shrinks. Your goal, by this gentle, safe, inward spiral, is to reach a circular orbit just above the horizon, an orbit with circumference just 1.0001 times larger than that of the horizon itself. There you can explore most of the horizon's properties, but still escape its fatal grip.

As your orbit slowly shrinks, however, something strange starts to happen. Already at a 100,000-kilometer circumference you feel it. Floating inside the capsule with your feet toward the hole and your head toward the stars, you feel a weak downward tug on your feet and upward tug on your head; you are being stretched like a piece of taffy candy, but gently. The cause, you realize, is the hole's gravity: Your feet are closer to the hole than your head, so the hole pulls on them harder than on your head. The same was true, of course, when you used to stand on the Earth; but the head-to-foot difference on Earth was so minuscule, less than one part in a million, that you never noticed it. By contrast, as you float in your capsule at a circumference of 100,000 kilometers, the head-to-foot difference is one-eighth of an Earth gravity ($\frac{1}{8}$ "*g*"). At the center of your body the centrifugal force of your orbital motion precisely counteracts the hole's pull. It is as though gravity did not exist; you float freely. But at your feet, the stronger gravity pulls down with an added $\frac{1}{16}$ *g*, and at your head the weaker gravity allows the centrifugal force to push up with an added $\frac{1}{16}$ *g*.

Bemused, you continue your inward spiral; but your bemusement quickly changes to worry. As your orbit grows smaller, the forces on your head and feet grow larger. At a circumference of 80,000 kilometers the difference is a $\frac{1}{4}$-*g* stretching force; at 50,000 kilometers it is a full Earth gravity stretch; at 30,000 kilometers it is 4 Earth gravities. Gritting your teeth in pain as your head and feet are pulled apart, you continue on in to 20,000 kilometers and a 15-*g* stretching force. More than this you cannot stand! You try to solve the problem by rolling up into a tight ball so your head and feet will be closer together and the difference in forces smaller, but the forces are so strong that they will not let you roll up; they snap you back out into a radial, head-to-foot stretch. If your capsule spirals in much farther, your body will give way; you will be torn apart! There is no hope of reaching the horizon's vicinity.

Frustrated and in enormous pain, you halt your capsule's descent, turn it around, and start carefully, gently, blasting your way back up through circular, coasting orbits of larger and larger circumference and then into the belly of the starship.

Entering the captain's chamber, you vent your frustrations on the ship's master computer, DAWN. "Tikhii, tikhii," she says soothingly (drawing words from the ancient Russian language). "I know you are upset, but it is really your own fault. You were told about those head-to-foot forces in your training. Remember? They are the same forces as produce the tides on the oceans of the Earth."[22]

Thinking back to your training, you recall that the oceans on the side of the Earth nearest the Moon are pulled most strongly by the Moon's gravity and thus bulge out toward the Moon. The oceans on the opposite side of the Earth are pulled most weakly and thus bulge out away from the Moon. The result is two oceanic bulges; and as the Earth turns, those bulges show up as two high tides every twenty-four hours. In honor of those tides, you recall, the head-to-foot gravitational force that you felt is called a *tidal force*. You also recall that Einstein's general relativity describes this tidal force as due to a curvature of space and warpage of time, or, in Einstein's language, a *curvature of spacetime*.[23] Tidal forces and spacetime distortions go hand in hand; one always accompanies the other, though in the case of ocean tides the distortion of spacetime is so tiny that it can be measured only with extremely precise instruments.

But what about Arnold? Why was he so blithely immune to the hole's tidal force? For two reasons, DAWN explains: first, because he was much smaller than you, only 10 centimeters high, and the tidal force, being the difference between the gravitational pulls at his head and his feet, was correspondingly smaller; and second, because he was made of a superstrong titanium alloy that could withstand the stretching force far better than your bones and flesh.

Then with horror you realize that, as he fell through the horizon and on in toward the singularity, Arnold must have felt the tidal force rise up in strength until even his superstrong titanium body could not resist it. Less than 0.0002 second after crossing the horizon, his disintegrat-

22. Chapter 2.
23. Ibid.

ing, stretching body must have neared the hole's central singularity. There, you recall from your study of general relativity back on Earth, the hole's tidal forces must come to life, dancing a chaotic dance, stretching Arnold's remains first in this direction, then in that, then in another, faster and faster, stronger and stronger, until even the individual atoms of which he was made are distorted beyond all recognition. That, in fact, is one essence of the singularity: It is a region where chaotically oscillating spacetime curvature creates enormous, chaotic tidal forces.[24]

Musing over the history of black-hole research, you recall that in 1965 the British physicist Roger Penrose used general relativity's description of the laws of physics to prove that a singularity must reside inside every black hole, and in 1969 the Russian troika of Lifshitz, Khalatnikov, and Belinsky used it to deduce that very near the singularity, tidal gravity must oscillate chaotically, like taffy being pulled first this way and then that by a mechanical taffy-pulling machine.[25] Those were the golden years of theoretical black-hole research, the 1960s and 1970s! But because the physicists of those golden years were not clever enough at solving Einstein's general relativity equations, one key feature of black-hole behavior eluded them. They could only conjecture that whenever an imploding star creates a singularity, it must also create a surrounding horizon that hides the singularity from view; a singularity can never be created "naked," for all the Universe to see. Penrose called this the "conjecture of cosmic censorship," since, if correct, it would censor all experimental information about singularities: One could never do experiments to test one's theoretical understanding of singularities, unless one were willing to pay the price of entering a black hole, dying while making the measurements, and not even being able to transmit the results back out of the hole as a memorial to one's efforts.

Although Dame Abygaile Lyman, in 2023, finally resolved the issue of whether cosmic censorship is true or not, the resolution is irrelevant to you now. The only singularities charted in your ship's atlases are those inside black holes, and you refuse to pay the price of death to explore them.

Fortunately, outside but near a black-hole horizon there are many phenomena to explore. You are determined to experience those phe-

24. Chapter 13.
25. Ibid.

nomena firsthand and report back to the World Geographic Society, but you cannot experience them near Hades' horizon. The tidal force there is too great. You must explore, instead, a black hole with weaker tidal forces.

General relativity predicts, DAWN reminds you, that as a hole grows more massive, the tidal forces at and above its horizon grow weaker. This seemingly paradoxical behavior has a simple origin: The tidal force is proportional to the hole's mass divided by the cube of its circumference; so as the mass grows, and the horizon circumference grows proportionally, the near-horizon tidal force actually decreases. For a hole weighing a million solar masses, that is, 100,000 times more massive than Hades, the horizon will be 100,000 times larger, and the tidal force there will be 10 billion (10^{10}) times weaker. That would be comfortable; no pain at all! So you begin making plans for the next leg of your voyage: a journey to the nearest million-solar-mass hole listed in Schechter's Black-Hole Atlas—a hole called Sagittario at the center of our Milky Way galaxy, 30,100 light-years away.

Several days later your crew transmit back to Earth a detailed description of your Hades explorations, including motion pictures of you being stretched by the tidal force and pictures of atoms falling into the hole. The description will require 26 years to cover the 26 light-year distance to Earth, and when it finally arrives it will be published with great fanfare by the World Geographic Society.

In their transmission the crew describe your plan for a voyage to the center of the Milky Way: Your starship's rocket engines will blast all the way with a 1-*g* acceleration, so that you and your crew can experience a comfortable 1-Earth-gravity force inside the starship. The ship will accelerate toward the galactic center for half the journey, then it will rotate 180 degrees and decelerate at 1 *g* for the second half. The entire trip of 30,100 light-years distance will require 30,102 years as measured on Earth; but as measured on the starship it will require only 20 years. In accordance with Einstein's laws of special relativity,[26] your ship's high speed will cause time, as measured on the ship, to "dilate"; and this *time dilation* (or *time warp*), in effect, will make the starship behave like a time machine, projecting you far into the Earth's future while you age only a modest amount.[27]

You explain to the World Geographic Society that your next trans-

26. Chapter 1.
27. Ibid.

mission will come from the vicinity of the galactic center, after you have explored its million-solar-mass hole, Sagittario. Members of the Society must go into deep-freeze hibernation for 60,186 years if they wish to live to receive your transmission (30,102 − 26 = 30,076 years from the time they receive your message until you reach the galactic center, plus 30,110 years while your next transmission travels from the galactic center to Earth).

Sagittario

After a 20-year voyage as measured in starship time, your ship decelerates into the Milky Way's center. There in the distance you see a rich mixture of gas and dust flowing inward from all directions toward an enormous black hole. Kares adjusts the rocket blast to bring the starship into a coasting, circular orbit well above the horizon. By measuring the circumference and period of your orbit and plugging the results into Newton's formula, you determine the mass of the hole. It is 1 million times the mass of the Sun, just as claimed in Schechter's Black-Hole Atlas. From the absence of any tornado-like swirl in the inflowing gas and dust you infer that the hole is not spinning much; its horizon, therefore, must be spherical and its circumference must be 18.5 million kilometers, eight times larger than the Moon's orbit around the Earth.

After further scrutiny of the infalling gas, you prepare to descend toward the horizon. For safety, Kares sets up a laser communication link between your space capsule and your starship's master computer, DAWN. You then drop out of the belly of the starship, turn your capsule so its jets point in the direction of your circling orbital motion, and start blasting gently to slow your orbital motion and drive yourself into a gentle inward (downward) spiral from one coasting circular orbit to another.

All goes as expected until you reach an orbit of circumference 55 million kilometers—just three times the circumference of the horizon. There the gentle blast of your rocket engine, instead of driving you into a slightly tighter circular orbit, sends you into a suicidal plunge toward the horizon. In panic you rotate your capsule and blast with great force to move back up into an orbit just outside 55 million kilometers.

"What the hell went wrong!?" you ask DAWN by laser link.

"Tikhii, tikhii," she replies soothingly. "You planned your orbit using Newton's description of the laws of gravity. But Newton's description is only an approximation to the true gravitational laws that govern the Universe.[28] It is an excellent approximation far from the horizon, but bad near the horizon. Much more accurate is Einstein's general relativistic description; it agrees to enormous precision with the true laws of gravity near the horizon, and it predicts that, as you near the horizon, the pull of gravity becomes stronger than Newton ever expected. To remain in a circular orbit, with this strengthened gravity counterbalanced by the centrifugal force, you must strengthen your centrifugal force, which means you must increase your orbital speed around the black hole: As you descend through three horizon circumferences, you must rotate your capsule around and start blasting yourself forward. Because instead you kept blasting backward, slowing your motion, gravity overwhelmed your centrifugal force as you passed through three horizon circumferences, and hurled you inward."

"Damn that DAWN!" you think to yourself. "She always answers my questions, but she never volunteers crucial information. She never warns me when I'm going wrong!" You know the reason, of course. Human life would lose its zest and richness if computers were permitted to give warning whenever a mistake was being made. Back in 2032 the World Council passed a law that a Hobson block preventing such warnings must be embedded in all computers. As much as she might wish, DAWN cannot bypass her Hobson block.

Suppressing your exasperation, you rotate your capsule and begin a careful sequence of forward blast, inward spiral, coast, forward blast, inward spiral, coast, forward blast, inward spiral, coast, which takes you from 3 horizon circumferences to 2.5 to 2.0 to 1.6 to 1.55 to 1.51 to 1.505 to 1.501 to . . . What frustration! The more times you blast and the faster your resulting coasting, circular motion, the smaller becomes your orbit; but as your coasting speed approaches the speed of light, your orbit only approaches 1.5 horizon circumferences. Since you can't move faster than light, there is no hope of getting close to the horizon itself by this method.

Again you appeal to DAWN for help, and again she soothes you and explains: Inside 1.5 horizon circumferences there are no circular orbits at all. Gravity's pull there is so strong that it cannot be counteracted by any centrifugal forces, not even if one coasts around and around the hole at the speed of light. If you want to go closer, DAWN says, you must abandon your circular, coasting orbit and instead descend directly

28. Chapter 2.

toward the horizon, with your rockets blasting downward to keep you from falling catastrophically. The force of your rockets will support you against the hole's gravity as you slowly descend and then hover just above the horizon, like an astronaut hovering on blasting rockets just above the Moon's surface.

Having learned some caution by now, you ask DAWN for advice about the consequences of such a strong, steady rocket blast. You explain that you wish to hover at a location, 1.0001 horizon circumferences, where most of the effects of the horizon can be experienced, but from which you can escape. If you support your capsule there by a steady rocket blast, how much acceleration force will you feel? "One hundred and fifty million Earth gravities," DAWN replies gently.

Deeply discouraged, you blast and spiral your way back up into the belly of the starship.

After a long sleep, followed by five hours of calculations with general relativity's black-hole formulas, three hours of plowing through Schechter's Black-Hole Atlas, and an hour of consultation with your crew, you formulate the plan for the next leg of your voyage.

Your crew then transmit to the World Geographic Society, under the optimistic assumption that it still exists, an account of your experiences with Sagittario. At the end of their transmission your crew describe your plan:

Your calculations show that the larger the hole, the weaker the rocket blast you will need to support yourself, hovering, at 1.0001 horizon circumferences. For a painful but bearable 10-Earth-gravity blast, the hole must be 15 trillion (15×10^{12}) solar masses. The nearest such hole is the one called Gargantua, far outside the 100,000 (10^5) light-year confines of our own Milky Way galaxy, and far outside the 100 million (10^8) light-year Virgo cluster of galaxies, around which our Milky Way orbits. In fact, it is near the quasar 3C273, 2 billion (2×10^9) light-years from the Milky Way and 10 percent of the distance to the edge of the observable part of the Universe.

The plan, your crew explain in their transmission, is a voyage to Gargantua. Using the usual 1-*g* acceleration for the first half of the trip and 1-*g* deceleration for the second half, the voyage will require 2 billion years as measured on Earth, but, thanks to the speed-induced warpage of time, only 42 years as measured by you and your crew in the starship. If the members of the World Geographic Society are not willing to chance a 4-billion-year deep-freeze hibernation (2 billion years for the starship to reach Gargantua and 2 billion years for its transmission to return to Earth), then they will have to forgo receiving your next transmission.

Gargantua

Forty-two years of starship time later, your ship decelerates into the vicinity of Gargantua. Overhead you see the quasar 3C273, with two brilliant blue jets squirting out of its center[29]; below is the black abyss of Gargantua. Dropping into orbit around Gargantua and making your usual measurements, you confirm that its mass is, indeed, 15 trillion times that of the Sun, you see that it is spinning very slowly, and you compute from these data that the circumference of its horizon is 29 light-years. Here, at last, is a hole whose vicinity you can explore while experiencing bearably small tidal forces and rocket accelerations! The safety of the exploration is so assured that you decide to take the entire starship down instead of just a capsule.

Before beginning the descent, however, you order your crew to photograph the giant quasar overhead, the trillions of stars that orbit Gargantua, and the billions of galaxies sprinkled over the sky. They also photograph Gargantua's black disk below you; it is about the size of the sun as seen from Earth. At first sight it appears to blot out the light from all the stars and galaxies behind the hole. But looking more closely, your crew discover that the hole's gravitational field has acted like a lens[30] to deflect some of the starlight and galaxy light around the edge of the horizon and focus it into a thin, bright ring at the edge of the black disk. There, in that ring, you see several images of each obscured star: one image produced by light rays that were deflected around the left limb of the hole, another by rays deflected around the right limb, a third by rays that were pulled into one complete orbit around the hole and then released in your direction, a fourth by rays that orbited the hole twice, and so on. The result is a highly complex ring structure, which your crew photograph in great detail for future study.

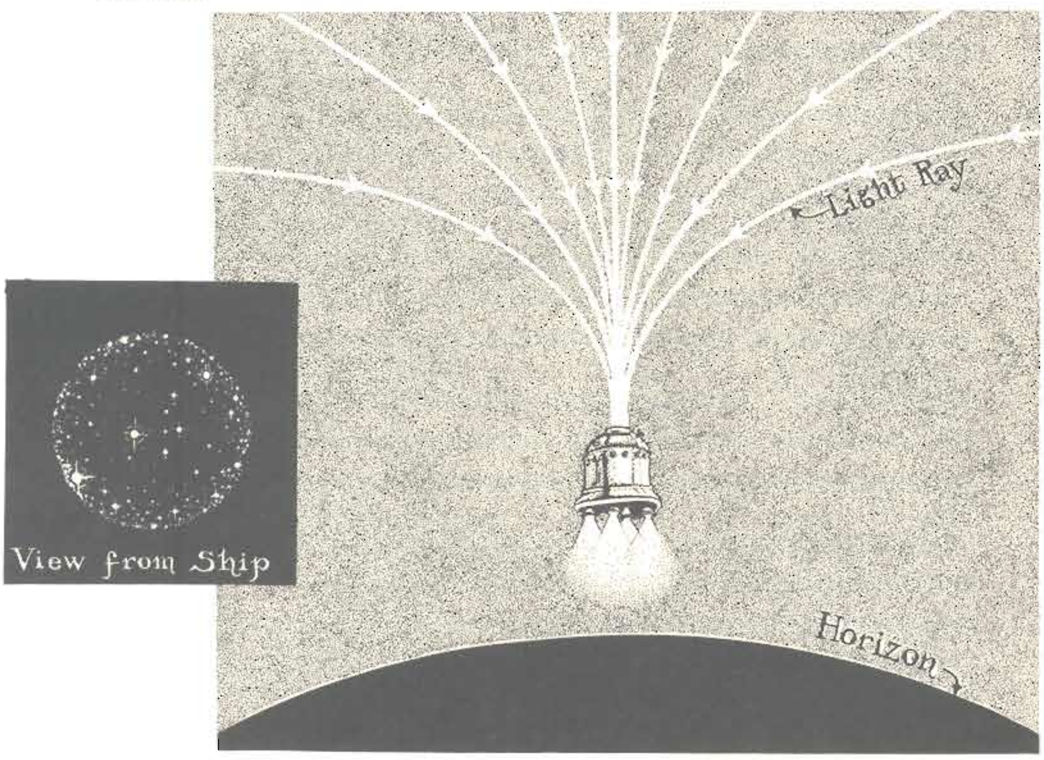
The photographic session complete, you order Kares to initiate the starship's descent. But you must be patient. The hole is so huge that, accelerating and then decelerating at 1 *g*, it will require 13 years of starship time to reach your goal of 1.0001 horizon circumferences!

29. Chapter 9.
30. Chapter 8.

As the ship descends, your crew make a photographic record of the changes in the appearance of the sky around the starship. Most remarkable is the change in the hole's black disk below the ship: Gradually it grows larger. You expect it to stop growing when it has covered the entire sky below you like a giant black floor, leaving the sky overhead as clear as on Earth. But no; the black disk keeps right on growing, swinging up around the sides of your starship to cover everything except a bright, circular opening overhead, an opening through which you see the external Universe (Figure P.4). It is as though you had entered a cave and were plunging deeper and deeper, watching the cave's bright mouth grow smaller and smaller in the distance.

In growing panic, you appeal to DAWN for help: "Did Kares miscalculate our trajectory? Have we plunged through the horizon? Are we doomed?!"

P.4 The starship hovering above the black-hole horizon, and the trajectories along which light travels to it from distant galaxies (the light rays). The hole's gravity deflects the light rays downward ("gravitational lens effect"), causing humans on the starship to see all the light concentrated in a bright, circular spot overhead.



"Tikhii, tikhii," she replies soothingly. "We are safe; we are still outside the horizon. Darkness has covered most of the sky only because of the powerful lensing effect of the hole's gravity. Look there, where my pointer is, almost precisely overhead; that is the galaxy 3C295. Before you began your plunge it was in a horizontal position, 90 degrees from the zenith. But here near Gargantua's horizon the hole's gravity pulls so hard on the light rays from 3C295 that it bends them around from horizontal to nearly vertical. As a result 3C295 appears to be nearly overhead."

Reassured, you continue your descent. The console displays your ship's progress in terms of both the radial (downward) distance traveled and the circumference of a circle around the hole that passes through your location. In the early stages of your descent, for each kilometer of radial distance traveled, your circumference decreased by 6.283185307 . . . kilometers. The ratio of circumference decrease to radius decrease was 6.283185307 kilometers/1 kilometer, which is equal to 2π, just as Euclid's standard formula for circles predicts. But now, as your ship nears the horizon, the ratio of circumference decrease to radius decrease is becoming much smaller than 2π: It is 5.960752960 at 10 horizon circumferences; 4.442882938 at 2 horizon circumferences; 1.894451650 at 1.1 horizon circumferences; 0.625200306 at 1.01 horizon circumferences. Such deviations from the standard Euclidean geometry that teenagers learn in school are possible only in a curved space; you are seeing the curvature which Einstein's general relativity predicts must accompany the hole's tidal force.[31]

In the final stage of your ship's descent, Kares blasts the rockets harder and harder to slow its fall. At last the ship comes to a hovering rest at 1.0001 horizon circumferences, blasting with a 10-*g* acceleration to hold itself up against the hole's powerful gravitational pull. In its last 1 kilometer of radial travel the circumference decreases by only 0.062828712 kilometer.

Struggling to lift their hands against the painful 10-*g* force, your crew direct their telescopic cameras into a long and detailed photographic session. Except for wisps of weak radiation all around you from collisionally heated, infalling gas, the only electromagnetic waves to be photographed are those in the bright spot overhead. The spot is small, just 3 degrees of arc in diameter, six times the size of the Sun as seen from Earth. But squeezed into that spot are images of all the stars that

31. Chapters 2 and 3.

orbit Gargantua, and all the galaxies in the Universe. At the precise center are the galaxies that are truly overhead. Fifty-five percent of the way from the spot's center to its edge are images of galaxies like 3C295 which, if not for the hole's lens effect, would be in horizontal positions, 90 degrees from the zenith. Thirty-five percent of the way to the spot's edge are images of galaxies that you know are really on the opposite side of the hole from you, directly below you. In the outermost 30 percent of the spot is a second image of each galaxy; and in the outermost 2 percent, a third image!

Equally peculiar, the colors of all the stars and galaxies are wrong. A galaxy that you know is really green appears to be shining with soft X-rays: Gargantua's gravity, in pulling the galaxy's radiation downward to you, has made the radiation more energetic by decreasing its wavelength from 5×10^{-7} meter (green) to 5×10^{-9} meter (X-ray). And similarly, the outer disk of the quasar 3C273, which you know emits infrared radiation of wavelength 5×10^{-5} meter, appears to be shining with green 5×10^{-7} meter light.

After thoroughly recording the details of the overhead spot, you turn your attention to the interior of your starship. You half expect that here, so near the hole's horizon, the laws of physics will be changed in some way, and those changes will affect your own physiology. But no. You look at your first mate, Kares; she appears normal. You look at your second mate, Bret; he appears normal. You touch each other; you feel normal. You drink a glass of water; aside from the effects of the 10-*g* acceleration, the water goes down normally. Kares turns on an argon ion laser; it produces the same brilliant green light as ever. Bret pulses a ruby laser on and then off, and measures the time it takes for the pulse of light to travel from the laser to a mirror and back; from his measurement he computes the speed of the light's travel. The result is absolutely the same as in an Earth-based laboratory: 299,792 kilometers per second.

Everything in the starship is normal, absolutely the same as if the ship had been resting on the surface of a massive planet with 10-*g* gravity. If you did not look outside the starship and see the bizarre spot overhead and the engulfing blackness all around, you would not know that you were very near the horizon of a black hole rather than safely on the surface of a planet—or you almost wouldn't know. The hole curves spacetime inside your starship as well as outside, and with sufficiently accurate instruments, you can detect the curvature; for example, by its tidal stretch between your head and your feet. But whereas the curvature is enormously important on the scale of the horizon's 300-trillion-kilometer circumference, its effects are minuscule on the scale of your 1-kilometer starship; the curvature-produced tidal force between one end of the starship and the other is just one-hundredth of a trillionth of an Earth gravity (10^{-14} g), and between your own head and feet it is a thousand times smaller than that!

To pursue this remarkable normality further, Bret drops from the starship a capsule containing a pulsed-laser-and-mirror instrument for measuring the speed of light. As the capsule plunges toward the horizon, the instrument measures the speed with which light pulses travel from the laser in the capsule's nose to the mirror in its tail and back. A computer in the capsule transmits the result on a laser beam up to the ship: "299,792 kilometers per second; 299,792; 299,792; 299,792 . . ." The color of the incoming laser beam shifts from green to red to infrared to microwave to radio as the capsule nears the horizon, and still the message is the same: "299,792; 299,792; 299,792 . . ." And then the laser beam is gone. The capsule has pierced the horizon, and never once as it fell was there any change in the speed of light inside it, nor was there any change in the laws of physics that governed the workings of the capsule's electronic systems.

These experimental results please you greatly. In the early twentieth century Albert Einstein proclaimed, largely on philosophical grounds, that the local laws of physics (the laws in regions small enough that one can ignore the curvature of spacetime) should be the same everywhere in the Universe. This proclamation has been enshrined as a fundamental principle of physics, the *equivalence principle.*[32] Often in the ensuing centuries the equivalence principle was subjected to experimental test, but never was it tested so graphically and thoroughly as in your experiments here near Gargantua's horizon.

You and your crew are now tiring of the struggle with 10 Earth gravities, so you prepare for the next and final leg of your voyage, a return to our Milky Way galaxy. Your crew will transmit an account of your Gargantua explorations during the early stages of the voyage; and since your starship itself will soon be traveling at nearly the speed of light, the transmissions will reach the Milky Way less than a year before the ship, as measured from Earth.

As your starship pulls up and away from Gargantua, your crew make a careful, telescopic study of the quasar 3C273 overhead[33] (Figure P.5).

32. Chapter 2.
33. Chapter 9.

Its jets—thin spikes of hot gas shooting out of the quasar's core—are enormous: 3 million light-years in length. Training your telescopes on the core, your crew see the source of the jets' power: a thick, hot, doughnut of gas less than 1 light-year in size, with a black hole at its center. The doughnut, which astrophysicists have called an "accretion disk," orbits around and around the black hole. By measuring its rotation period and circumference, your crew infer the mass of the hole: 2 billion (2×10^9) solar masses, 7500 times smaller than Gargantua, but far larger than any hole in the Milky Way. A stream of gas flows from the doughnut to the horizon, pulled by the hole's gravity. As it nears the horizon the stream, unlike any you have seen before, swirls around and around the hole in a tornado-type motion. This hole must be spinning fast! The axis of spin is easy to identify; it is the axis about which the gas stream swirls. The two jets, you notice, shoot out along the spin axis. They are born just above the horizon's north and south poles, where they suck up energy from the hole's spin and from the doughnut,[34] much like a tornado sucks up dust from the earth.

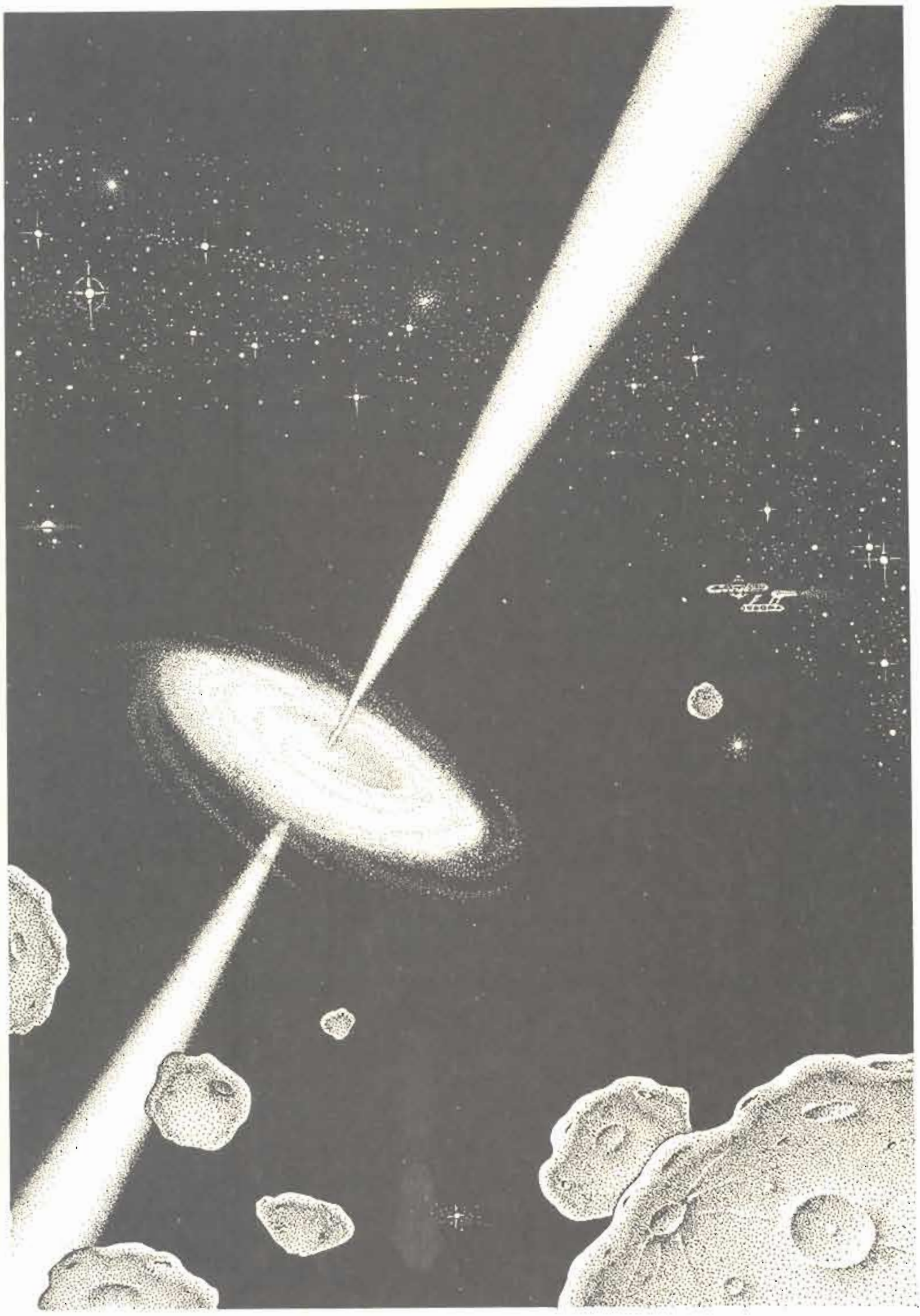
The contrast between Gargantua and 3C273 is amazing: Why does Gargantua, with its 1000 times greater mass and size, not possess an encircling doughnut of gas and gigantic quasar jets? Bret, after a long telescopic study, tells you the answer: Once every few months a star in orbit around 3C273's smaller hole strays close to the horizon and gets ripped apart by the hole's tidal force. The star's guts, roughly 1 solar mass worth of gas, get spewed out and strewn around the hole. Gradually internal friction drives the strewn-out gas down into the doughnut. This fresh gas compensates for the gas that the doughnut is continually feeding into the hole and the jets. The doughnut and jets thereby are kept richly full of gas, and continue to shine brightly.

Stars also stray close to Gargantua, Bret explains. But because Gargantua is far larger than 3C273, the tidal force outside its horizon is too weak to tear any star apart. Gargantua swallows stars whole without spewing their guts into a surrounding doughnut. And with no doughnut, Gargantua has no way of producing jets or other quasar violence.

As your starship continues to rise out of Gargantua's gravitational grip, you make plans for the journey home. By the time your ship reaches the Milky Way, the Earth will be 4 billion years older than when you left. The changes in human society will be so enormous that you don't want to return there. Instead, you and your crew decide to

34. Chapters 9 and 11.

P.5 The quasar
nut of gas ("acc
hole's spin axis.



P.5 The quasar 3C273: a 2-billion-solar-mass black hole encircled by a doughnut of gas ("accretion disk") and with two gigantic jets shooting out along the hole's spin axis.

colonize the space around a spinning black hole. You know that just as the spin energy of the hole in 3C273 helps power the quasar's jets, so the spin energy of a smaller hole can be used as a power source for human civilization.

You do not want to arrive at some chosen hole and discover that other beings have already built a civilization around it; so instead of aiming your starship at a rapidly spinning hole that already exists, you aim at a star system which will give birth to a rapidly spinning hole shortly after your ship arrives.

In the Milky Way's Orion nebula, at the time you left Earth, there was a *binary star system* composed of two 30-solar-mass stars orbiting each other. DAWN has calculated that each of those stars should have imploded, while you were outbound to Gargantua, to form a 24-solar-mass, nonspinning hole (with 6 solar masses of gas ejected during the implosion). Those two 24-solar-mass holes should now be circling around each other as a *black-hole binary*, and as they circle, they should emit ripples of tidal force (ripples of "spacetime curvature") called *gravitational waves.*[35] These gravitational waves should push back on the binary in much the same way as an outflying bullet pushes back on the gun that fires it, and this *gravitational-wave recoil* should drive the holes into a slow but inexorable inward spiral. With a slight adjustment of your starship's acceleration, you can time your arrival to coincide with the last stage of that inward spiral: Several days after you arrive, you will see the holes' nonspinning horizons whirl around and around each other, closer and closer, and faster and faster, until they coalesce to produce a single whirling, spinning, larger horizon.

Because the two parent holes do not spin, neither alone can serve as an efficient power source for your colony. However, the newborn, rapidly spinning hole will be ideal!

Home

After a 42-year voyage your starship finally decelerates into the Orion nebula, where DAWN predicted the two holes should be. There they are, right on the mark! By measuring the orbital motion of interstellar atoms as they fall into the holes, you verify that their horizons are not spinning and that each weighs 24 solar masses, just as DAWN

35. Chapter 10.

predicted. Each horizon has a circumference of 440 kilometers; they are 30,000 kilometers apart; and they are orbiting around each other once each 13 seconds. Inserting these numbers into the general relativity formulas for gravitational-wave recoil, you conclude that the two holes should coalesce seven days from now. There is just time enough for your crew to prepare their telescopic cameras and record the details. By photographing the bright ring of focused starlight that encircles each hole's black disk, they can easily monitor the holes' motions.

You want to be near enough to see clearly, but far enough away to be safe from the holes' tidal forces. A good location, you decide, is a starship orbit ten times larger than the orbit in which the holes circle each other—an orbital diameter of 300,000 kilometers and orbital circumference of 940,000 kilometers. Kares maneuvers the starship into that orbit, and your crew begin their telescopic, photographic observations.

Over the next six days the two holes gradually move closer to each other and speed up their orbital motion. One day before coalescence, the distance between them has shrunk from 30,000 to 18,000 kilometers and their orbital period has decreased from 13 to 6.3 seconds. One hour before coalescence they are 8400 kilometers apart and their orbital period is 1.9 seconds. One minute before coalescence: separation 3000 kilometers, period 0.41 second. Ten seconds before coalescence: separation 1900 kilometers, period 0.21 second.

Then, in the last ten seconds, you and your starship begin to shake, gently at first, then more and more violently. It is as though a gigantic pair of hands had grabbed your head and feet and were alternately compressing and stretching you harder and harder, faster and faster. And then, more suddenly than it started, the shaking stops. All is quiet.

"What was that?" you murmur to DAWN, your voice trembling.

"Tikhii, tikhii," she replies soothingly. "That was the undulating tidal force of gravitational waves from the holes' coalescence. You are accustomed to gravitational waves so weak that only very delicate instruments can detect their tidal force. However, here, close to the coalescing holes, they were enormously strong—strong enough that, had we parked our starship in an orbit 30 times smaller, it would have been torn apart by the waves. But now we are safe. The coalescence is complete and the waves are gone; they are on their way out into the Universe, carrying to distant astronomers a symphonic description of the coalescence."[36]

36. Chapter 10.

Training one of your crew's telescopes on the source of gravity below, you see that DAWN is right, the coalescence is complete. Where before there were two holes there now is just one, and it is spinning rapidly, as you see from the swirl of infalling atoms. This hole will make an ideal power generator for your crew and thousands of generations of their descendants.

By measuring the starship's orbit, Kares deduces that the hole weighs 45 solar masses. Since the parent holes totaled 48 solar masses, 3 solar masses must have been converted into pure energy and carried off by the gravitational waves. No wonder the waves shook you so hard!

As you turn your telescopes toward the hole, a small object unexpectedly hurtles past your starship, splaying brilliant sparks profusely in all directions, and then explodes, blasting a gaping hole in your ship's side. Your well-trained crew and robots rush to their battle stations, you search vainly for the attacking warship—and then, responding to an appeal for her help, DAWN announces soothingly over the ship's speaker system, "Tikhii, tikhii; we are not being attacked. That was just a freak primordial black hole, evaporating and then exploding."[37]

"A what?!" you cry out.

"A primordial black hole, evaporating and then destroying itself in an explosion," DAWN repeats.

"Explain!" you demand. "What do you mean by *primordial*? What do you mean by *evaporating and exploding*? You're not making sense. Things can fall into a black hole, but nothing can ever come out; nothing can 'evaporate.' And a black hole lives forever; it always grows, never shrinks. There is no way a black hole can 'explode' and destroy itself. That's absurd."

Patiently as always, DAWN educates you. "Large objects—such as humans, stars, and black holes formed by the implosion of a star—are governed by the *classical* laws of physics," she explains, "by Newton's laws of motion, Einstein's relativity laws, and so forth. By contrast, tiny objects—for example, atoms, molecules, and black holes smaller than an atom—are governed by a very different set of laws, the *quantum* laws of physics.[38] While the classical laws forbid a normal-sized black hole ever to evaporate, shrink, explode, or destroy itself, not so the quantum laws. They demand that any atom-sized black hole gradually evaporate and shrink until it reaches a critically small circumference,

37. Chapter 12.
38. Chapters 4–6, 10, 12–14.

about the same as an atomic nucleus. The hole, which despite its tiny size weighs about a billion tons, must then destroy itself in an enormous explosion. The explosion converts all of the hole's billion-ton mass into outpouring energy; it is a trillion times more energetic than the most powerful nuclear explosions that humans ever detonated on Earth in the twentieth century. Just such an explosion has now damaged our ship," DAWN explains.

"But you needn't worry that more explosions will follow," DAWN continues. "Such explosions are exceedingly rare because tiny black holes are exceedingly rare. The only place that tiny holes were ever created was in our Universe's big bang birth, twenty billion years ago; that is why they are called *primordial* holes. The big bang created only a few such primordial holes, and those few have been slowly evaporating and shrinking ever since their birth. Once in a great while one of them reaches its critical, smallest size and explodes.[39] It was only by chance—an extremely improbable occurrence—that one exploded while hurtling past our ship, and it is exceedingly unlikely that our starship will ever encounter another such hole."

Relieved, you order your crew to begin repairs on the ship while you and your mates embark on your telescopic study of the 45-solar-mass, rapidly spinning hole below you.

The hole's spin is obvious not only from the swirl of infalling atoms, but also from the shape of the bright-ringed black spot it makes on the sky below you: The black spot is squashed, like a pumpkin; it bulges at its equator and is flattened at its poles. The centrifugal force of the hole's spin, pushing outward, creates the bulge and flattening.[40] But the bulge is not symmetric; it looks larger on the right edge of the disk, which is moving away from you as the horizon spins, than on the left edge. DAWN explains that this is because the horizon can capture rays of starlight more easily if they move toward you along its right edge, against the direction of its spin, than along its left edge, with its spin.

By measuring the shape of the spot and comparing it with general relativity's black-hole formulas, Bret infers that the hole's spin angular momentum is 96 percent of the maximum allowed for a hole of its mass. And from this angular momentum and the hole's mass of 45 Suns you compute other properties of the hole, including the spin rate of its

39. Chapter 12.
40. Chapter 7.

horizon, 270 revolutions per second, and its equatorial circumference, 533 kilometers.

The spin of the hole intrigues you. Never before could you observe a spinning hole up close. So with pangs of conscience you ask for and get a volunteer robot, to explore the neighborhood of the horizon and transmit back his experiences. You give the robot, whose name is Kolob, careful instructions: "Descend to ten meters above the horizon and there blast your rockets to hold yourself at rest, hovering directly below the starship. Use your rockets to resist both the inward pull of gravity and the tornado-like swirl of space."

Eager for adventure, Kolob drops out of the starship's belly and plunges downward, blasting his rockets gently at first, then harder, to resist the swirl of space and remain directly below the ship. At first Kolob has no problems. But when he reaches a circumference of 833 kilometers, 56 percent larger than the horizon, his laser light brings the message, "I can't resist the swirl; I can't; I can't!" and like a rock caught up in a tornado he gets dragged into a circulating orbit around the hole.[41]

"Don't worry," you reply. "Just do your best to resist the swirl, and continue to descend until you are ten meters above the horizon."

Kolob complies. As he descends, he is dragged into more and more rapid circulating motion. Finally, when he stops his descent and hovers ten meters above the horizon, he is encircling the hole in near perfect lockstep with the horizon itself, 270 circuits per second. No matter how hard he blasts to oppose this motion, he cannot. The swirl of space won't let him stop.

"Blast in the other direction," you order. "If you can't circle more slowly than 270 circuits per second, try circling faster."

Kolob tries. He blasts, keeping himself always 10 meters above the horizon but trying to encircle it faster than before. Although he feels the usual acceleration from his blast, you see his motion change hardly at all. He still circles the hole 270 times per second. And then, before you can transmit further instructions, his fuel gives out; he begins to plummet downward; his laser light zooms through the electromagnetic spectrum from green to red to infrared to radio waves, and then turns black with no change in his circulating motion. He is gone, down the hole, plunging toward the violent singularity that you will never see.

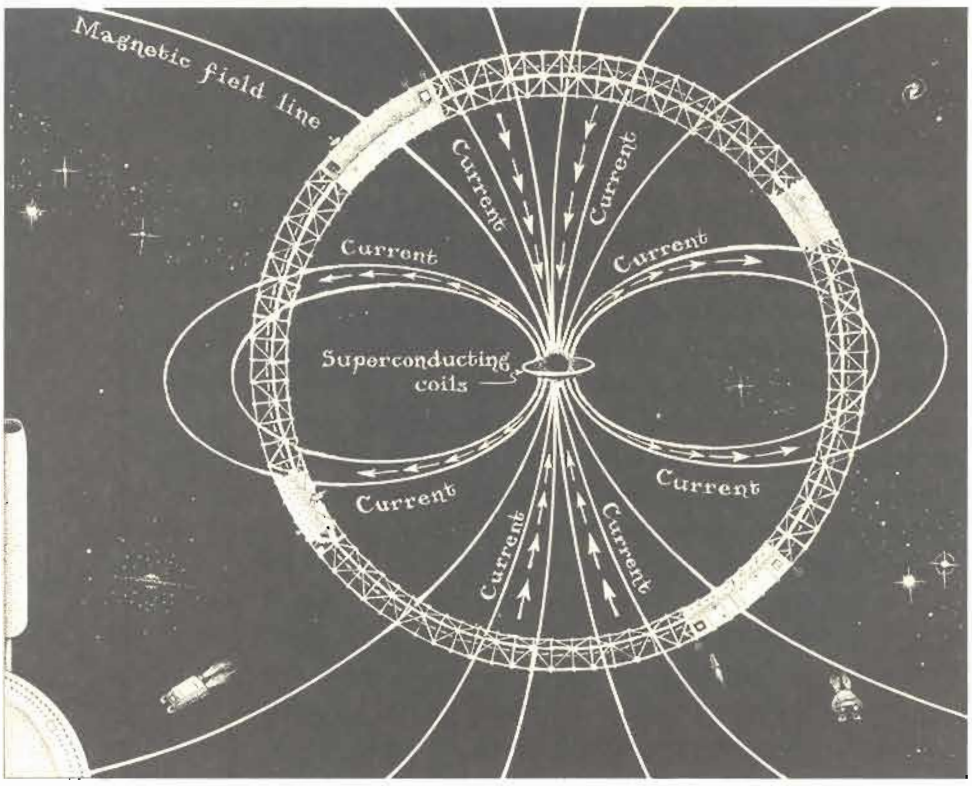
41. Chapter 7.

After three weeks of mourning, experiments, and telescopic studies, your crew begin to build for the future. Bringing in materials from distant planets, they construct a girder-work ring around the hole. The ring has a circumference of 5 million kilometers, a thickness of 3.4 kilometers, and a width of 4000 kilometers. It rotates at just the right rate, two rotations per hour, for centrifugal forces to counterbalance the hole's gravitational pull at the ring's central layer, 1.7 kilometers from its inner and outer faces. Its dimensions are carefully chosen so that those people who prefer to live in 1 Earth gravity can set up their homes near the inner or outer face of the ring, while those who prefer weaker gravity can live nearer its center. These differences in gravity are due in part to the rotating ring's centrifugal force and in part to the hole's tidal force—or, in Einstein's language, to the curvature of spacetime.

The electric power that heats and lights this ring world is extracted from the black hole: Twenty percent of the hole's mass is in the form of energy that is stored in the tornado-like swirl of space outside but near the horizon.[42] This is 10,000 times more energy than the Sun will radiate as heat and light in its entire lifetime!—and being outside the horizon, it can be extracted. Never mind that the ring world's energy extractor is only 50 percent efficient; it still has a 5000 times greater energy supply than the Sun.

The energy extractor works on the same principle as do some quasars[43]: Your crew have threaded a magnetic field through the hole's horizon and they hold it on the hole, despite its tendency to pop off, by means of giant superconducting coils (Figure P.6). As the horizon spins, it drags the nearby space into a tornado-like swirl which in turn interacts with the threading magnetic field to form a gigantic electric power generator. The magnetic field lines act as transmission lines for the power. Electric current is driven out of the hole's equator (in the form of electrons flowing inward) and up the magnetic field lines to the ring world. There the current deposits its power. Then it flows out of the ring world on another set of magnetic field lines and down into the hole's north and south poles (in the form of positrons flowing inward). By adjusting the strength of the magnetic field, the world's inhabitants can adjust the power output: weak field and low power in the world's early years; strong field and high power in later years. Gradually as the power is extracted, the hole will slow its spin, but it

42. Chapters 7 and 11.
43. Chapters 9 and 11.



P.6 A city on a girder-work ring around a spinning black hole, and the electromagnetic system by which the city extracts power from the hole's spin.

will take many eons to exhaust the hole's enormous store of spin energy.

Your crew and countless generations of their descendants can call this artificial world "home" and use it as a base for future explorations of the Universe. But not you. You long for the Earth and the friends whom you left behind, friends who must have been dead now for more than 4 billion years. Your longing is so great that you are willing to risk the last quarter of your normal, 200-year life span in a dangerous and perhaps foolhardy attempt to return to the idyllic era of your youth.

Time travel into the future is rather easy, as your voyage among the holes has shown. Not so travel into the past. In fact, such travel might be completely forbidden by the fundamental laws of physics. However, DAWN tells you of speculations, dating back to the twentieth century, that backward time travel might be achieved with the aid of a hypothetical space warp called a *wormhole*.[44] This space warp consists of two

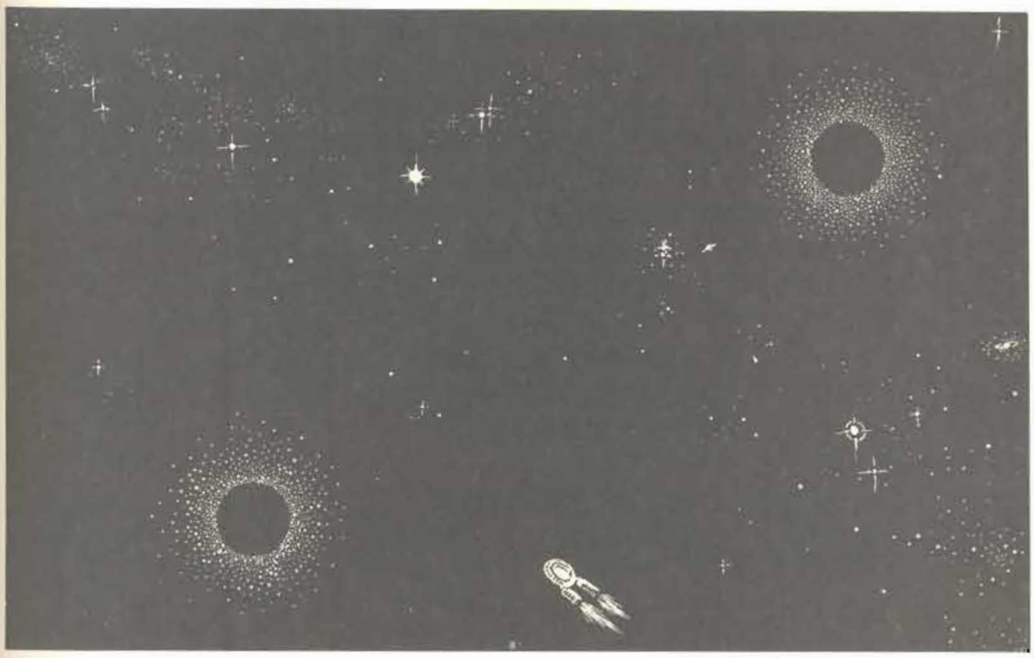
44. Chapter 14.

P.7 The two mouths
will emerge from the
hole's throat) that ext

entrance holes (the
holes but without h
(Figure P.7). Anyt
short tube (the wo
mouth. The tube ca
through *hyperspac*
possible for time to
than through our U
hole in one directio
go backward in ou
direction, from rig
would be a time wa

The laws of qua
holes of this type e
must be so tiny, jus
fleeting—far too b

45. Chapters 13 and 1



P.7 The two mouths of a hypothetical wormhole. Enter either mouth, and you will emerge from the other, having traveled through a short tube (the wormhole's throat) that extends not through our Universe, but through hyperspace.

entrance holes (the wormhole's *mouths*), which look much like black holes but without horizons, and which can be far apart in the Universe (Figure P.7). Anything that enters one mouth finds itself in a very short tube (the wormhole's *throat*) that leads to and out of the other mouth. The tube cannot be seen from our Universe because it extends through *hyperspace* rather than through normal space. It might be possible for time to hook up through the wormhole in a different way than through our Universe, DAWN explains. By traversing the wormhole in one direction, say from the left mouth to the right, one might go backward in our Universe's time, while traversing in the opposite direction, from right to left, one would go forward. Such a wormhole would be a time warp, as well as a space warp.

The laws of quantum gravity demand that exceedingly tiny wormholes of this type exist,[45] DAWN tells you. These quantum wormholes must be so tiny, just 10^{-33} centimeter in size, that their existence is only fleeting—far too brief, 10^{-43} second, to be usable for time travel. They

45. Chapters 13 and 14.

must flash into existence and then flash out in a random, unpredictable manner—here, there, and everywhere. Very occasionally a flashing wormhole will have one mouth near the ring world today and the other near Earth in the era 4 billion years ago when you embarked on your voyage. DAWN proposes to try to catch such a wormhole as it flickers, enlarge it like a child blowing up a balloon, and keep it open long enough for you to travel through it to the home of your youth.

But DAWN warns you of great danger. Physicists have conjectured, though it has never been proved, that an instant before an enlarging wormhole becomes a time machine, the wormhole must self-destruct with a gigantic, explosive flash. In this way the Universe might protect itself from time-travel paradoxes, such as a man going back in time and killing his mother before he was conceived, thereby preventing himself from being born and killing his mother.[46]

If the physicists' conjecture is wrong, then DAWN might be able to hold the wormhole open for a few seconds, with a large enough throat for you to travel through. By waiting nearby as she enlarges the wormhole and then plunging through it, within a fraction of a second of your own time you will arrive home on Earth, in the era of your youth 4 billion years ago. But if the time machine self-destructs, you will be destroyed with it. You decide to take the chance . . .

☆ ☆ ☆

The above tale sounds like science fiction. Indeed, part of it is: I cannot by any means guarantee that there exists a 10-solar-mass black hole near the star Vega, or a million-solar-mass hole at the center of the Milky Way, or a 15-trillion-solar-mass black hole anywhere at all in the Universe; they are all speculative but plausible fiction. Nor can I guarantee that humans will ever succeed in developing the technology for intergalactic travel, or even for interstellar travel, or for constructing ring worlds on girder-work structures around black holes. These are also speculative fiction.

On the other hand, I can guarantee with considerable but not complete confidence that black holes exist in our Universe and have the precise properties described in the above tale. If you hover in a blasting starship just above the horizon of a 15-trillion-solar-mass hole, I guarantee that the laws of physics will be the same inside your starship as

46. Chapter 14.

on Earth, and that when you look out at the heavens around you, you will see the entire Universe shining down at you in a brilliant, small disk of light. I guarantee that, if you send a robot probe down near the horizon of a spinning hole, blast as it may it will never be able to move forward or backward at any speed other than the hole's own spin speed (270 circuits per second in my example). I guarantee that a rapidly spinning hole can store as much as 29 percent of its mass as spin energy, and that if one is clever enough, one can extract that energy and use it.

How can I guarantee all these things with considerable confidence? After all, I have never seen a black hole. Nobody has. Astronomers have found only indirect evidence for the existence of black holes[47] and no observational evidence whatsoever for their claimed detailed properties. How can I be so audacious as to guarantee so much about them? For one simple reason. Just as the laws of physics predict the pattern of ocean tides on Earth, the time and height of each high tide and each low tide, so also the laws of physics, if we understand them correctly, predict these black-hole properties, and predict them with no equivocation. From Newton's description of the laws of physics one can deduce, by mathematical calculations, the sequence of Earth tides for the year 1999 or the year 2010; similarly, from Einstein's general relativity description of the laws, one can deduce, by mathematical calculations, everything there is to know about the properties of black holes, from the horizon on outward.

And why do I believe that Einstein's general relativity description of the fundamental laws of physics is a highly accurate one? After all, we know that Newton's description ceases to be accurate near a black hole.

Successful descriptions of the fundamental laws contain within themselves a strong indication of where they will fail.[48] Newton's description tells us itself that it will probably fail near a black hole (though we only learned in the twentieth century how to read this out of Newton's description). Similarly, Einstein's general relativity description exudes confidence in itself outside a black hole, at the hole's horizon, and inside the hole all the way down almost (but not quite) to the singularity at its center. This is one thing that gives me confidence in general relativity's predictions. Another is the fact that, although general relativity's black-hole predictions have not yet been tested

47. Chapters 8 and 9.
48. Last section of Chapter 1.

directly, there have been high-precision tests of other features of general relativity on the Earth, in the solar system, and in binary systems that contain compact, exotic stars called pulsars. General relativity has come through each test with flying colors.

Over the past twenty years I have participated in the theoretical-physics quest which produced our present understanding of black holes and in the quest to test black-hole predictions by astronomical observation. My own contributions have been modest, but with my physicist and astronomer colleagues I have reveled in the excitement of the quest and have marveled at the insight it has produced. This book is my attempt to convey some sense of that excitement and marvel to people who are not experts in either astronomy or physics.

of

Professor Wilh
University of I
Leipzig, Germ

Esteemed Herr

Please forgive
Professor, in th
I shall start
he studied at t
passed his dipl
flying colors la
unsuccessfully
him to continu
All those in po
talents; in any
and diligent ar
My son ther