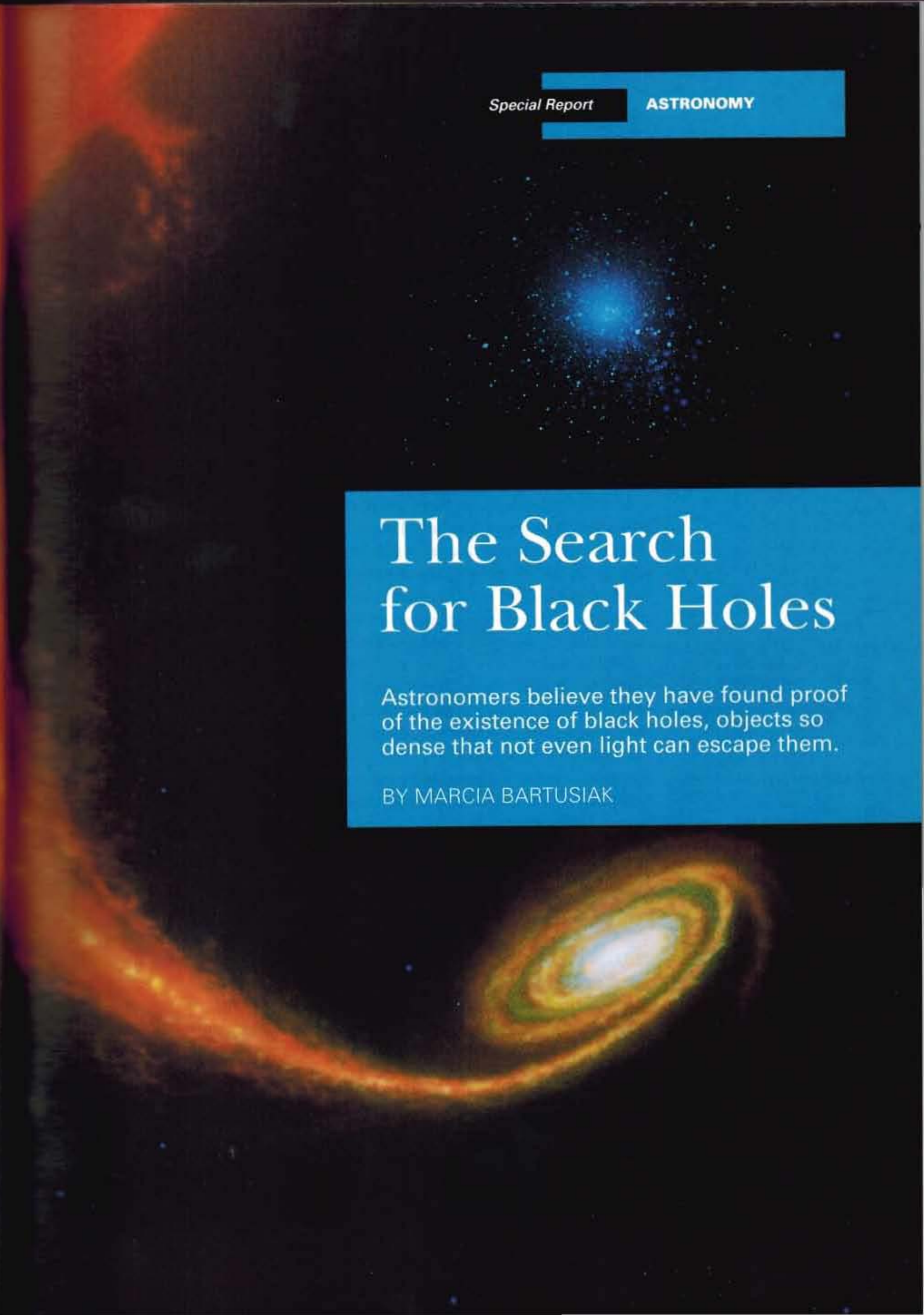

The Search for Black Holes

Astronomers believe they have found proof of the existence of black holes, objects so dense that not even light can escape them.

BY MARCIA BARTUSIAK

Preceding pages: In an artist's rendering of a two-star system, one of the stars has collapsed to become a black hole (lower right). The hole itself cannot be seen, but its intense gravity draws gases away from the companion star in a hot, swirling torrent.

In the celestial zoo, there is no stranger creature than a black hole. It is the astronomical equivalent of the kraken, an enormous sea monster that coils its long tentacles around unwary ships and pulls them down to their doom. But the kraken exists only in legend. Black holes, more incredible and fearsome than any terror of the deep, are real—or so astronomers are now convinced.

The name *black hole* is an apt one for these monsters of the depths of space. They are objects with such powerful gravity that nothing, not even light, can escape from them. A black hole is an utterly dark abyss—one that draws matter and energy to itself and holds them in an iron grip.

The proof that black holes exist is accumulating rapidly. Astronomers have been reporting evidence of probable black holes for several years, and in May 1994 astronomers using the recently repaired Hubble Space Telescope announced the most conclusive observation yet. They said a swirling concentration of matter at the center of a galaxy known as M87 could be explained only by the presence of a huge black hole with the *mass* (quantity of matter) of up to 3 billion suns.

Black holes come in various sizes, theorists believe. Many are formed from the collapsed remnants of very large stars. Others, like the near-certain black hole in M87, are supermassive objects lurking at the heart of some galaxies. There may even be mini black holes, far smaller than an atom, that originated in the *big bang*, the huge explosion of matter and energy that scientists think gave birth to the universe some 15 billion years ago.

Because black holes have such strange characteristics, physicists and astronomers thought for years that they existed only on paper, as a mysterious solution to a set of mathematical equations. That black holes might actually exist seemed beyond the bounds of possibility. Since the late 1960's, however, most doubts about the reality of black holes have been dispelled, and astronomers have been searching the heavens for them.

Early ideas about "dark stars"

Although the search for black holes began fairly recently, the idea of black holes can actually be traced back more than two centuries, to early speculations about the nature of gravity. The first person to theorize the existence of anything like a black hole was an English scientist and church rector named John Michell. In 1783, Michell suggested that if a star were as dense as the sun but had a diameter 500 times larger, the star's gravity would be so powerful that no light could escape from it. The star would appear as a black void in space.

Today, scientists know that the kind of star Michell was imagining can't exist in nature. Still, Michell's work explored a concept that is vital to our present-day understanding of black holes, the notion of escape velocity. Escape velocity is the speed that something—a cannonball, space shuttle, or anything else—must attain to break free of another object's gravitational pull. The stronger the gravitational pull,

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the greater the speed necessary. Michell calculated that the escape velocity for his gargantuan star would be greater than the speed of light (which is now known to be 299,792 kilometers [186,282 miles] per second). Like a stone thrown into the air, a ray of light moving outward from the giant star would curve back downward.

The concept of escape velocity is based on fundamental discoveries about gravity made in the 1600's by the English physicist and mathematician Isaac Newton. Newton had found that the gravitational attraction between two objects is related to the distance between them. If the distance between two bodies is halved, the gravitational force between them becomes four times as great. If the distance doubles, the attraction decreases to one-fourth what it had been. The distance measurement in these calculations is the distance from one object's center of mass to that of the other object. The center of mass is the point around which an object's mass is evenly distributed.

If two objects are touching, the distance between their centers of mass could be made shorter if one or both of the objects could be squeezed into a smaller volume. Consider the example of the Earth and a space shuttle. If the Earth could somehow be compressed to half its normal diameter, a space shuttle on a launching pad would be half as far from Earth's center of mass as before. As a result, Earth's gravitational pull on the shuttle would be four times stronger, and the escape velocity would increase by 1.414 (the square root of 2—escape velocity increases by a different amount than gravitational attraction).

Newton's formula shows that Michell's scenario is not the only way to imagine a star whose gravity prevents light from escaping. The same result would occur if an ordinary star were somehow compressed into a small enough volume. As the star shrank, its surface would get closer and closer to its center of mass, and the escape velocity at the surface would climb. At some point, the star would be so compact and dense that the escape velocity would exceed the speed of light.

Einstein enters the picture

Until the 1900's, speculations about such "dark stars"—no one had yet called them black holes—were considered interesting but of no practical concern. But then the work of the German-American physicist Albert Einstein in 1916 provided a new theory of gravity that led to our present understanding of black holes.

The key to understanding Einstein's view of gravity is his notion that three-dimensional space is intimately linked with a fourth dimension, time, to form what he called space-time. According to Einstein's general theory of relativity, gravity is a distortion of the four dimensions of space-time—rather than invisible tendrils of attraction between objects, as Newton had assumed. We can envision this by thinking of space-time as a boundless rubber sheet. Large masses, such as a star, indent the flexible mat of space-time much the way a bowling ball would create a depression in a soft mattress. Any rocket, planet, or light beam skimming by the star would follow the natural depression

Glossary

Accretion disk: A flattened spiral of matter that is being drawn by gravity into a black hole, becoming extremely hot and emitting X rays in the process.

Escape velocity: The speed an object must attain to escape from another object's gravitational field.

Event horizon: An invisible spherical boundary surrounding a black hole at the point where the escape velocity equals the speed of light (299,792 kilometers [186,282 miles] per second); it is called the event horizon because no event occurring within it can be seen from the outside.

Gravity waves: Ripples in space-time, caused by a catastrophic celestial event such as the collapse of a star into a black hole, that spread outward through the universe at the speed of light.

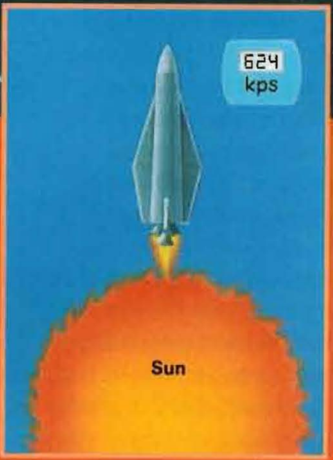
Schwarzschild radius: The point at which the escape velocity from an object that is contracting from gravity equals the speed of light. The Schwarzschild radius is the distance from a black hole's singularity to the event horizon.

Singularity: A point of infinite density at the center of a completely collapsed black hole containing all of the hole's mass.

Space-time: The four-dimensional "fabric" of the universe, consisting of the three dimensions of space linked with a fourth dimension, time.

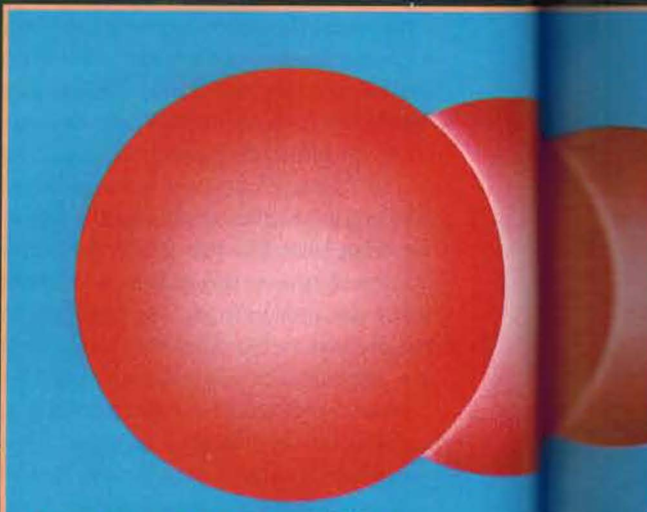
The physics of a black hole

The first black holes were discovered on paper, when physicists calculated the gravitational pull of very massive and dense stars. Scientists knew that an object at the surface of such a star would have to accelerate to tremendously high speeds to break free of the star's intense gravity. If the star's matter were packed densely enough, nothing, not even the star's own light, could travel fast enough to escape.



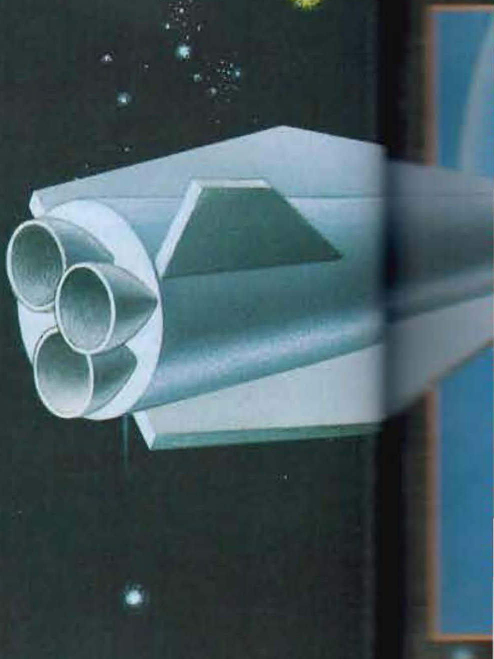
Scientists can calculate the gravitational pull of a star in terms of the *escape velocity* associated with it—the speed an object must attain to break free of the star's gravity. The escape velocity for a spaceship or any other object on the sun, for example, is 624 kilometers per second (388 miles per second). A spaceship moving at a lower speed would eventually fall back to the sun.

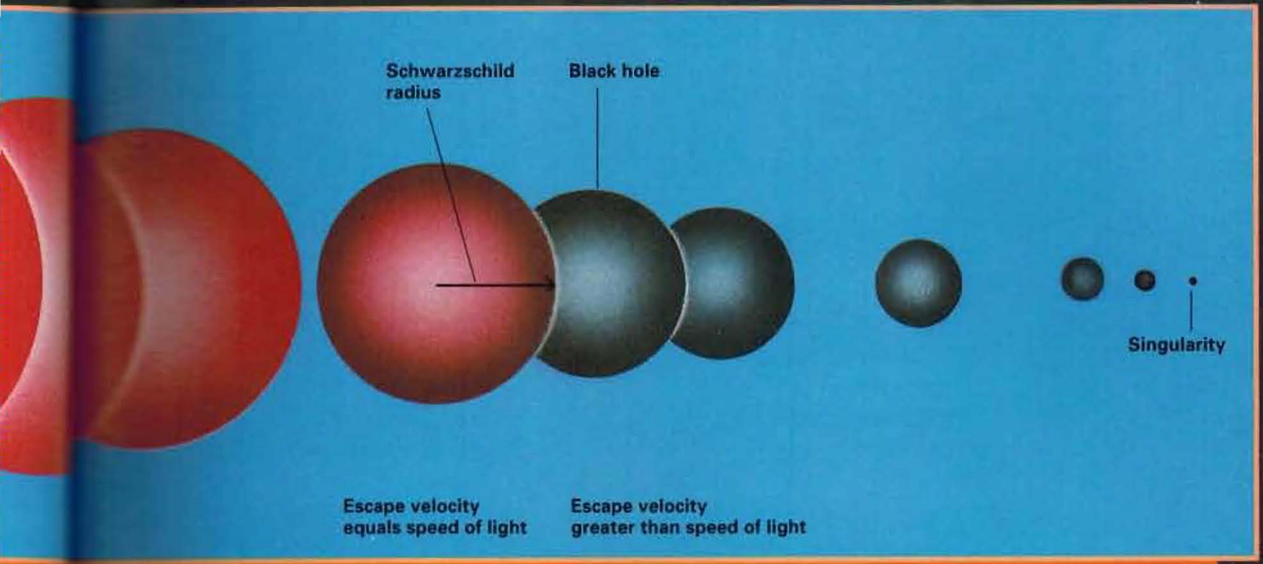
The laws of physics say that the gravitational attraction between two objects increases as the centers of the objects get closer together. If two objects are already in contact with each other, this increase could occur only if the matter in one or both of the objects were compressed into a smaller volume. For example, if the sun could somehow be squeezed to half its diameter, the escape velocity for a spaceship at its surface would rise to 882 kilometers per second (548 miles per second).



Escape velocity less than speed of light

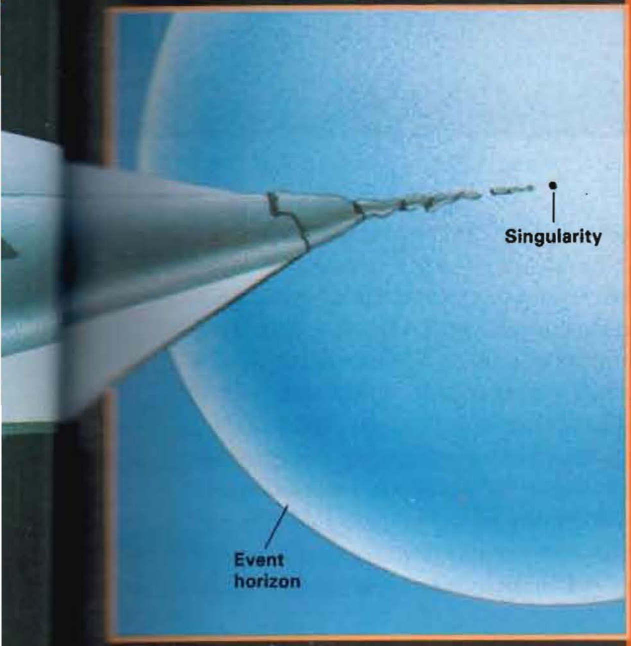
Physicists imagined what would happen if a star became smaller and smaller without losing any of its mass. Because the star's outer edge would get ever closer to the center of the star, the escape velocity would get increasingly higher.





When the star is squeezed down to a certain size, the escape velocity equals the speed of light—299,792 kilometers (186,282 miles) per second. The distance from the center of such a star to its outer edge is called the *Schwarzschild radius.* The Schwarzschild radius varies according to a star's mass—the more massive the star is, the longer the radius. Once a star shrinks within the Schwarzschild radius, not even light can escape from it. It has become a black hole.

According to scientists' calculations, any object that is squeezed within its Schwarzschild radius will continue to contract by gravity. Within a moment, it contracts to a point of infinite density called a *singularity.*



A black hole consists of both the singularity and a spherical region of empty space traced out by the Schwarzschild radius. The surface of that sphere is an invisible boundary known as the *event horizon.* An unwary spaceship that crossed that point of no return would be drawn helplessly toward the singularity. In its final moments, the ship would be stretched like taffy by the enormous gravitational field of the singularity and then torn to pieces before being crushed out of existence. But the fate of the doomed spaceship would be unseen by anyone watching from outside the event horizon, to whom the black hole would look like an utterly dark and featureless disk. That is why the boundary of a black hole is called the event horizon—because no event that occurs within it can be observed from outside the black hole.

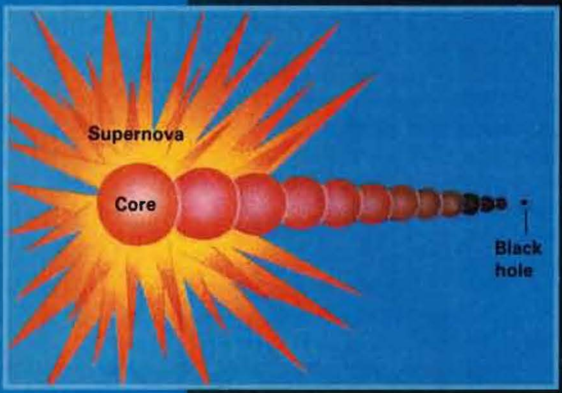
How black holes are born

Astronomers and physicists think the heavens are populated by three kinds of black holes, each of which formed in a different manner. "Ordinary" black holes were created by the collapse of large stars. Supermassive black holes formed at the heart of many galaxies. And mini black holes may have been created during the explosive birth of the universe.

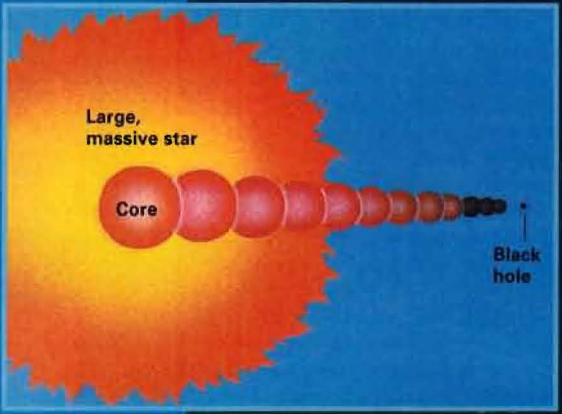
From burned-out stars

Two types of stars can turn into black holes when they run out of the fuel that keeps them burning.

An extremely large star—one about 8 to 25 times as massive as the sun—usually dies violently as a *supernova* (exploding star). If the core of the star that remains after the explosion contains at least three times the mass of the sun, it will collapse from the weight of its own gravity, shrinking past the Schwarzschild radius and becoming a black hole.



The core of a star that is more than 25 times as massive as the sun may collapse without creating an explosion. If the core is at least three times as massive as the sun, it will shrink past the Schwarzschild radius to form a black hole.



in space-time carved out by the star. If the object veered too close, it might fall into the star.

As soon as Einstein published his equations, researchers began trying to discover their implications, seeing with pen and paper how the new and improved view of gravity operated in certain situations. In 1916, a paper written by the German astronomer Karl Schwarzschild explored what would happen if all the mass of an object such as the sun were squeezed down to a very small size. It was during this theoretical tinkering that Schwarzschild revealed the strange and astounding properties of what we now call black holes.

Schwarzschild determined that a mass compressed to a small enough size would be surrounded by a spherical region of empty space-time

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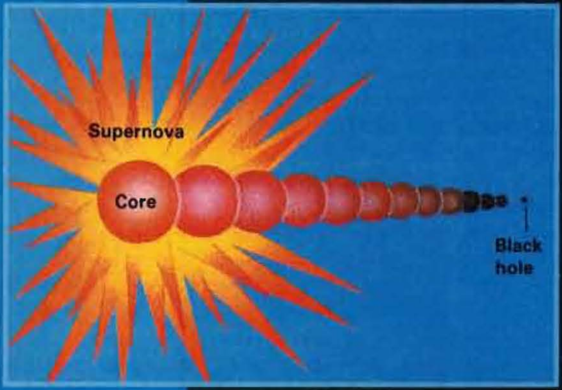

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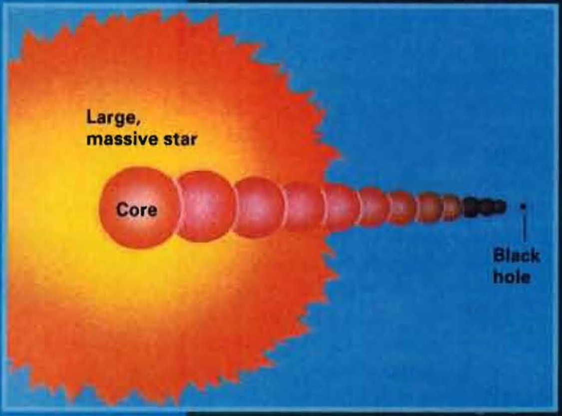

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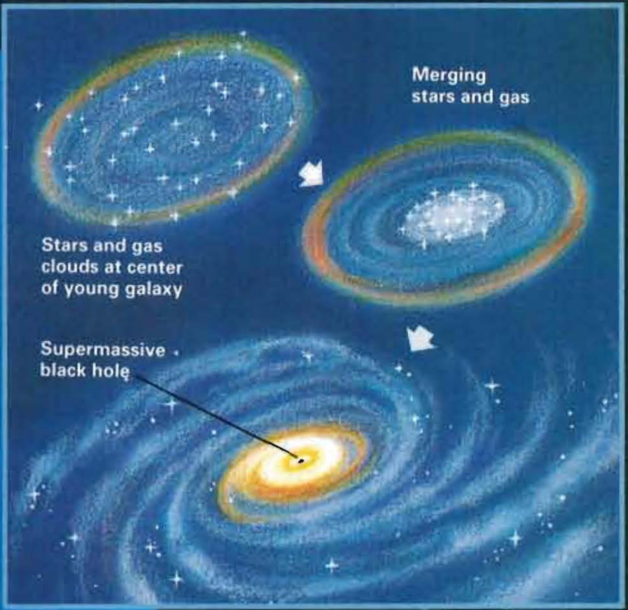
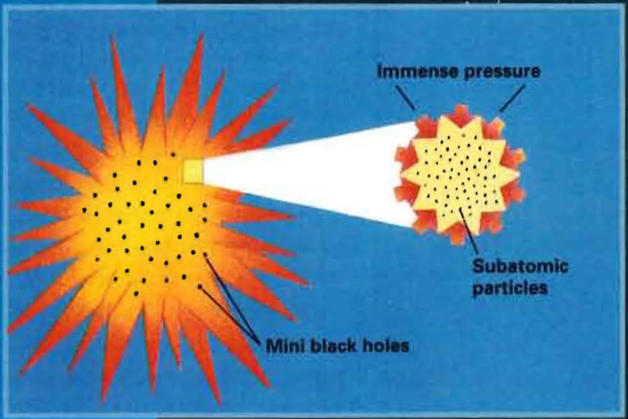
From matter in the center of galaxies

Scientists believe that supermassive black holes formed at the center of many galaxies in the early days of the universe. In a young galaxy, huge gas clouds and swarms of stars rotate in a swirling mass. At the center of the galaxy, stars and gas clouds may become so closely packed that they are drawn together by gravity, eventually forming a single large mass. Continued gravitational contraction produces a black hole with the mass of millions or billions of suns.



From the violent birth of the universe

Countless mini black holes may have formed in a fraction of a second during the *big bang,* the titanic explosion of matter and energy that gave birth to the universe. The tremendous pressures within the big bang could have squeezed pockets of subatomic particles to incredibly high densities, converting them to mini black holes far smaller than an atom.



from which nothing—not a particle of matter nor a glimmer of light—could escape. The radius of this sphere, called the *Schwarzschild radius,* is the point where the escape velocity from the object is exactly equal to the speed of light, the ultimate speed limit in the universe. The radius varies according to the amount of mass. The greater the mass, the larger the Schwarzschild radius.

The outer edge of the spherical region of empty space-time is a crucial element of a black hole. It marks a gravitational point of no return. This boundary is known as the *event horizon,* because no event that occurs within it—where the escape velocity is even higher than the speed of light—can be observed from the outside. Once you crossed that invisible border, there would be no way out, only a sure plummet into the pit in space-time dug out by the black hole. Neither would there be any way of communicating with those you left behind, because any radio signal directed to the outside world would be trapped by the intense gravitational field. Completely cut off from the rest of the universe, you would be on a one-way trip to oblivion. Your bizarre journey would end only when the black hole's tremendous gravity stretched you like a rubber band, tore you to pieces, and finally crushed you out of existence.

General relativity showed that any quantity of matter—a million stars or a handful of sand—could become a black hole if it could be squeezed into a small enough sphere. The Schwarzschild radius for the sun, for example, is about 3 kilometers (2 miles). If the sun could be forced into a sphere with that radius, no light could escape from it, and it would be a black hole. Its light extinguished, the sun would then continue to contract under its own gravity. Within a tiny fraction of a second, it would shrink to a point called a *singularity.* All the sun's mass would be contained in that one point. The event horizon would remain at a distance of 3 kilometers from the singularity.

From neutron stars to black holes

Schwarzschild's calculations were essentially an academic exercise. After all, how could any mass be compressed within its Schwarzschild radius? In the late 1930's, however, theoretical work directed by the American physicist J. Robert Oppenheimer (who later headed the development of the first atomic bomb) indicated that our universe might actually be churning out black holes as the end point in the lives of very massive stars.

Oppenheimer contemplated a star that has exhausted its store of hydrogen. Hydrogen fuels the nuclear reactions in the *core* (central region) that produce a star's tremendous heat and light. The outward pressure of the hot gases provides a counterbalance to the inward pull of the star's gravity. When the nuclear reactions cease, the core of the star is no longer able to support itself, and gravity causes it to contract. For a star as massive as our sun, the core shrinks to about the size of the Earth and continues to glow as a star called a white dwarf. The white dwarf's gravity cannot jam the star's atoms any closer. For a star a bit heavier than the sun, however, the core collapses even further to form a tiny *neutron star,* a ball about 30 kilometers (18.6 miles) wide consisting purely of subatomic particles called neutrons. Here the mass of a million Earths is packed into a sphere the size of a city. A teaspoonful of a neutron star would weigh about a billion tons.

But what if the star is even more massive? Oppenheimer and his collaborators showed that there is a maximum mass for a neutron star, now believed to be about three times that of the sun. Above that mass, not even tightly packed neutrons can withstand the force of gravity. Collapse to a black hole is inevitable.

While Oppenheimer's findings were certainly fascinating, most astronomers regarded them as no more than a mathematical speculation. It was still somewhat radical to believe that a star could even be scrunched into a neutron star. A Swiss-American astronomer, Fritz Zwicky, had suggested in 1934 that *supernovae* (exploding stars) were associated with the formation of neutron stars, but no one took the idea very seriously. A star shrinking to a black hole seemed more unlikely still.

Astronomers' indifference to the subject of collapsed stars didn't change much until the 1960's. Credit for finally arousing their interest goes to the noted theorist John A. Wheeler of Princeton University in New Jersey. Wheeler felt certain that stars undergoing the ultimate collapse had a reality beyond the equations in Oppenheimer's dust-covered journal articles. Perhaps Wheeler's greatest contribution was in finally naming these bizarre objects. In 1967, he dubbed them *black holes*, a name that caught on at once.

Wheeler's certainty that black holes must exist was further advanced by recent developments in astronomy. Earlier in 1967, astronomers had finally detected their first neutron star, and by the end of 1968 at least two dozen more had been identified. Today, astronomers know of hundreds of neutron stars. As Zwicky had predicted, many of them were found to be the remnants of supernovae. Once it was confirmed that neutron stars truly inhabit the heavens, the thought of black holes became easier to contemplate.

With black holes finally a respectable subject for study, theorists began to imagine the various forms black holes can take. Schwarzschild's calculations dealt with nonrotating black holes, but most black holes probably rotate. That is because black holes—at least ones of any appreciable size—are formed from stars. And stars, like just about everything else in the universe, from planets to galaxies, rotate. In a rotating black hole, Einstein's equations revealed, the singularity would be a ring rather than a point. Space travelers venturing into a large, rotating black hole could conceivably pass through the ring without harm—if they had enough energy and technological know-how to keep the passage open. But where would that lead? Some theorists have speculated that a black hole punches through space-time and ends up in a separate universe or in another part of our universe. If true, a ring singularity could be a tunnel to those otherworldly destinations. But such ideas cannot be verified for now. Indeed, recent calculations suggest that stray radiation from space falling into a black hole would pinch off the tunnel. So, cosmic portholes of this sort may be closer to science fiction than science fact.

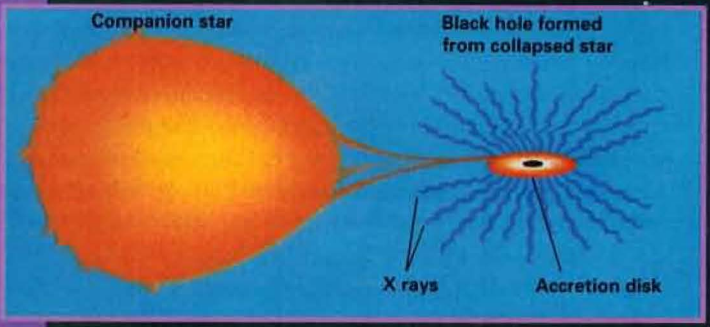
Black holes from single stars—or billions of them

What does seem to be a fact is that black holes exist, and that becoming a black hole is the inevitable end point of the most massive stars. Although just one star in millions is massive enough to end its life as a black hole, the typical galaxy contains at least 100 billion stars, so black holes resulting from collapsed stars would hardly be rarities. The Milky Way alone probably contains hundreds of them.

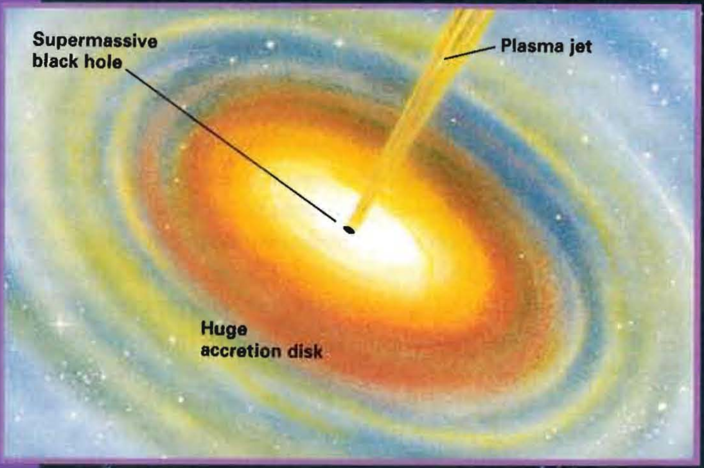
How to find a black hole

Although black holes do not emit light, astronomers know how to search for them—by looking for their effects on nearby stars and gas clouds.

A black hole in a *binary* (two-star) system should be fairly easy to spot, because the black hole's strong gravity tears gases away from the visible star. The gas swirls around the event horizon in a flattened cloud called an *accretion disk* before being swallowed up. Friction and pressure in the disk cause the gases to become exceedingly hot and to emit X rays, which could be detected from Earth.



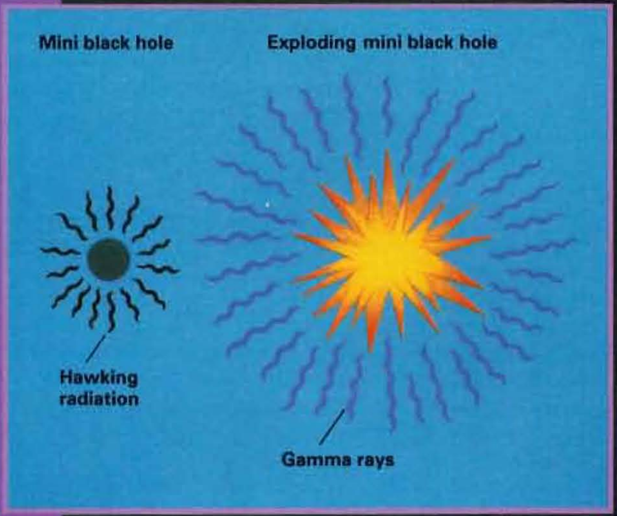
A supermassive black hole in another galaxy may make its presence known even more dramatically. The accretion disk of such a huge black hole could be so big that it would be visible in astronomers' telescopes. Other visible signs of a supermassive black hole would be jets of *plasma* (hot, electrically charged gases) shot far into space by the disk's magnetic lines of force.



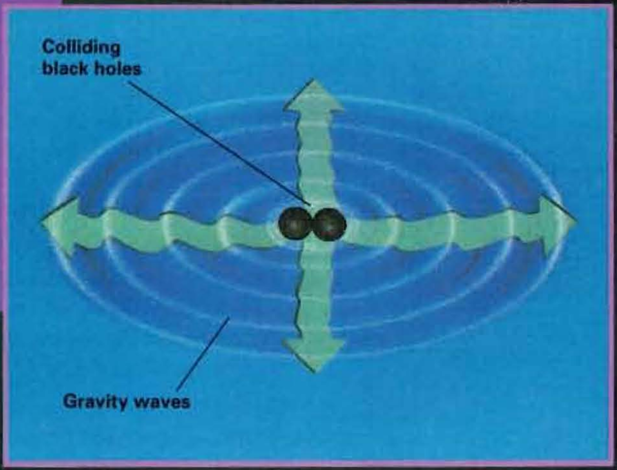
Since the 1960's, research on very massive stars has clarified how they can become black holes. A star with a mass more than about eight times that of the sun usually ends its life as a supernova when its core runs out of fuel, collapses under its own weight, and forms a neutron star. Additional matter falling onto the rigid surface of the neutron star rebounds in a shattering explosion that rips apart the outer layers of the original star. A neutron star is often the surviving remnant of a supernova. But a neutron star that gains extra mass during the explosion may become massive enough to collapse further into a black hole.

Astronomers think that in very massive stars—those with a total mass more than about 25 times that of the sun—the core may already have enough mass to become a black hole. When such a star's nuclear reac-

Mini black holes should be detectable because of a phenomenon called *Hawking radiation,* a type of radiation emitted just outside the event horizon. According to physicists' calculations, Hawking radiation causes black holes to lose tiny amounts of mass over time. The loss is insignificant for large black holes, but many mini black holes created during the big bang should now be running out of matter. Physicists think that in its final hours, a mini black hole becomes tremendously hot and then explodes, producing a detectable burst of high-energy radiation called gamma rays.



The collision and merger of two black holes should produce *gravity waves,* "spacequakes" that travel at the speed of light from the site of violent celestial events. Researchers are now trying to detect these waves with highly sensitive instruments.



tions cease, no supernova occurs. The star's core just quietly shrinks and becomes a black hole.

Even more awesome than black holes resulting from collapsed stars are the supermassive black holes that astronomers suspect lie at the center of the Milky Way and many other large galaxies. These enormous black holes are thought to have formed when galaxies were first taking shape, as huge gas clouds and dense herds of stars were drawn together by their mutual gravity. Galactic black holes may be so massive that they have an event horizon hundreds of millions of kilometers across, making some of them comparable in size to the Earth's orbit about the sun.

Well before reporting the almost certain presence of a supermassive black hole in the M87 galaxy in 1994, astronomers had found indirect evidence for these gigantic black holes. They did so by observing the motions of stars in nearby galaxies, including our closest large neighbor, the Andromeda galaxy. In 1987, for example, astronomers Alan Dressler of the Observatories of the Carnegie Institution of Washington, in Pasadena, Calif., and Douglas O. Richstone of the University of Michigan in Ann Arbor studied stars in the central part of Andromeda. They found that the stars in that region of the galaxy are crowded together and move unusually fast, suggesting that the stars are racing around a dark central object containing the mass of up to 70 million suns.

Supermassive black holes are thought to explain the tremendous fountains of energy spewing from the celestial objects known as quasars. These dazzling objects, situated billions of light-years away from us at the edge of the visible universe, were first sighted in the 1960's. (A light-year is the distance light travels in one year, about 9.5 trillion kilometers [5.9 trillion miles].) Astronomers theorize that quasars are galaxies in an early stage of life. In each quasar, they believe, a supermassive black hole at the center of the developing galaxy is consuming nearby stars and gas, in the process emitting as much energy as a trillion suns.

That energy, according to the theory, is produced when matter being drawn toward the black hole orbits the hole in a tightening spiral called an *accretion disk,* as if it were water flowing down a space-time drain. As the matter gets ever closer to the hole, it accelerates to nearly the speed of light. Compression and friction cause the matter to become progressively hotter, until its temperature is in the tens of millions of degrees. The hot gases emit enormous amounts of radiation and high-energy particles.

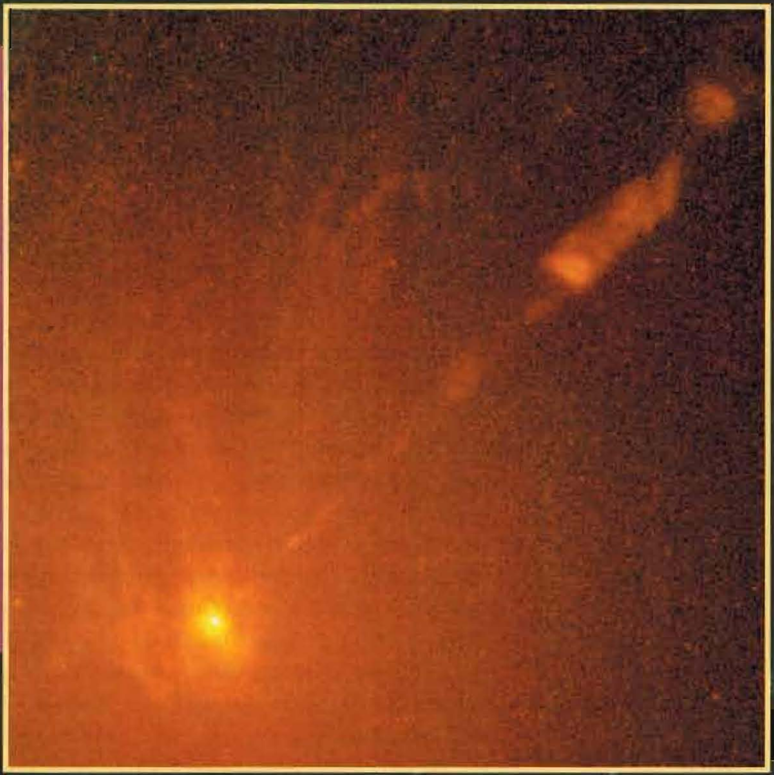
Astronomers don't think there are many quasars around today, because the quasars we now see at the edge of the visible universe were emitting their stupendous energies when the universe was young. We are just now seeing them because it took billions of years for their light to reach us across the vast expanse of space. Many nearby galaxies were undoubtedly also quasars long ago, until their central black holes ran out of nearby matter to consume.

Mini black holes and their disappearing act

At the opposite extreme from supermassive black holes are mini black holes. The possible existence of these objects was first suggested in 1971 by British physicist Stephen Hawking of Cambridge University. Hawking suggested that the incredible densities that existed in the turbulent first moments of the big bang could have compressed pockets of matter into countless tiny black holes.

At about the same time, Hawking surprised the scientific community by announcing that "black holes ain't so black." They emit radiation, though in very tiny amounts. Hawking realized this after studying the effects of *quantum mechanics*—the physical laws governing the world of

A bright disk of hot gases glows at the heart of a galaxy named M87, shown in a 1994 Hubble Space Telescope image. Calculations indicate that the disk of gases is rotating so fast that it must be swirling around a huge black hole with the mass—and gravity—of up to 3 billion suns. A jet of matter streams away from the disk toward the upper right. In May 1994, astronomers reported that the Hubble data on M87 provided conclusive evidence that black holes exist.



elementary particles—in the vicinity of black holes. According to quantum mechanics, even the vacuum of space isn't really empty. It is filled with pairs of *virtual particles*—subatomic particles, created from energy "borrowed" from the vacuum, that blink into fleeting existence. Ordinarily, virtual particles exist for the briefest of moments before vanishing again. At the event horizon of a black hole, however, things can work out a bit differently. The black hole's strong gravity can draw one virtual particle over the event horizon. At the same time, the other member of the pair extracts enough energy from the black hole's gravitational field to become a real particle that moves away from the hole. Because matter and energy are equivalent—that is, one can be transformed into the other—the black hole loses a bit of mass whenever this phenomenon occurs.

For a massive black hole, this quantum-mechanical process, known as *Hawking radiation*, is insignificant. A black hole with the mass of a few suns would need more than 10 million trillion trillion trillion trillion trillion years to shrink away to nothingness in this manner. But for a mini black hole, these mass losses are very significant. The tiniest black holes would have disappeared long ago, but ones with the mass of a mountain would be shedding the last of their mass right about now. At the end, according to this theory, a mini black hole dies in a final and violent burst of pure energy. Astronomers have not yet detected any unusual bursts of radiation from space that would indicate minihole explosions, but they are keeping their sensors tuned for the distinctive pop, just in case.

Looking for black holes

Although astronomers may never be able to detect a mini black hole, the search for larger black holes is heating up. But how do you see something that by definition cannot be seen? By looking for telltale celestial footprints. Even though a black hole itself is invisible, its incredibly powerful gravitational field would wreak havoc on surrounding matter, and those effects can be detected. If a black hole is a member of a *binary* (two-star) system, for example, it would tear gases away from its partner and gobble them up. X rays emitted by the accretion disk could be detected by astronomers' instruments.

Astronomers suspect that such a process is generating the powerful X rays being emitted from a source in the Milky Way known as Cygnus X-1 (because of its location in the constellation Cygnus the Swan). Cygnus X-1 was first spotted in the 1960's, when pioneering rocket flights lofted sensitive X-ray detectors far above Earth's atmosphere. Follow-up observations with ground-based optical and radio telescopes determined that Cygnus X-1's X rays come from a binary system in which a giant bluish star orbits an invisible companion once every 5½ days. The orbital motion of the visible star tells astronomers that the unseen object must have a mass 6 to 15 times that of our sun. The dark companion is unlikely to be a normal star because a star so massive would almost certainly be visible. And it cannot be a neutron star because a neutron star cannot have a mass more than three times that of the sun. That leaves one other suspect: a black hole.

Cygnus X-1 was astronomy's first prime candidate for a black hole, and only a handful of other possible black holes formed from dead stars have been found so far. Among them are V404 Cygni, another suspicious object in Cygnus; LMC X-3, an erratic X-ray source in a nearby galaxy called the Large Magellanic Cloud; and A0620-00, an orange sunlike star whipping around a dark companion in the Monoceros constellation.

While astronomers must rely on circumstantial evidence to deduce the presence of these black holes, they are finding that they can often observe the accretion disks around suspected supermassive black holes directly. Many of the largest black holes, including ones that once powered quasars, are apparently now sitting quietly at the centers of galaxies, having devoured all the matter in their vicinity. But some have evidently flared up again, forming a new accretion disk. That could happen when a black hole has been provided with more stars and gas to feed on—as occurs, for example, when galaxies occasionally collide.

The accretion disk around a supermassive black hole that is swallowing large amounts of matter can be so enormous, stretching across much of the core of a galaxy, that it can be visible in telescopes. The accretion disk of the apparent black hole in M87 is an estimated 500 light-years in diameter. Some of the matter in an accretion disk, in the form of a *plasma* (hot, electrically charged particles), is deflected upward or downward along magnetic lines of force generated by the disk. A jet of matter is visible in M87, and astronomers have observed such jets streaming out of certain other galaxies.

The search for black holes should be aided by a form of astronomical observation that researchers began working on in the 1960's: gravity-wave detection. According to Einstein's theory of general relativity, gravity waves radiate outward in all directions at the speed of light whenever space-time is fiercely disrupted—as would happen when a star collapses into a black hole. Unlike light waves, gravity waves do not travel *through* space. They are "spacequakes," agitations of the fabric of space-time itself. Anyone in the path of the waves would experience space-time contracting and expanding, though these gravitational quivers would be very subtle and hard to detect once they had expanded across vast stretches of space. Gravity waves from a star that had exploded in a distant corner of the Milky Way would change the dimensions of the page you are reading, but by no more than one-thousandth the width of a proton, one of the particles in an atomic nucleus.

Around the world in 1994, physicists were operating finely tuned instruments to detect these incredibly tiny swells in space-time. These gravity-wave "telescopes" function like extremely sensitive versions of a seismometer, the instrument that geologists use to amplify and record the motion of earthquakes. Some gravity-wave detectors use automobile-size cylindrical bars that would "ring" like bells whenever a sizable gravity wave passed through them. Others employ a set of suspended weights that would sway ever so slightly as a series of gravity waves alternately squeezed and stretched the space between them.

The strongest gravity waves we could detect would be generated by the collision and merger of two nearby black holes. That could occur in a binary system in which both stars had become black holes. It might also be possible to discern supermassive black holes in far-off galaxies as they devour their celestial victims. Whatever a black hole was up to, it would give itself away by the distinctive ripples it transmits through space-time. If scientists are able to detect those unmistakable signatures, they will have added to the mounting visible evidence of black holes. Such findings ensure that the black hole, far from being a mythological beast, is a full-fledged member of the celestial zoo.

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