Black hole

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Key Concepts

- A black hole is a region of spacetime exerting a gravitational field so strong that neither matter nor radiation can escape.
- Within a boundary known as the event horizon, the escape velocity needed to overcome the gravitational attraction of a black hole exceeds the speed of light, meaning that nothing that crosses over the event horizon can ever leave.
- Black holes fall into two general classes, depending on their mass: stellar black holes and supermassive black holes.
- Observations of black holes rely on indirect methods using the gravitational interaction of the black hole with its surroundings.
- At the center of a black hole, a finite mass can theoretically be compressed into a point of zero volume, creating an infinitely dense state of matter known as a singularity.

A region of spacetime exerting a gravitational field so strong that neither matter nor radiation can escape. Black holes are extreme cosmic objects predicted by German-born U.S. physicist Albert Einstein's theory of general relativity. Within a boundary known as the event horizon, the escape velocity needed to overcome the gravitational attraction of the black hole exceeds the speed of light, meaning that nothing that crosses over the event horizon can ever leave. Black holes are therefore by definition invisible, but because of their powerful gravitational fields, they can be indirectly observed through the highly conspicuous effects they have on their cosmic environment. These effects include the gravitational intake of matter through accretion disks, a process which generates tremendous heat and light and is well-observed at scales from binary star systems to the cores of galaxies. In the absence of ongoing accretion, black holes should also theoretically cause severe localized warping of spacetime, gravitationally lensing light from luminous sources and distorting their appearance (Fig. 1). *See also:* ASTRONOMY; ESCAPE VELOCITY; GRAVITATION; GRAVITATIONAL LENS; RELATIVITY.

Black hole classes

In general, physicists recognize two broad classes of black holes, categorized by their masses. *See also:* MASS.

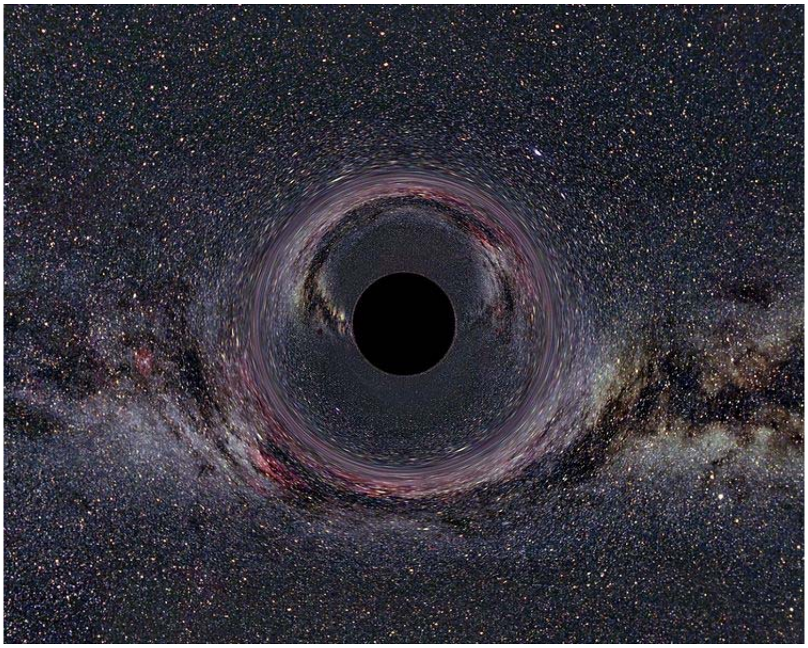

Fig. 1 An artist's impression of the gravitational lensing caused by a black hole's warping of localized spacetime. (Credit: Ute Kraus, Physics education group Kraus, Universität Hildesheim)

Stellar black holes

Stellar black holes form from supergiant stars with an initial mass of approximately 10 times the mass of the Sun (solar masses) or more. When they reach the end of their lives, these colossal stars explode as supernovae, with a remaining core of approximately 3 solar masses collapsing into a black hole. Stars with a bit less initial mass collapse at the end of their lives into neutron stars that, although highly dense, do not pack as much matter into as small a volume as a black hole, and thus do not gravitationally create event horizons. Typical "dwarf" stars like the Sun evolve into remnants known as white dwarf stars. A stellar mass black hole can possess anywhere from a few to several dozens of solar masses. *See also:* GRAVITATIONAL COLLAPSE; NEUTRON STAR; STAR; STELLAR EVOLUTION; STELLAR POPULATION; SUN; SUPERGIANT STAR; SUPERNOVA.

Supermassive black holes

Supermassive black holes, found in the cores of nearly all galaxies, can contain anywhere from millions to billions of times the Sun's mass. The formation of supermassive black holes remains speculative. Hypotheses include the direct collapse of extremely massive gas clouds in the early universe into a likewise extremely massive "seed" black hole, which then voraciously consumed matter and merged with other black holes. This hypothesis explains how supermassive black holes could have formed, as they evidently have, within the relatively short time cosmic period of the first billion years following the big bang. Another hypothesis in this vein involves the formation of supermassive stars with tens of thousands of times the mass of the Sun, which then collapsed into

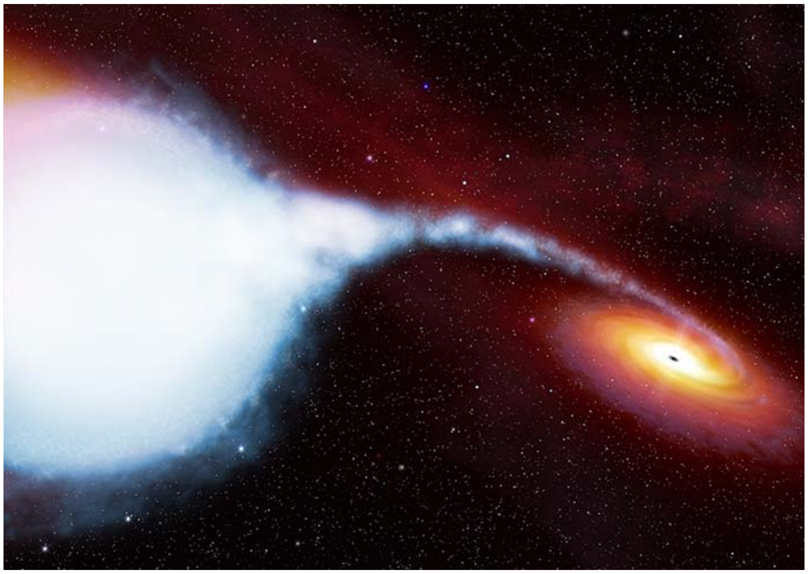

Fig. 2 **Artist's impression of Cygnus X-1, a binary x-ray system located about 6,000 light-years from Earth and the first widely accepted astronomical discovery of a black hole. A hot, massive star (at left) is having mass drawn from it by the gravitational pull of a black hole (at right). The matter spirals around the black hole as an accretion disk. Friction within the disk causes its contents to heat up and emit high-energy light as x-rays. [Credit: NASA, ESA, Martin Kornmesser (ESA/Hubble)]**

supermassive black hole seeds. *See also:* BIG BANG THEORY; GALAXY; GALAXY FORMATION AND EVOLUTION; SUPERMASSIVE BLACK HOLES; SUPERMASSIVE STAR.

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 detection of a black hole in this manner involved the binary x-ray system Cygnus X-1 in 1971. These binary systems are composed of a massive, 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. *See also:* BINARY STAR; FRICTION; X-RAY ASTRONOMY; 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 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.

Another line of observational evidence for the existence of, in this case, supermassive black holes is drawn from active galactic nuclei (AGNs), whose luminosities are significantly higher 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 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 by the supermassive black hole as it devours matter from an accretion disk. Twin jets of material moving at near-light-speed blast outward from the black hole's poles as well; such astrophysical jets are commonly created by spinning objects, such as protostars. The most luminous AGN are known as quasars; AGN whose jets are pointed directly at Earth are known as blazars. *See also:* HIGH-ENERGY ASTROPHYSICS; PROTOSTAR; QUASAR.

Yet another way to indirectly detect supermassive black holes and infer their mass is by measuring the velocities of stars in their vicinity. This approach has informed calculations of the mass of the supermassive black hole at the center of our Milky Way Galaxy, associated with the radio source Sagittarius A* (pronounced "A star"). 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 about 4 million solar masses. *See also:* MILKY WAY GALAXY.

Black holes and gravitational waves

A new way of studying black holes and inferring their existence is through gravitational waves, also known as gravitational radiation. These are ripples in the spacetime fabric of the universe, initially predicted—as well as black holes themselves—by Einstein's theory of general relativity in 1915. Massive objects, such as black holes, should create gravitational waves when they accelerate. *See also:* GRAVITATIONAL RADIATION; RELATIVITY; SPACETIME.

The first instrument with the required sensitivity to detect the infinitesimal signatures of gravitational is the Laser Interferometer Gravitational-wave Observatory (LIGO). The instrument can detect displacements between mirrors, recorded by reflecting lasers, on the order of a ten-thousandth the diameter of a proton caused by gravitational waves passing through Earth. In 2015, LIGO detected the signature of two colliding black holes with 36 and 29 solar masses apiece—a mass range not previously observed for stellar black holes (Fig. 3). The merger did not generate electromagnetic radiation or the emission of any other particles, thus showing how gravitational wave astronomy will allow the study of previously inaccessible natural phenomena. Multiple gravitational wave detections since are advancing our understanding of black hole properties and the environments where they form in abundance, such as in dense star clusters known as globular clusters. *See also:* GLOBULAR CLUSTERS; LIGO (LASER INTERFEROMETER GRAVITATIONAL-WAVE OBSERVATORY); PHOTON; STAR CLUSTERS.

A highly anticipated gravitational wave-spawning event is the collision of a black hole with a neutron star, which should yield observable light and therefore offer further insights into compact objects, astrophysics, and fundamental physics. Future gravitational wave observatories are planned to seek the signals theoretically

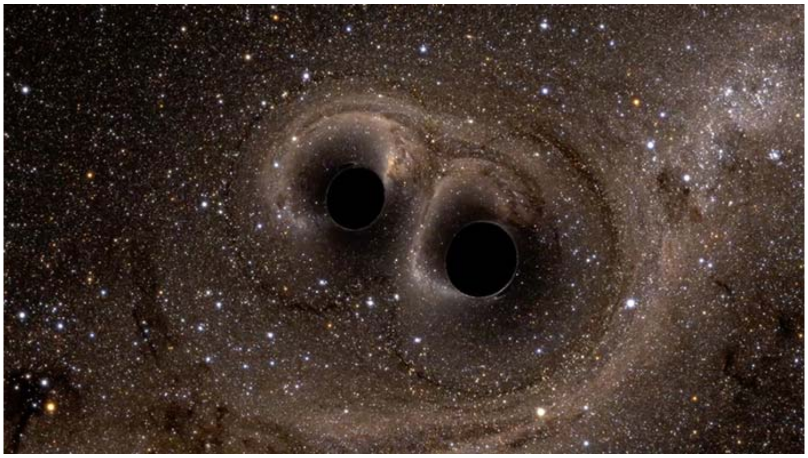

Fig. 3 **An artist's impression of two colliding black holes. (Credit: SXS)**

generated by sources including supermassive black hole mergers and from the earliest moments of the big bang. *See also:* PHYSICS.

Fate of black holes

According to general relativity, a finite mass can theoretically be compressed into a point of zero volume at the center of a black hole, creating an infinitely dense state of matter known as a singularity. The black hole solutions of general relativity, ignoring quantum-mechanical effects as described later, are completely stable. Once massive black holes form, they should theoretically remain forever, and subsequent processes (for example, the accumulation of matter) only increase their size. Two black holes are able to coalesce and form a single, larger black hole, as LIGO has detected, but a single black hole could not split up into two smaller ones.

However, in 1974, English theoretical physicist and mathematician Stephen Hawking showed that when quantum effects are properly taken into account, a black hole should emit thermal radiation. The radiation would result from the quantum mechanical prediction that pairs of particles spontaneously form in the vacuum of space. These particles usually instantly annihilate each other, one being matter and the other being antimatter. Sometimes, though, a particle pair should form with one particle inside the black hole's event horizon and the other outside this boundary. The particle outside the event horizon would escape into space as so-called Hawking radiation, taking with it a tiny portion of the black hole's mass.

Over time, Hawking's hypothesis suggests that black holes can shrink and eventually disappear—so long as they are emitting Hawking radiation faster than they are accumulating matter or energy. Yet wherever in space a black hole might be located, it would receive significant, ambient radiation from other stars and the big bang itself through the cosmic microwave background. Because this ambient radiation is thought to be much larger than any emitted Hawking radiation, the black hole would not shrink. Even if the ambient radiation somehow did not reach the black hole, the time required for a typical black hole (formed from the collapse of a star) to completely decay is much longer than the age of the universe. The upshot: In the history of the universe, no black holes have disappeared due to Hawking radiation. *See also:* COSMIC BACKGROUND RADIATION.

The possibility remains that there are smaller black holes than those formed in stellar collapses. Theoretically, for instance, 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. 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 in the universe's history, and those with a larger mass would still exist.

The final stage of a black hole's 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 the black hole 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 masses or having evaporated via a Hawking radiation process. Some physicists have suggested that the Large Hadron Collider—the most powerful particle accelerator built to date and that has operated since 2010—might produce miniature black holes that immediately evaporate due to Hawking radiation and thus be indirectly detectable. *See also:* LARGE HADRON COLLIDER (LHC); PARTICLE ACCELERATOR.

Keywords

black hole; event horizon; Schwarzschild solution; Kerr solution; Schwarzschild radius; Hawking radiation; active galactic nuclei; gravitational waves; LIGO; black hole merger; general relativity

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: Why might Hawking radiation never be detectable?

Bibliography

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Additional Readings

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