Black hole

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Key Concepts

- A black hole is believed to be the end result when a star with three or more solar masses exhausts its nuclear fuel and collapses under its own intense gravity to form a space-time singularity.
- The singularity of a black hole is enveloped by a surface called the horizon that allows particles and light to enter but not to leave.
- The two types of black holes are Kerr black holes, or rotating black holes, and Schwarzschild black holes, or nonrotating black holes.
- Initially, black holes were only a theoretical consequence of Einstein's general theory of relativity. Astronomers have now identified at least 15 black holes in just the Milky Way Galaxy.

One of the end points of gravitational collapse, in which the collapsing matter fades from view, leaving only a center of gravitational attraction behind. Any other given point in space has a past and a future. A black hole is a region that has a past but no future, or at least none that is accessible to an external observer. The center of a black hole is said to be a singular region of space-time. The existence of such a singularity is predicted by the theory of general relativity. If a star of more than about 3 solar masses has completely burned its nuclear fuel, it should collapse to a black hole. The resulting object is independent of the properties of the matter that produced it and can be completely described by specifying its mass, spin, and charge.

The most striking feature of this object is the existence of a surface, called the horizon, that completely encloses the collapsed matter. The horizon is an ideal one-way membrane; that is, particles and light can go inward through the surface, but none can go outward. As a result, the object is dark, that is, black, and hides from view a finite region of space (a hole).

Arguments concerning the existence of black holes originally centered on the fact that there are many stars of more than 3 solar masses and that there seemed to be no outcome of collapse other than the formation of a black hole. In 1971, however, some direct observational evidence for a black hole was obtained in the binary x-ray system Cygnus X-1. Since that time, black holes have been identified by similar evidence in a number of other x-ray binaries, two notable examples being A0620–00 in the Milky Way Galaxy and LMC X-3 in the Large

Magellanic Cloud. There are more than 15 identified black holes in the Milky Way Galaxy. In addition, supermassive black holes may be responsible for the large energy output of quasars and other active galactic nuclei, and there is growing evidence that black holes also exist at the centers of many other galaxies, including the Milky Way Galaxy. *See also:* GRAVITATIONAL COLLAPSE; RELATIVITY.

Theory

Shortly after Albert Einstein formulated the general theory of relativity in 1916, the solution of the field equations corresponding to a nonrotating black hole was found. For many years, this solution, called the Schwarzschild solution, was used to describe the gravitational attraction outside a spherical star. However, the interpretation of the Schwarzschild solution as a solution for a black hole was not made at the time. More than 20 years elapsed before it was shown that such a black hole could, and probably would, be formed through the gravitational collapse of a nonrotating star of sufficient mass. It was not until 1963 that the solution for a spinning black hole, the Kerr solution, was found. This was particularly important, since most stars are rotating, and the rotation rate is expected to increase when such stars collapse. Although some collapsing rotating stars might avoid becoming black holes by ejecting matter, thereby reducing their mass, many stars will evolve to a stage of catastrophic collapse in which the formation of a black hole is the only conceivable outcome. However, unlike in the case of nonrotating black holes, no one has shown that a collapsing rotating star of sufficient mass must form a Kerr black hole. On the other hand, it has been shown that if the collapse of a star proceeds past a certain point, the star must evolve to a singularity, that is, an infinitely dense state of matter beyond which no further evolution is possible. Such singularities are found inside black holes in all known black hole solutions. It has only been conjectured that the singularity produced in a collapse must be inside a black hole; however, the existence of a naked singularity would have undesirable consequences, such as allowing the violation of fundamental laws of physics that appeal to the conservation of mass-energy and to causality. The cosmic censorship theorem is based on the conjecture that the formation of a naked singularity is impossible. *See also:* STELLAR EVOLUTION.

Black hole solutions have also been found for the case in which the black holes have a charge, that is, an electrical as well as a gravitational influence. However, since matter on a large scale is electrically neutral, black holes with any significant charge are not expected in astronomy. Similarly, black hole solutions allow black holes to possess magnetic charge, that is, a magnetic single-pole interaction. Although some elementary-particle theories predict that particles with magnetic charge, called magnetic monopoles, should exist, sufficient experimental evidence to confirm their existence is not yet available. Even if monopoles did exist, they would play little part in the formation of black holes, and so astronomical black holes are expected to be both electrically and magnetically neutral. *See also:* MAGNETIC MONOPOLES.

Uniqueness theorems about black holes make it likely that at least some Kerr black holes would be formed. Uniqueness theorems address the question of how many kinds of black holes could exist and how complicated their structure could be. These theorems show that black holes must have a simple structure. In fact, the mass, spin, charge, and magnetic charge are all that are needed to specify a black hole completely. Furthermore, any distortion of a black hole, such as that caused by a chunk of matter falling inside, is removed by a burst of radiation. Therefore, although the collapse of a rotating star would be quite complicated, it appears that the final system, the Kerr black hole, would be relatively simple and independent of the details of collapse.

The possible formation of black holes depends critically on what other end points of stellar evolution are possible. Chunks of cold matter can be stable, but their mass must be considerably less than that of the Sun. For masses on the order of a solar mass, only two stable configurations are known for cold, evolved matter. The first, the white dwarf, is supported against gravitational collapse by the same quantum forces that keep atoms from collapsing. However, these forces cannot support a star whose mass exceeds about 1.2 solar masses. (A limiting value of 1.4 solar masses was first found by S. Chandrasekhar and is known as the Chandrasekhar limit. More realistic models of white dwarfs, taking nuclear reactions into account, lower this number somewhat, but the actual value depends on the composition of the white dwarf.) The second stable configuration, the neutron star, is supported against gravitational collapse by the same forces that keep the nucleus of an atom from collapsing. There is also a maximum mass for a neutron star, estimated to be between 1 and 3 solar masses, with the uncertainty being due to the poor knowledge of nuclear forces at high densities. Both white dwarfs and neutron stars have been observed, the former for many years at optical wavelengths and the latter more recently in the studies of radio pulsars and binary x-ray sources. *See also:* NEUTRON STAR; PULSAR; WHITE DWARF STAR.

It would appear from the theory that if a collapsing star of more than 3 solar masses does not eject matter, it has no choice but to become a black hole. There are, of course, many stars with mass larger than 3 solar masses, and it is expected that a significant number of them will reach the collapse stage without having ejected sufficient matter to take them below the 3-solar-mass limit. Furthermore, more massive stars evolve more rapidly, enhancing the rate of formation of black holes. It seems reasonable to conclude that a considerable number of black holes should exist in the universe. One major problem is that, since the black hole is dark, it is itself essentially unobservable. Fortunately, some black holes may be observable in the sense that the black hole maintains its gravitational influence on other matter, and thus it can make its presence known. This is precisely how, in a binary system in which a black hole has a massive stellar companion, some of the ejecta from the evolving massive star are accreted by the black hole and yield a distinct x-ray signature. Otherwise, the detection of a black hole would be limited to observations of the collapse of a star to a black hole, a rare occurrence in the Milky Way Galaxy and one that happens very quickly. Astronomers expect that such collapses would occur about once every thousand years in our galaxy. By continuously surveying many thousands of galaxies, one could therefore hope to detect black hole formation. This is the goal of detectors that are under construction to search for gravitational waves from stars that are collapsing and binary neutron stars that are merging to form black holes. *See also:* GRAVITATIONAL RADIATION.

Structure

For a nonrotating black hole, the radius of the horizon (Schwarzschild radius) is determined entirely by the mass. Defining R so that the surface area of the spherical horizon is $4\pi R^2$, the equation relating R to the mass M is $R =$

$2GM/c^2$, where G is the constant of gravity and c is the speed of light. Classical general relativity would allow M to take on all possible values, but quantum effects suggest that the lowest possible value of M is about 10^{-8} kg (2×10^{-8} lb). However, the lower-mass black holes may not be astronomically relevant, since collapsing stars with masses less than about a solar mass (2×10^{30} kg or 4×10^{30} lb) would become white dwarfs or neutron stars. It is thought that low-mass black holes could exist only if they were created at the time of the origin of the universe.

An astronomical black hole of 5 solar masses would have a radius of about 20 km (12 mi). This size is comparable to that expected for neutron stars. The density to which matter would have to be compressed in order to form such a black hole is comparable to that found in neutron stars or in the nuclei of atoms. Black holes with a mass larger than 1000 solar masses may be formed from the collapse of supermassive stars. The existence of such supermassive stars has not been proven, but supermassive stars and supermassive black holes are thought to be at the cores of quasars and active galactic nuclei. The infall of matter released by colliding stars in the dense nuclei of galaxies feeds such black holes, releasing gravitational energy as the matter falls in, and provides the energy that powers active galactic nuclei. A supermassive black hole with a mass of a few thousand solar masses would have a radius comparable to the radius of the Earth. Black holes of 10^6 to 10^9 solar masses are likely to exist in the center of some galaxies, including the Milky Way Galaxy. These could be formed either through the collapse of a supermassive star with a possible subsequent accretion of matter, or through the coalescing of a large number of black holes of more modest mass. The density required to form these very massive black holes is low, approaching that of ordinary terrestrial densities. There is now considerable evidence that black holes exist in the cores of many galaxies. *See also:* GALAXY, EXTERNAL; MILKY WAY GALAXY; QUASAR; SUPERMASSIVE STARS.

For nonrotating black holes, the horizon is also a surface of infinite redshift; that is, light emitted from just above the surface reaches a distant observer with a much lower frequency and energy than it had when it was emitted. As a result, an object that falls into a black hole appears to an observer to take an infinite time to reach the Schwarzschild radius, with the observed light coming from the object redshifting quickly to darkness as the approach is made. The picture would be quite different for an observer associated with the falling object. The “rider” would reach the Schwarzschild radius in a finite time, feeling nothing more unusual than gravitational tidal forces. However, once inside, the person would be trapped, since even light that moves outward cannot escape. The theory predicts that this individual, as well as everything else within the horizon, would be crushed to infinite density within a short time.

For rotating black holes, the surface of infinite redshift lies outside the horizon except at the poles, as illustrated in **Fig. 1**. The region between the two surfaces is called the ergosphere. This region is important because it contains particle trajectories that have negative energy relative to an outside observer. Roger Penrose showed that it is possible, although perhaps unlikely astronomically, to use these trajectories to recover even more than the rest mass energy of matter sent into a rotating black hole, with the extra energy coming from the slowing down of the rotation of the black hole. Others have proposed that radiation incident on a rotating black hole could be similarly amplified.

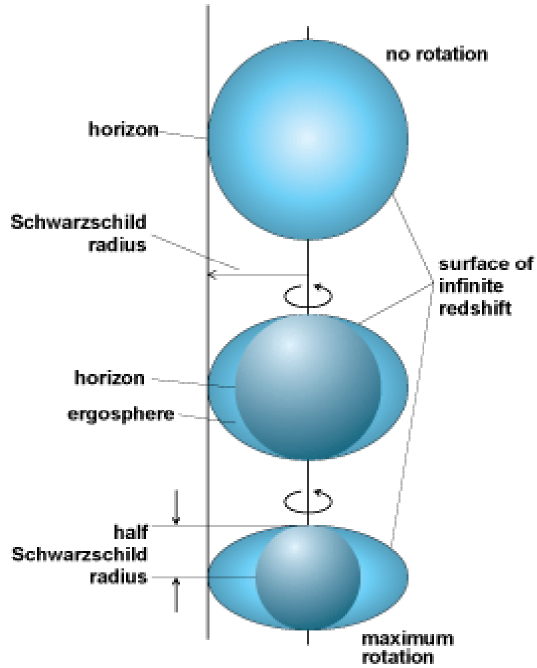

Fig. 1 **Diagrams of black holes. The upper diagram shows a nonrotating black hole, described by the Schwarzschild solution, in which the horizon is also a surface of infinite redshift. The lower two diagrams show rotating black holes, described by the Kerr solution, in which the surface of infinite redshift lies outside the horizon except at the poles, and the region between the two surfaces is called the ergosphere. (*From J. M. Pasachoff and A. Filippenko, The Cosmos: Astronomy in the New Millennium, 3d ed., Cengage, Belmont, CA, 2007*)**

The black hole solutions of general relativity, ignoring quantum-mechanical effects as described later, are completely stable. Once massive black holes form, they will remain forever, and subsequent processes (for example, the accumulation of matter) only increase their size. Two black holes could coalesce to form a single, larger black hole, but a single black hole could not split up into two smaller ones. This irreversibility in time led researchers to consider analogies between black holes and the thermal properties of ordinary matter, in which there is a similar irreversibility as matter becomes more disordered as time goes on. In 1974, Steven Hawking showed that when quantum effects are properly taken into account, a black hole should emit thermal radiation, composed of all particles and quanta of radiation that exist. This established the black hole as a thermal system, with a temperature that is inversely proportional to its mass. Since a radiating system loses energy and therefore loses mass, a black hole can shrink and decay if it is radiating faster than it is accumulating matter. For black holes formed from the collapse of stars, the temperature is about 10^{-7} K (2×10^{-7}°F above absolute zero, −459.67°F). Regardless of where such black holes are located, the ambient radiation incident on the black hole from other stars, and from the big bang itself, is much larger than the thermal radiation emitted by the black hole, implying that the black hole would not shrink. Even if the ambient radiation is shielded from the black hole, the time required for the black hole to decay is much longer than the age of the universe, so that, in practice, black holes formed from the collapse of a star are essentially as stable as they were thought to be before the Hawking radiation was predicted.

Theoretically, black holes of any mass could have been created at the beginning of the universe in the big bang. For smaller-mass black holes, the Hawking radiation process would be quite important, since the temperatures would be very high. For example, a black hole created with mass of 1.72×10^{11} kg (3.8×10^{11} lb), about the mass of a large hill, would have radiated away all of its mass just recently, assuming that no mass had been accreted in the meantime. Black holes created with a mass smaller than this value would have disappeared earlier, and those with a larger mass would still exist. The final stage of evaporation would be quite violent and would take place quickly. As a black hole radiates, it loses mass, and its temperature rises. But a higher temperature means that it radiates and loses mass at a faster rate, raising its temperature even further. The final burst, as the black hole gives up the remainder of its mass, would be a spectacular event. The final emission would contain all radiation and particles that could exist, even those not generated by existing accelerators. At present, there is no evidence that points to the existence of black holes with small mass or to their evaporation by the Hawking radiation process.

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Observation

Observations of black holes—which, by definition, are not directly detectable—rely on indirect methods using the gravitational interaction of the black hole with its surroundings. The first successful detections were accomplished in binary x-ray systems. These systems are thought to be close binary systems composed of a massive and very dense object—a black hole or a neutron star—and a companion star. Because of strong gravitational forces, the companion star loses mass, which settles down into an accretion disk around the compact object (**Fig. 2**). Frictional forces cause the matter in the disk to spiral inward and also heat up the disk, causing it to emit thermal x-rays.

A neutron star is distinguished from a black hole as the compact object by analyzing the internal motion of the binary system and calculating the mass of the compact body. In the notable case of the x-ray binary system Cygnus X-1, the mass determination gives a value of about 10 solar masses, a value much larger than the maximum mass for a gravitationally stable neutron star and therefore strong evidence for the existence of a black hole in this system. About 30 candidates for black hole x-ray binaries have been detected in the Milky Way Galaxy, of which about half have secure mass estimates that support the black hole assumption.

Another line of observational evidence for the existence of black holes is drawn from active galactic nuclei (AGNs), whose luminosities are several times larger than those of the largest nonactive galaxies. Variations in the luminosities of AGNs on time scales of tens of hours indicate a central engine whose diameter should be of the order of the product of the variation time scale and the speed of light. To generate observed AGN luminosities in a spherical volume defined by this diameter in nuclear processes like those taking place in stars, one would need

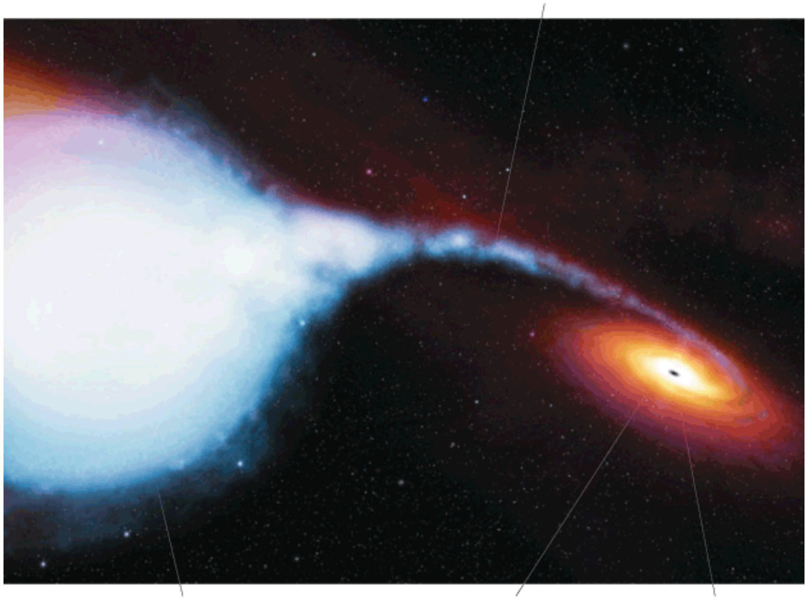

Fig. 2 **Concept of a binary x-ray source. The accretion disk around the compact object (black hole or neutron star) gives off x-rays. (*ESA, Illustration by Martin Kommesser, copyright © ESA/AECF; from J. M. Pasachoff and A. Filippenko, The Cosmos: Astronomy in the New Millennium, 3d ed., Cengage, Belmont, CA, 2007*)**

such large quantities of matter that the gravitational potential energy would far exceed the nuclear energy. Therefore, the origin of the luminosity is attributed to the transformation of potential energy into radiation.

The arguments in favor of a scenario in which potential energy is released in the accretion of gas onto a supermassive black hole are twofold. First, optical and ultraviolet emission lines of AGNs show Doppler broadening corresponding to velocities of 2000–10,000 km/s (1200–6000 mi/s), indicating that gas is moving around a massive compact region. Second, AGNs display jets that are well collimated and straight, two properties that a central engine consisting of many bodies cannot achieve easily, favoring a single black hole as the central engine. *See also:* DOPPLER EFFECT.

Mass determinations of black holes in AGNs rely on measurements of the properties of the accretion disk, such as the rotational velocity of this disk at different separations from the central engine after correcting for projection effects. In the case of a Keplerian rotation around the center, as for the galaxy M87, the rotational velocity should become smaller with increasing radius, and should be proportional to the square root of the enclosed mass. The mass of the central black hole is derived to be 3×10^9 solar masses for M87. Another frequently used technique is to measure the spectrum of the accretion disk. Since the accretion disk is optically thick, radiation that is on its way through the disk will be scattered many times before it leaves the surface of the disk, generating a disk that is nearly in thermodynamic equilibrium. The spectra of such disks have the form of a black body spectrum, with characteristic temperature depending on the black hole mass and the mass accretion rate onto the black hole.

Typical values derived using this method find black holes with masses in the range of 1×10^6 to 3×10^9 solar masses.

The majority of estimates of the masses of black holes in the centers of normal galaxies are based on techniques using stellar dynamical methods. The orbits of stars in galaxies are affected significantly only by gravitational forces exerted on them. Unlike gas in an accretion disk, stars have significant random motions. A measure of the random motions of the stars is the so-called velocity dispersion, which characterizes the distribution of the different stellar velocities. Random motions of stars contribute to their overall velocity in addition to their systemic rotational velocity. Therefore, it is necessary to measure not only the rotational velocity at different radii, as in the case of a gas accretion disk, but also the velocity dispersion at different radii. As a further observational input to measure the black hole mass, the galaxy's luminosity density at different radii is needed. This is necessary because the black hole mass determination involves modeling the stellar structure in the galaxy. In practice, one assumes a model for the orbital structure of the stars in the galaxy and calculates the density of the stars at each radius from the luminosity density, assuming a constant mass-to-light ratio. From the model, it is now possible to calculate the velocity dispersion from the rotational velocity and vice versa. In the case of a black hole at the center, it is not possible to use a constant mass-to-light ratio at all radii to recover the observed velocity dispersion from the observed rotational velocity of the galaxy using the model. Instead, one finds a steep increase in the mass-to-light ratio when going to small radii. Using the mass-to-light ratio, it is then possible to calculate the black hole mass. More than 60 black hole masses in the centers of galaxies have been obtained using this and similar techniques, and more are being calculated.

Another stellar dynamical measurement of a black hole mass is the one in the center of our Milky Way Galaxy. In this case, the orbits of individual stars have been measured in the vicinity of the center over a period of more than 15 years. The orbits of the stars are Kepler ellipses, which allow calculation of the mass of the central body with high precision. The calculations reveal a black hole mass of 3×10^6 solar masses at the center of the Milky Way Galaxy; it is believed to be associated with the radio source Sagittarius A*. *See also:* ASTROPHYSICS, HIGH-ENERGY; BINARY STAR; X-RAY ASTRONOMY.

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Keywords

black hole; horizon; Schwarzschild solution; Kerr solution; Schwarzschild radius; ergosphere; Hawking radiation; active galactic nuclei

Test Your Understanding

1. How does the horizon of a black hole act as a one-way membrane?
2. How were black holes first detected?
3. Critical Thinking: How do the event horizons differ between rotating and nonrotating black holes?

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