# Evidence for Black Holes

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**Black holes are common objects in the universe. Each galaxy contains large numbers—perhaps millions—of stellar-mass black holes, each the remnant of a massive star. In addition, nearly every galaxy contains a supermassive black hole at its center, with a mass ranging from millions to billions of solar masses. This review discusses the demographics of black holes, the ways in which they interact with their environment, factors that may regulate their formation and growth, and progress toward determining whether these objects really warp spacetime as predicted by the general theory of relativity.**

Black holes are places where gravity is so strong that nothing that enters them—not even light—can escape. Within a finite region surrounding the center of a black hole, all light rays and physically realizable trajectories of particles are directed inward. Space and time are so distorted that there is literally no way out.

Classical black holes are described by vacuum solutions of the Einstein field equations of general relativity, which imply that they contain a singularity beyond which trajectories cannot continue. The nature of the singularity is not fully understood, and it is probable that existing physical theories break down close to the singularity. But from an astrophysicist's point of view this hardly matters, because the singularity is hidden from view. It lies beyond the event horizon, the surface that bounds the region of no escape. The size of the horizon surrounding a nonrotating, uncharged black hole is characterized by the Schwarzschild radius, $R_S = 2GM_\bullet/c^2$, where $G$ is Newton's constant of gravity, $M_\bullet$ is the mass of the hole, and $c$ is the speed of light. $R_S$ is about 3 km for a black hole of $M_\bullet = 1\ M_\odot$ (solar mass). Curiously, although it is believed that conditions can become chaotic and violently unpredictable as matter traverses the region inside the horizon, the exteriors of black holes are believed to behave in predictable and relatively simple ways. Black hole horizons are among the most comprehensively understood phenomena predicted by theory [see (*1*) for a nontechnical introduction to the theoretical properties of black holes; see (*2*) for an undergraduate-level presentation of mathematical aspects of black hole physics].

One aspect of this simplicity is the fact that any black hole can be characterized by its mass, angular momentum, and electric (or certain other types of quantum) charge. Charge may not be important in an astrophysical setting, so black holes effectively can be described by two parameters. Far from the horizon, black holes exert a gravitational influence just like any spherical body of the same mass. If the Sun collapsed symmetrically and became a black hole, there would be no change in Earth's orbit. Black holes have been discovered primarily by measuring their gravitational effects on distant bodies. By applying the Newtonian laws of gravity, astronomers have established that dark masses exist at the centers of galaxies (*3*). If these masses are not black holes, they would have to be dense clusters of very faint objects. In at least two cases, the concentration of such a cluster would have to be so extreme as to render this interpretation highly implausible (*4*). In other objects the cluster interpretation cannot be ruled out with certainty, although it seems improbable. Likewise, certain x-ray–emitting binary stars have been shown to contain a compact object too massive to be a neutron star or any other pressure-supported body, leaving a black hole as the only plausible alternative (*5, 6*). In most instances, these gravitational interactions are measured on scales several orders of magnitude larger than the putative event horizon. The argument that these objects are black holes is therefore indirect and is based on the elimination of other possibilities.

In many cases, however, we can observe radiation emitted by gas located just outside the horizon, or jets of plasma flowing outward from the region around the horizon, at close to the speed of light (*7*). A major objective of black hole research is to use such observations to map the structure of spacetime near the horizon, thus testing whether these objects have exactly the properties predicted by general relativity. For example, we are well on our way toward being able to measure the tornado-like twisting of spacetime attributable to a black hole's spin (Fig. 1).

The energy liberated by matter close to the horizon is prodigious and can markedly affect a black hole's surroundings. Large black holes at the centers of galaxies have been implicated in the energy balance of gas thousands of light years away, and they may play a crucial role in the galaxy formation process (*8*). The collapse of massive stellar cores to form stellar-mass black holes could be responsible for triggering certain types of gamma-ray bursts, the most luminous phenomenon known (*9*). Thus, black holes are not only astonishing physical entities in their own right, as well as laboratories for the most extreme conditions encountered in the post–big bang universe; they are also key players in phenomena with which we have long been familiar. To understand stars, galaxies, and the gas that lies between them, we must understand how black holes form, where they form, and how they affect their environments.

## Black Hole Demographics

Two populations of black holes have been established observationally. Stellar-mass black holes are presumably the collapsed remnants of massive stars. Except for two recent candidates based on gravitational microlensing surveys (*10, 11*), all of the several dozen stellar-mass black hole candidates have been found in x-ray binaries, close binary systems in which matter is transferred from a normal star to the black hole and emits x-rays before disappearing beneath the horizon. The rapid variability and spectral peak at x-ray wavelengths imply that the emitting region is extremely compact (smaller than a few hundred km). To distinguish black hole candidates from accreting neutron stars, which are also found in x-ray binaries, it is necessary to establish that the accreting compact object is too massive to be a neutron star [i.e., more than about 2 or 3 $M_\odot$, where the range stems from uncertainties in the stiffness of matter at nuclear densities (*6*)]. This is done by applying Newtonian mechanics to measured and estimated parameters of the binary orbit, including the orbital period, orbital speed of the normal star, radius and spectral type of the normal star, and orbital inclination with respect to the line of sight (*5*). Usually, one obtains a lower limit on the mass of the compact object, which in a number of cases comfortably exceeds the maximum mass of a neutron star.

There is little hope of detecting the much more numerous stellar-mass black holes that are presumably isolated or in noninteracting binary systems, because they do not capture enough gas from the interstellar medium to be observable. Given that stars more massive than 20 to 40 $M_\odot$ probably form black holes (*12*), the number of stellar-mass black holes in the Milky Way Galaxy could be as large as 10 million to 1 billion. The range is due to

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uncertainties in the initial mass function and star formation history as well as the complexities of stellar collapse calculations.

Supermassive black holes are found at the centers of galaxies. They were first proposed to explain the prodigious energy outputs of quasars and are now understood to be the primary source of energy in all types of active galactic nuclei (AGN) (*13*). But although only one in 100 galaxies is active at any time, we now know that most if not all galaxies have supermassive black holes in their nuclei (*3*). These black holes are not accreting at a high rate, and in fact they are underluminous relative to expectations based on the availability of accretable gas (*14*). They are detectable only through their gravitational effects on distant stars and gas.

The strongest dynamical evidence for a supermassive black hole comes from the center of the Milky Way. Observations in the infrared, radio, and x-ray bands—which can pierce the thick dust obscuring the Galactic Center in the optical—reveal a compact, nonstellar source of radiation, Sgr A*, surrounded by a cluster of stars. By measuring stellar proper motions and radial velocities, it has been possible to infer that the position of Sgr A* coincides with a dark mass of $3 \times 10^6$ to $4 \times 10^6$ $M_\odot$. Orbits of several stars have been mapped (*15–17*), probing the black hole's gravitational field to within 1000 $R_S$ (60 times the radius of Earth's orbit) (Fig. 2). The compact radio emission and x-ray flares produced by Sgr A* (*18*) presumably come from gas accreting onto the black hole at a low rate ($10^{-10}$ to $10^{-7}$ $M_\odot$ year$^{-1}$, depending on assumptions).

The second strongest case for a supermassive black hole is equally remarkable. Maser emission produced by water molecules in the nucleus of the galaxy NGC 4258 delineates a nearly perfectly Keplerian thin disk (*19*). Observers using very-long-baseline radio interferometry have mapped the radial velocities, proper motions, and accelerations of the masers in three regions of the disk, overdetermining its kinematics. The rotation curve fits a Keplerian model so well that the black hole mass, $M_\bullet = 39 \times 10^6$ $M_\odot$, is the most accurate known. Although the masers probe a region of radius ~40,000 $R_S$, it would be difficult to explain the rotation curve by anything other than a single compact mass at the center of the disk (*4*).

Several dozen other nearby galaxies have yielded dynamical evidence for supermassive black holes from measurements of stellar velocity dispersions and rotation curves of stars or gas in the nucleus (*3*). The measurements typically probe regions of radius $>10^5$ $R_S$. Therefore, the evidence is less compelling than the case for the Galactic Center or NGC 4258 black hole, but is nonetheless strong because of the amount of mass that must otherwise be hidden in the nucleus.

The masses of supermassive black holes are strongly correlated with the properties of their host galaxies, indicating a connection between black hole formation and galaxy formation. The nature of the connection is unclear. Black hole masses correlate roughly linearly with the mass of the galaxy's bulge, and they appear to be even more tightly correlated with the bulge velocity dispersion, σ, exhibiting a proportionality $M_\bullet \propto \sigma^4$ (*20–22*) (Fig. 3).

Inventories of quasar light (*23*) suggest that supermassive black holes grew mainly by accreting gas rather than by mergers of smaller black holes. If even a few percent of the liberated energy emerged in kinetic form, there would have been enough energy to unbind the gas in the protogalactic host. Thus, supermassive black holes might have limited their own growth—or even the final mass of the host galaxy—by depositing this energy in their surroundings. Such feedback could have given rise to the observed correlations (*24, 25*). Indeed, similar feedback effects from accreting black holes may play an important role in the energetics of nearby clusters of galaxies (*8*). Alternatively, dynamical processes during galaxy formation

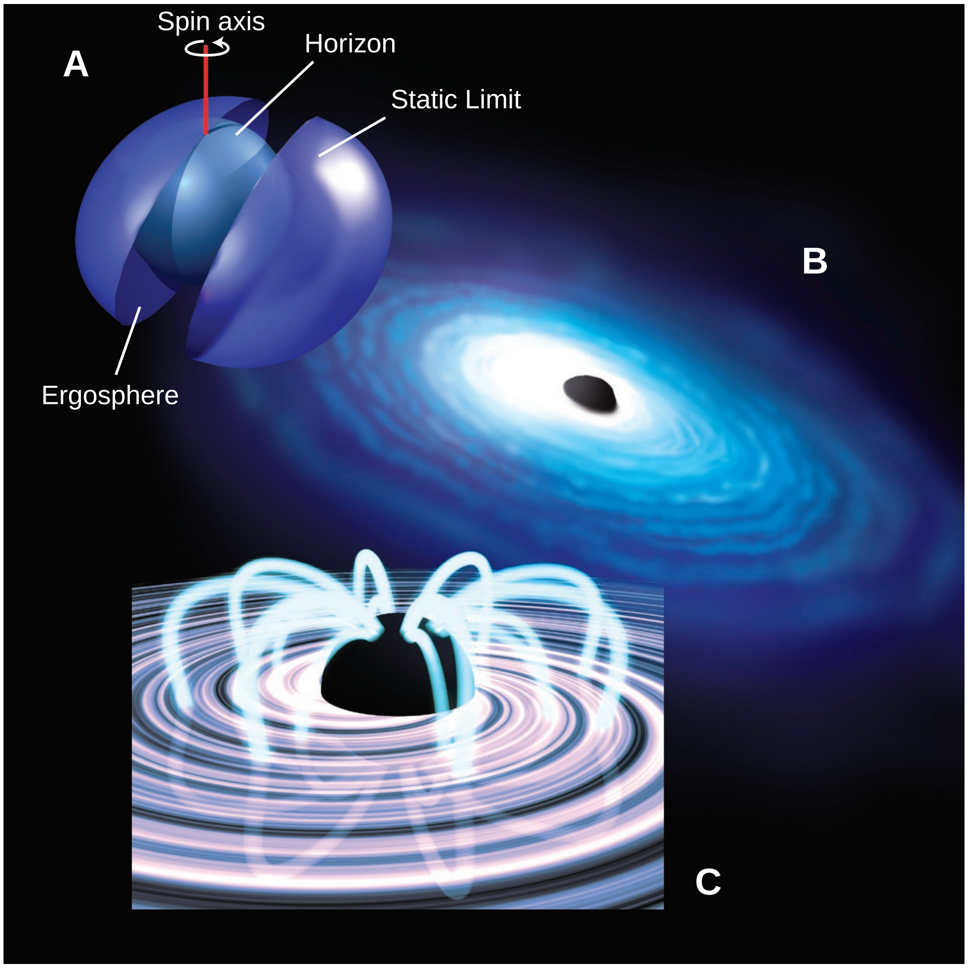


**Fig. 1.** Anatomy of a spinning black hole. (**A**) The event horizon, or surface of no-return, lies inside the static limit. Between the two surfaces, in the region known as the ergosphere, all trajectories must rotate in the same sense as the black hole. The ergosphere contains most of the black hole's spin energy, which can be extracted by magnetic fields. (**B**) Appearance of an accretion disk around a black hole. Gas on the left side is rotating toward the observer, and its emission is blueshifted; gas on the right side is rotating away from the observer, and its emission is redshifted. Emission from gas in front of the black hole is redshifted as a result of the gravitational redshift combined with the transverse Doppler shift. Actual size on the sky would be $<1 \times 10^{-6}$ arc sec (comparable to the size of newsprint seen from the distance of the Moon); such angular resolution could be attained with x-ray interferometers currently being designed. (**C**) Magnetic field is amplified inside the disk and erupts to form a corona. Magnetic field penetrating the ergosphere extracts energy from the black hole, which can accelerate a jet (if the field lines trail off into space) or enhance the emission from the disk (if the field lines connect to the disk, as shown here).

could have regulated the amount of matter that collected in the center and eventually formed the black hole (*26*).

There is intense interest in the possible existence of a third population of black holes, the so-called intermediate-mass black holes (IMBHs) (*27*). These would fill the gap in mass between stellar-mass and supermassive black holes. They could be the remnants of very massive (and hypothetical) Population III stars that formed from metal-free material in the early universe, or could have resulted from stellar mergers in dense star clusters. Their existence (or lack thereof) could tell us a lot about the conditions under which black holes formed and whether supermassive holes grew from much smaller ones, either by hierarchical mergers or by runaway accretion. As yet there is no solid evidence for such a population. It has been suggested that they could be associated with a class of x-ray binaries called ultraluminous x-ray sources (ULXs), which may require intermediate black hole masses in order to avoid disruption by radiation pressure (*28*). There is evidence that some ULXs may have cooler accretion disks than stellar-mass black holes, which supports the IMBH interpretation (*29*). But one cannot rule out alternative models that explain ULXs in terms of anisotropic emission (*30*) or radiation hydrodynamical effects (*31*) without recourse to masses higher than those of ordinary stellar-mass black holes. There are also candidates for IMBHs on the basis of velocity dispersions in globular clusters and gravitational microlensing surveys, but at present the evidence is not strong.

## Interactions of Black Holes with Surrounding Matter

Black holes cannot swallow matter whose angular momentum per unit mass exceeds ~2 $R_S c$. Astrophysically, this is a tiny amount of angular momentum. For example, in order to fall into a Sun-turned-black-hole, Earth would have to lose 99.99% of its orbital angular momentum. Contrary to popular belief, black holes are not cosmic vacuum cleaners. Gas orbiting under the gravitational influence of a black hole is thought to lose angular momentum to more distant gas via the magnetorotational instability (MRI) (*32*). In the presence of shear associated with orbital motion, a weak magnetic field is amplified to a fraction of the gas pressure within a few orbital periods. The resulting cross-correlation between the radial and tangential components of magnetic field causes a torque that transfers angular momentum outward. Thus, the magnetic stress behaves analogously to a shear viscosity, although with some very different (and not fully understood) detailed properties. As in any viscous fluid, the transport of angular momentum by MRI must be accompanied by dissipative heating and the outward transport of energy through the gas.

If the gas is able to radiate away the dissipated energy, it will settle into a geometrically thin Keplerian accretion disk (*33*). Gas in such a disk spirals inward gradually through a sequence of nearly circular orbits until it reaches the innermost stable circular orbit (ISCO). Once inside the ISCO, gas can fall into the black hole without any further loss of angular momentum. The ISCO is located well outside the event horizon, at 3 $R_S$, for a nonrotating hole and approaches the horizon (at $R_S/2$) for a rapidly spinning hole, provided that the gas is orbiting in the same sense as the hole's rotation. The total energy radiated by the disk is roughly half the gravitational potential energy at the ISCO; the other half is retained as kinetic energy of orbital motion, which disappears into the black hole along with the gas. Assuming that the stress is negligible inside the ISCO, this implies that each gram of accreting material radiates a fraction of its rest mass energy, ranging from 6% for a nonrotating hole to 42% for a hole near maximal rotation. The radiative efficiency could be even larger if magnetic stresses operate across the ISCO (*34*). These huge efficiencies, compared to the maximum ~1% efficiency of thermonuclear reactions, led to the early suggestions that only gravitational energy could power quasars. Indeed, thin accretion disks are the principal ingredients in models of x-ray binaries and luminous AGN such as quasars and Seyfert galaxies.

More often than not, gas accreting onto a black hole is not able to radiate efficiently (*14*). Dissipated energy is retained as heat, generating pressure that inflates the flow into a geometrically thick disk or torus. There is a reciprocal relation between the temperature of the gas and the distance from the black hole in units of $R_S$. When this ratio is smaller than $10^3$, the gas temperature exceeds $10^9$ K and electron thermal velocities approach the speed of light. Under these conditions, electrons lose energy rapidly. If they are continually resupplied with energy by the ions, which do not radiate efficiently, they will quickly drain away the heat in the accretion flow, which will then settle into a thin disk. This implies that the gas in a nonradiative accretion flow must be characterized by two temperatures; that is, the electron component is much colder than the ion component (*35, 36*). Even where Coulomb collisions are unable to keep electrons and ions in equipartition, plasma instabilities have the potential to transfer energy between the two species. The fact that this does not seem to happen may indicate that the magnetic energy density remains small relative to the thermal pressure (*37*).

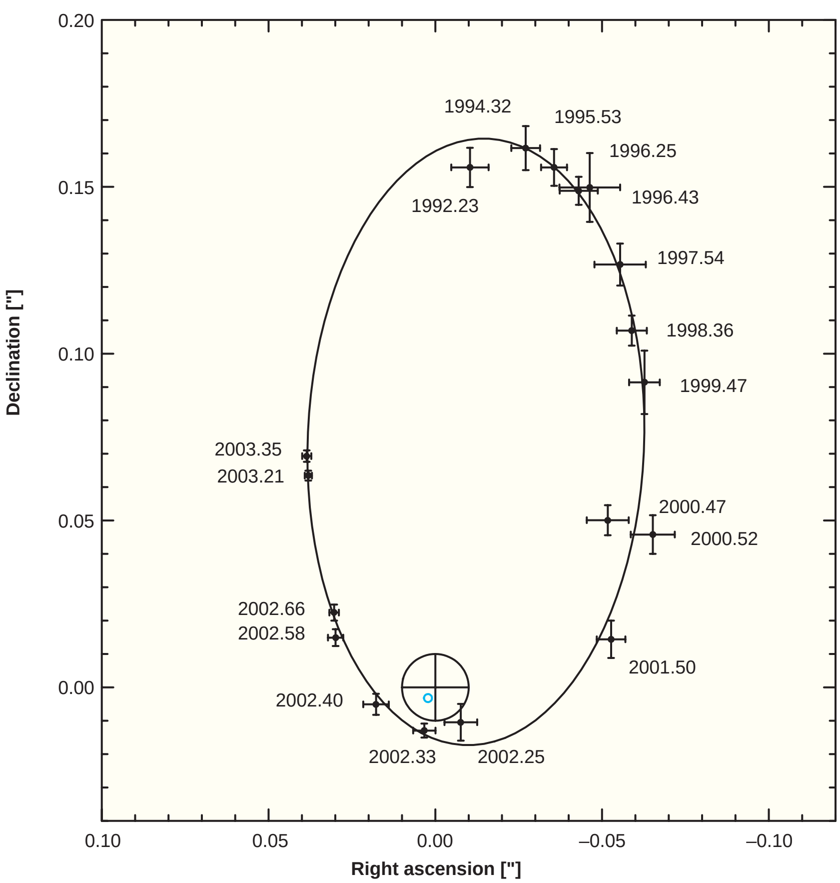


**Fig. 2.** Orbit of the star S2 around Sgr A* [figure 1 of (*17*)]. The continuous curve shows the projected best fit Keplerian orbit, which has a period of 15.6 years and comes within 2000 Schwarzschild radii of the position of Sgr A* (shown as the large cross within a circle). The small blue open circle marks the focus of the elliptical orbit. Ghez *et al*. (*16*) report the orbits of several additional stars, including one that comes within 1000 $R_S$ of the putative black hole. Dates within years are shown as decimal fractions of years.

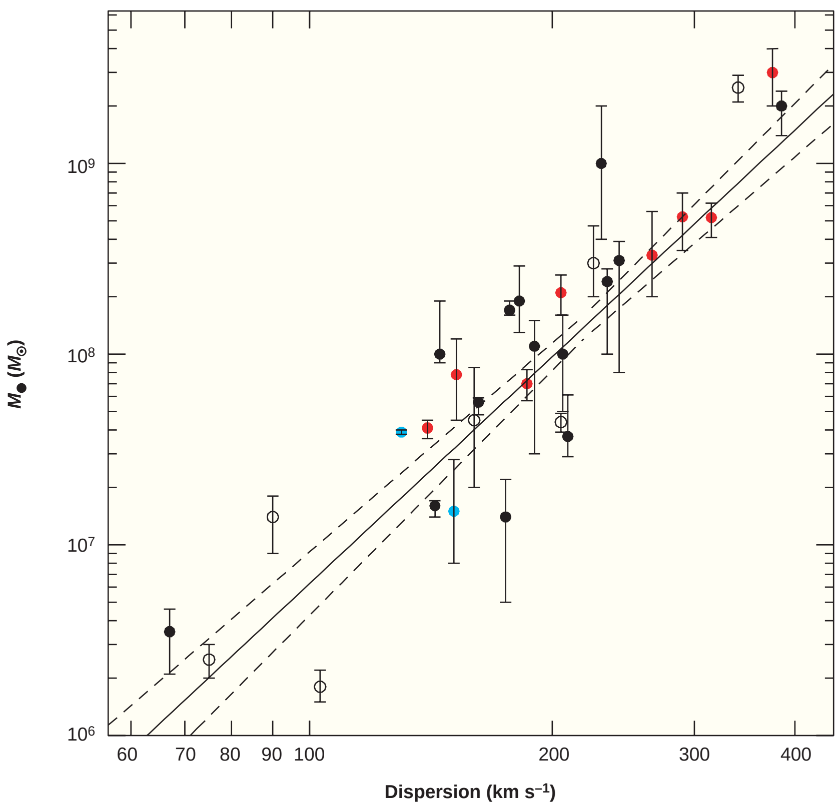


**Fig. 3.** Black hole masses plotted against bulge velocity dispersions of the host galaxy [figure 7 of (*22*); reproduced by permission of the American Astronomical Society]. Mass measurements are based on stellar (open and solid black circles), gas (solid red circles), and maser (solid green circles) kinematics. The solid line shows the best-fit $M - \sigma$ correlation; the dashed lines show one standard deviation on either side. Open and solid circles denote data from two different research groups.

If the energy liberated by accretion is not radiated away, where does it go? One possibility is that it is advected into the black hole (*38*). However, this leads to serious stability problems and is probably untenable. The reason is that much of the energy liberated close to the black hole is transferred, by the torque, to material farther out. This leaves the distant material with more than enough energy to escape from the black hole's gravitational field. The likely result is that only a small fraction of the gas that comes under the hole's gravitational influence, on the order of the ratio of $R_S$ to the accretion radius (where the free-fall speed first equals the sound speed in the gas), is actually accreted. The rest is probably expelled by the outward flux of energy before it comes near the horizon (*39–41*) (Fig. 4). This tendency of black holes to reject all but a tiny fraction (typically, $10^{-5}$ or smaller) of the matter supplied to them can explain why supermassive black holes are often so underluminous, despite their gas-rich environments. The outward energy transport converts a steep density profile ($\propto r^{-3/2}$) into a much shallower one ($\propto r^{-1/2}$), diminishing the emissivity of the gas close to the horizon (*42*).

Relativistic jets are the most striking manifestations of outflow from the vicinity of black holes. Observations show that jets are accelerated and collimated close to the black hole (*43*), probably by magnetic fields (*7*). In AGN they reach speeds as high as 90 to 99.9% of the speed of light [corresponding to a range of Lorentz factors of ~2 to 20 (*44*)] and, in some cases, retain a highly relativistic velocity and tight collimation out to enormous distances from the black hole.

Jets seem to be a generic way for accretion disks to rid themselves of excess energy and angular momentum; they also appear in subrelativistic systems such as protostars. However, the energy source for black hole jets need not be limited to the accretion flow. Magnetic fields, supported by currents in the external gas, can extract energy from the spin of the black hole via the Blandford-Znajek (BZ) effect (*45*). Because the spin energy of a black hole resides in the spacetime outside the horizon (mainly in the region known as the ergosphere, where all trajectories are dragged in the direction of spin), no physical laws are violated when a black hole is spun down. In theory, up to 29% of a black hole's rest mass energy can be liberated in this way. If some of the magnetic field lines that couple to the black hole spin also thread the accretion disk, the BZ effect could also contribute to the disk's luminosity (*34*).

The relative contributions of accretion power and the BZ effect to jet production are uncertain. Jets are found in only about 10% of AGN, including objects that appear to have accretion flows similar to systems without jets. Curiously, AGN with powerful jets are almost exclusively associated with elliptical galaxies, which suggests that somehow the black hole knows about galactic structure on scales eight orders of magnitude larger than the event horizon. According to the spin hypothesis, the connection arises because black holes in ellipticals are spinning at close to the maximal rate as a result of their history of mergers (*46*), and are thus capable of generating large jet powers via the BZ effect. However, other studies suggest that black hole spin might not depend so sensitively on galactic environment (*47, 48*). Other factors, such as the magnetic topology or outer boundary conditions of the accretion flow, may be as important (or more important) in determining whether jets form.

In this connection, the discovery of jets from a class of x-ray binaries called microquasars is noteworthy (*49*). Jets from microquasars are not produced continuously, but emerge after outbursts that may represent the sudden draining of the inner accretion disk. Because dynamical time scales close to the event horizon are proportional to the black hole mass, events that last thousands to hundreds of thousands of years in AGN may have analogs lasting minutes to days in microquasars, giving us a time-lapse view of evolving phenomena that would otherwise escape detection. As discussed below, the speeded-up phenomenology of microquasars may allow us to measure the spins of their black holes, providing a test for the spin hypothesis.

## Are They Really Black Holes?

Despite the overwhelming circumstantial evidence for black holes, the measurements discussed so far do not establish that the dark masses and compact objects we detect are the black holes whose properties are predicted so precisely by general relativity. Even the enormous release of energy during accretion will occur in any gravitational potential well of comparable depth—for example, that of a neutron star. To really confirm the existence of black holes and to test general relativity in the strong gravity limit, we must devise diagnostics sensitive to the curvature of spacetime near the horizon. Such measurements are now being made with varying degrees of success. Note that the existence of an event horizon is the only truly distinctive feature of a black hole. Neutron stars may have an innermost stable circular orbit if they are sufficiently compact (*6*). Likewise, the dragging of inertial frames occurs around any body with angular momentum, although its effects should be most pronounced close to a rapidly spinning black hole. All three phenomena, however, are consequences of the curvature of spacetime according to general relativity.

Evidence for the event horizon has been surprisingly difficult to establish observationally. One of the most frustrating aspects of

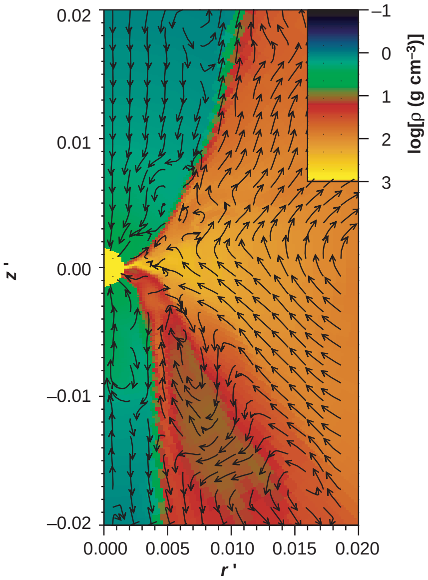


**Fig. 4.** Snapshot of logarithmic density overplotted by direction of the poloidal velocity, from a two-dimensional simulation of magnetohydrodynamic flow onto a black hole [figure 8b of (*41*)]. Matter is supplied continuously at a scaled radius of 1.2 (not shown), along with a weak radial magnetic field. Conditions near the black hole are modeled by a "pseudo-Newtonian" gravitational potential that mimics the effects of general relativity. Magnetic stresses generated inside the rotating torus (red-orange) block low-angular-momentum material (green) from accreting along the rotational axis, and expel most of the rotating material as well. As a result, only 1% of the matter supplied at $r = 1.2$ is swallowed by the black hole.

studying x-ray binaries has been the difficulty in distinguishing neutron stars from black holes by means other than mass estimates. Neutron stars have surfaces that halt the inflow of matter, whereas black holes have horizons through which matter passes freely; hence, accreting neutron stars should exhibit some extra emissivity, and perhaps a distinctive spectral signature, from matter impacting the surface. No clear spectral discriminants have been identified, but there are differences between the x-ray luminosities of quiescent x-ray novae—essentially microquasars—containing black hole and neutron stars (*50*). For the comparison to be meaningful, the sample must be carefully controlled so that the binaries have similar mass-transfer rates, which are thought to correlate with the orbital period. The results are suggestive but not definitive. The mass-transfer rates refer to the mass supplied to the outer accretion flow, not the accretion rate actually reaching the compact object. Because the inner accretion flows in quiescence are radiatively inefficient, only a small fraction of the supplied mass presumably reaches the compact object (*39*). It is not known whether there are systematic differences in the accreted fraction (attributable, e.g., to the different masses of the primaries or the different radiation environments). Moreover, residual accretion energy left over from outbursts would be stored in the neutron star's crust and emitted during quiescence (*51*), so it is not even clear that the observed emission reflects the real-time accretion rate.

Prospects are much better for detecting phenomena associated with the ISCO. The ISCO, which depends on both the mass and spin of the black hole, sets a characteristic inner radius for an accretion disk. X-ray observations of extremely broad spectral lines from partially ionized iron have provided direct evidence for disk-like flow close to the ISCO (*52*). These lines are thought to arise from fluorescence of relatively cool, optically thick gas exposed to hard x-rays produced in an optically thin corona. If the fluorescing gas forms the inner part of an accretion disk orbiting a black hole, then the line profile should display a relatively narrow blue wing boosted in intensity by the radial Doppler shift, and a broad red wing shaped by the combination of gravitational redshift and transverse Doppler shift. The best studied case, the Seyfert galaxy MCG–6-30-15, shows these features (Fig. 5), and its rapid variability confirms that the line is produced close to the horizon. The line profile can be used to deduce the spin of the black hole, although the fit may be nonunique because the structure of the corona is weakly constrained and emission could arise from inside the ISCO (*53*). In a couple of observed cases, iron line spectra may be revealing the dissipation of spin energy extracted from a rapidly rotating black hole and deposited in the innermost regions of the disk. Both MCG–6-30-15 (*54*) and the microquasar XTE J1650-500 (*55*) show such extreme redshifted emission that they are difficult to reconcile with any model in which the power in the line derives from gravitational binding energy liberated by the accretion flow.

In addition to setting a length scale, the ISCO sets a variety of time scales, including an orbital time, vertical and radial oscillation time scales for perturbations about nearly circular orbits, and a precessional time scale associated with the dragging of inertial frames by the spin of the black hole. Because these time scales are properties of the black hole's spacetime rather than the gas dynamics of the accretion flow, they should define specific frequencies that are insensitive to fluctuations in the luminosity or spectrum. Moreover, these frequencies should be among the highest associated with an accreting black hole, ranging from μHz for the most massive AGN to several hundred Hz for x-ray binaries. At least five microquasars show quasi-periodic oscillations (QPOs) at stable, high frequencies (*56*). Three of these show pairs of QPOs with simple frequency ratios, suggesting resonance effects. Although the mechanism that creates the modulations is unknown, attention has been drawn to diskoseismic modes of accretion disks. According to general relativity, the radial oscillation frequency has a maximum outside the ISCO and declines both inward (vanishing at the ISCO, which is why circular orbits become unstable there) and outward (where it approaches the Keplerian orbital frequency). Consequently, the inner part of an accretion disk around a black hole (or a sufficiently compact neutron star with a weak magnetic field) can behave like a resonant cavity, capable of trapping and amplifying wave modes that resonate with the various characteristic frequencies (*57*). The relevant modes, their amplification mechanisms, and their spectral signatures still remain to be identified. Once this is done, we should be able to measure black hole spins as reliably as we can measure their masses and test for other predicted features of spacetime curvature as well.

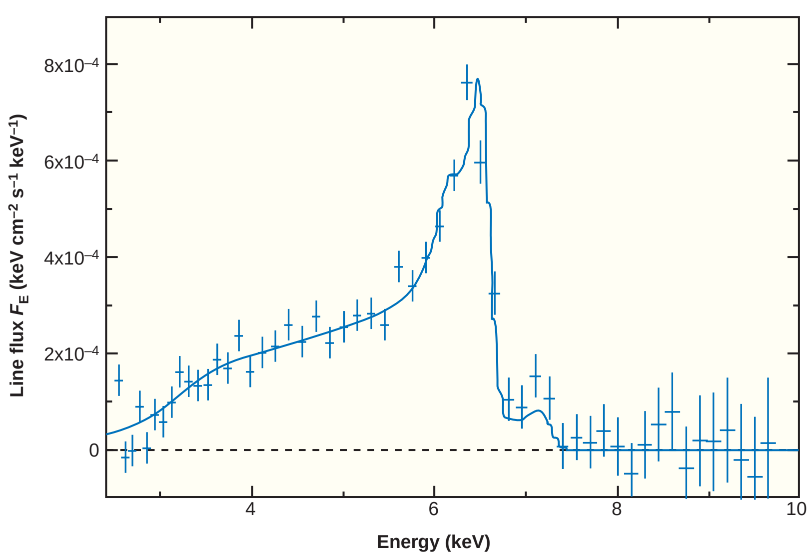


**Fig. 5.** Spectrum of the broad iron Kα line in MCG–6-30-15 taken with the XMM-Newton satellite [figure 3 of (*52*)], showing the combined effects of spectral distortions described in Fig. 1B.

**Prospects**

The evidence for black holes has firmed up substantially during the past 5 years, and we have every reason to expect the pace of discovery to accelerate. High-resolution x-ray spectroscopy and timing measurements will continue with existing satellites and will improve with the next generation of x-ray observatories, notably Constellation-X. Long-duration observations will test whether the high-frequency oscillations observed in microquasars also exist, at scaled-down frequencies, in their more massive counterparts. Understanding the demographics of black hole spin as well as mass will give us a much clearer idea of how black holes formed. A longer term but realistic goal is the direct imaging by x-ray interferometry of the accretion disk around a black hole (Fig. 1B).

Whereas x-ray measurements probe the stationary spacetimes of black holes, gravitational wave detectors will enable us to study the dynamics of spacetime as black holes form and merge. A future generation of the Laser Interferometer Gravitational-Wave Observatory (LIGO) may reveal which dying stars form black holes promptly, which undergo delayed collapse, and whether gamma-ray bursts really represent the birth of stellar-mass black holes. The Laser Interferometer Space Antenna (LISA), tuned to the slower pace of supermassive black holes, should detect stellar-mass objects falling into supermassive black holes as well as the mergers of supermassive black hole binaries (*58*). Even before LISA flies, we may see the clear signal of a star being torn apart and swallowed by a supermassive black hole (*59*).

Numerical simulations are finally reaching the point (limited mainly by computer speed) at which we can perform fully three-dimensional, magnetohydrodynamic simulations of accretion flows onto black holes. General relativistic codes are being developed and tested. We look forward to codes that can handle the microphysics of the gas as well, which will enable us to address a variety of questions: How is magnetic energy dissipated during accretion? Are two-temperature flows possible? How much matter and energy is ejected from accretion flows? What propels jets? We also anticipate progress in simulating the effects of black holes on their large-scale environments. Incorporated into cosmological simulations, these feedback calculations may clarify the origin of the "$M - \sigma$" relation and the role of black holes in galaxy formation.

Physicists will continue to study the interiors of black holes intensively (and theoretically) for clues to the fundamental structure of matter, the quantum nature of spacetime, and the possible existence of extra dimensions. For the public, black holes will retain their metaphorical implications of disappearance and mystery. Astrophysicists, on the other hand, have recently appreciated how commonplace black holes are. As we learn more about their formation and how they interact with their environments, we will understand their roles in shaping the formation and evolution of the galaxies we see around us.

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60. Supported by NSF grant AST-9876887.