Black Hole Accretion

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Black holes are most often detected by the radiation produced when they gravitationally pull in surrounding gas, in a process called accretion. The efficiency with which the hot gas radiates its thermal energy strongly influences the geometry and dynamics of the accretion flow. Both radiatively efficient thin disks and radiatively inefficient thick disks are observed. When the accreting gas gets close to the central black hole, the radiation it produces becomes sensitive to the spin of the hole and the presence of an event horizon. Analysis of the luminosities and spectra of accreting black holes has yielded tantalizing evidence for both rotating holes and event horizons. Numerical simulations imply that the relativistic jets often seen from accreting black holes may be powered in part by the spin of the hole.

Accretion is the term used by astrophysicists to describe the inflow of matter toward a central gravitating object or toward the center of mass of an extended system. Accretion is one of the most ubiquitous processes in astrophysics and is responsible for forming much of the structure we see around us. Galaxies formed early in the universe as gas flowed in toward the center of gravitational potential wells established by dark matter (*1*). Stars form inside galaxies even today as gas clouds collapse and fragment under their own self-gravity and then grow by accreting surrounding gas (*2*). Planets—including Earth—form as gas and rocks coalesce in the debris surrounding a new star (*3*). Perhaps the most spectacular observational manifestations of accretion occur, however, when the central object is a black hole.

Black holes are among the most striking predictions of Einstein's theory of General Relativity: So much mass is compressed into such a small volume that gravity overwhelms all other forces, and nothing—not even light—can escape. Instead of a normal surface, a black hole has an event horizon, a virtual surface that separates the outside world from the region of the black hole from which nothing escapes. Remarkably, General Relativity predicts that macroscopic black holes such as those that are studied in astrophysics are extremely simple objects; they can be completely described by just two parameters: their mass and spin (rotation rate) (*4–6*).

Astronomers now recognize that black holes come in many varieties, from holes with masses a few times $M_\odot$, the mass of the Sun ($\sim 2 \times 10^{33}$ g), to supermassive holes with masses between 10^6 and 10^9 $M_\odot$. Whether there are intermediate-mass black holes between these two extremes remains uncertain and is the focus of much current research (*7*). Black holes with masses of ~ 10 $M_\odot$ form when stars in the range ~ 30 to 100 $M_\odot$ exhaust their nuclear fuel and collapse under their own weight (*8*); there are perhaps 10 million such black holes in a galaxy like the Milky Way. Most are dark and invisible, but some become powerful sources of x-rays when they accrete matter from a companion star; these are called x-ray binaries (XRBs). More speculatively, the accretion of matter onto a newly formed black hole at the center of a collapsing star may give rise to gamma-ray bursts, the most energetic explosions in the universe (*9*).

In addition to these smaller holes, there is now compelling evidence that nearly every galaxy contains a much more massive black hole at its center. These range in mass from $\sim 10^6$ to 10^9 $M_\odot$, with the mass of the central black hole being closely tied to that of the bulge (*10*) of its host galaxy, $M_{BH} \approx 10^{-3}$ M_{bulge} (*11–13*). The most direct evidence for such a massive black hole is at the center of the Milky Way, where the elliptical orbits of stars around the black hole have been measured, allowing a precise determination of its mass $\approx 3.7 \times 10^6$ $M_\odot$ (*14*, *15*). When one of these massive black holes accretes gas from its surroundings, it is called an active galactic nucleus (AGN). An AGN can be extremely luminous (up to 10^{48} erg s^{-1}), outshining all of the stars in its host galaxy.

Although the existence of central massive black holes is empirically well established, their formation process remains poorly understood. The tight connection between black hole mass and galaxy mass provides a strong hint, however, and suggests that the formation of a massive black hole is intimately tied to the formation of the host galaxy in which it resides. A promising explanation for this coupling is that as the black hole grows by accretion, it deposits sufficient momentum and energy into its surroundings to blow gas out of the galaxy, thereby shutting off its own fuel supply (*16–18*). This process may also determine the total number of stars formed in a given galaxy and may regulate structure on scales as large as those of clusters of galaxies (*19*, *20*). Thus, far from being mere curiosities, black holes may actually play an active role in the growth and evolution of structure in the universe.

Accretion Physics

Gas flowing in toward a central object almost inevitably has angular momentum that prevents it from directly reaching the object. Instead, the gas settles into a disk-like structure whose orientation is defined by the angular momentum of the gas (Fig. 1). This simple physics is responsible for the prevalence of disks in astrophysics, in systems as diverse as the disk of gas that defines the Milky Way and the disk of planets that defines the solar system. Given the barrier posed by angular momentum, some form of friction is required to allow gas to flow in toward the central object. Magnetic forces in an ionized plasma probably supply this friction in many systems, efficiently transporting angular momentum outward and allowing accretion to proceed (*21*, *22*).

In addition to transporting angular momentum, magnetic stresses also convert some of the gravitational potential energy of the accreting gas into heat. The processes by which this occurs are complex and poorly understood, but the amount of energy released does not depend sensitively on these details and can be reliably estimated. The dynamics of the resulting accretion disk then depends critically on whether this thermal energy is radiated away. We can divide accretion flows into two major classes on the basis of their radiative efficiency $\varepsilon \equiv L/\dot{M}c^2$, where L is the luminosity produced by the accretion flow, $\dot{M}$ is the mass accretion rate, and c is the speed of light (and thus $\dot{M}c^2$ is the rate at which rest mass energy is accreted).

If the dissipated energy is radiated away on a time scale shorter than the time it takes the gas to flow into the black hole, the gas cools rapidly and settles into a thin accretion disk (the vertical thickness of the disk is typically in the range 0.1 to $\sim 3\%$ of the radius, i.e., much thinner than the simulation shown in Fig. 1). The efficiency ε is then ~ 0.06 to 0.4, depending on the spin of the black hole; thus, thin accretion disks around black holes are the most efficient known source of power in the universe, up to ~ 50 times as efficient as nuclear fusion in stars (*23*). By contrast, if

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the gas cannot radiate its energy away, it forms a hot thick accretion disk (*24*) with $\varepsilon \ll 1$ (the disk thickness is then 20% or more of the radius, as in Fig. 1).

Accretion onto a black hole can take either of these two forms (Fig. 2). At low accretion rates $\dot{M}$ much less than the Eddington rate $\dot{M}_{Edd}$ (*25*), corresponding to low-luminosity XRBs and AGN, observations primarily favor thick disks (*24*). The most compelling example is the supermassive black hole in our own galactic center, which is surprisingly dim ($L \approx 10^{36}$ erg s^{-1}, only ~100 times that of our Sun) and is a very inefficient accretor [$\varepsilon \approx 10^{-6}$ as estimated from the mass supply rate at large distances (*26*), although only a small fraction of this gas may actually reach the hole, as discussed below]. In systems such as this, the accretion is thought to take place via a hot two-temperature collisionless plasma in which the protons are much hotter than the electrons. The physics of such plasmas is not fully understood (*27*).

In the opposite limit of very high accretion rates, $\dot{M} \gg \dot{M}_{Edd}$, the inflowing gas again does not radiate efficiently because there is so much accreting material that the radiation produced by the inflowing gas is trapped in the accretion flow and cannot escape before falling into the black hole (*28*). This is true until $\dot{M} \approx 10^{15}\ \dot{M}_{Edd}$ (~1 $M_\odot$ s^{-1} for a solar-mass black hole), at which point the inflowing gas radiates away its gravitational binding energy via neutrinos rather than electromagnetic waves (*29*, *30*). At still higher accretion rates, even neutrinos are trapped in the inflowing gas and we again have thick disks. Such high accretion rates are never reached for black holes in XRBs or AGN, where characteristic rates are below the Eddington rate. They can, however, be achieved in the process of forming neutron stars and solar-mass black holes in the core collapse of massive stars (i.e., supernovae). Recent observations show that some gamma-ray bursts—explosions that release ~10^{51} ergs as gamma-rays in a few seconds—are associated with supernovae (*31*, *32*) and may be the signatures of newly formed black holes accreting the debris of their parent stars at ~1 $M_\odot$ s^{-1} and ejecting ultrarelativistic jets (*9*).

Finally, Fig. 2 illustrates a Goldilocks-like regime of accretion rates, $\dot{M} \approx \dot{M}_{Edd}$, in which accretion proceeds via a thin disk that efficiently radiates away its gravitational potential energy. The precariousness of this regime has been highlighted by recent work showing that the fate of gas in an accretion flow depends critically on whether the disk is thin or thick. In thin disks, most of the mass supplied at large radii reaches the central black hole. By contrast, in thick disks, very little of the supplied mass ends up accreting into the hole. Instead, most of the mass circulates in convective motions (*33*, *34*) or is driven away in an unbound outflow (*35*, *36*). This in turn causes the amount of radiation from the accretion flow to decrease drastically. Because the fate of supplied matter depends so strongly on the mode of accretion (thin versus thick), it is likely that bright accreting black holes occupy a somewhat narrow range of accretion rates (Fig. 2).

In or Out?

The outflows from thick disks may be related to another outstanding observational and theoretical puzzle. Observations reveal that many accreting systems have powerful outflows of mass and energy. These are not unique to accreting black holes—young accreting stars show powerful outflows, as do some accreting neutron stars—but the outflows from black holes, particularly the collimated jets from massive black holes (*37*, *38*), are probably the most remarkable (Fig. 3).

Recent work—including direct numerical simulations of magnetized accreting plasma in General Relativity—has clarified the possible origin of these outflows. Simulations (Fig. 1) reveal a mildly relativistic outflow that emerges self-consistently from the accretion flow (*39*, *40*). The outflow is stronger and energetically more important for rapidly rotating black holes. Some of the

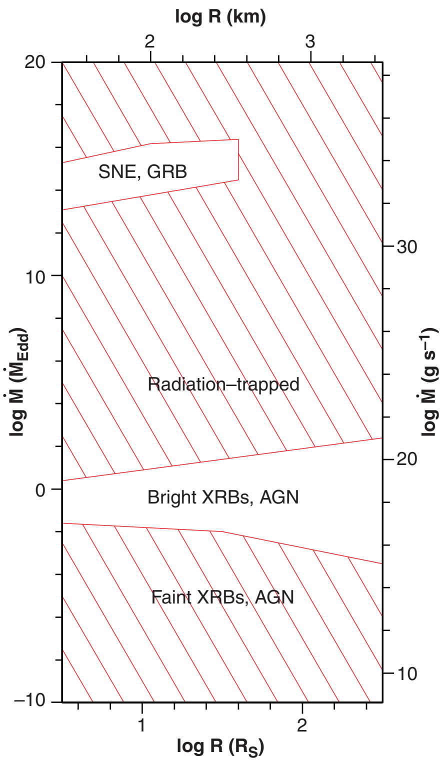


Fig. 2. Thin- and thick-disk regimes in the parameter space of accretion rate and radius. The figure covers 30 orders of magnitude in accretion rate to illustrate the broad applicability of this theoretical classification. The bottom horizontal axis is the radius of the accreting gas in units of the event horizon; the left vertical axis is the accretion rate in Eddington units (*25*). The top horizontal axis and right vertical axis give physical units for a 3 $M_\odot$ black hole. Shaded regions denote radiatively inefficient thick disks; nonshaded regions denote radiatively efficient thin disks. SNE, supernova explosions; GRB, gamma-ray bursts.

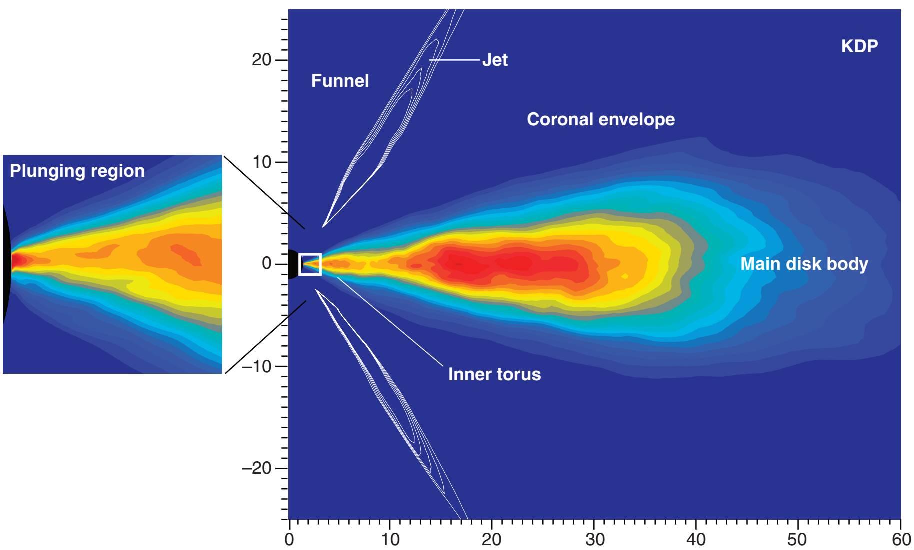


Fig. 1. The inner regions of an accretion disk around a black hole, as calculated in a General Relativistic magnetohydrodynamic numerical simulation (*39*). The black hole is at coordinates (0,0) with an event horizon of radius unity. The accretion disk rotates around the vertical direction (the axis of the nearly empty funnel region). Its density distribution is shown in cross section, with red representing the highest density and dark blue the lowest. Above the disk is a tenuous hot magnetized corona, and between the corona and the funnel is a region where there is ejection of mildly relativistic plasma, which may be related to the formation of jets. The example shown here corresponds to a radiatively inefficient thick disk. In the opposite limit of a thin disk, the vertical thickness of the disk would be much smaller, sometimes as small as 0.1% of the radius.

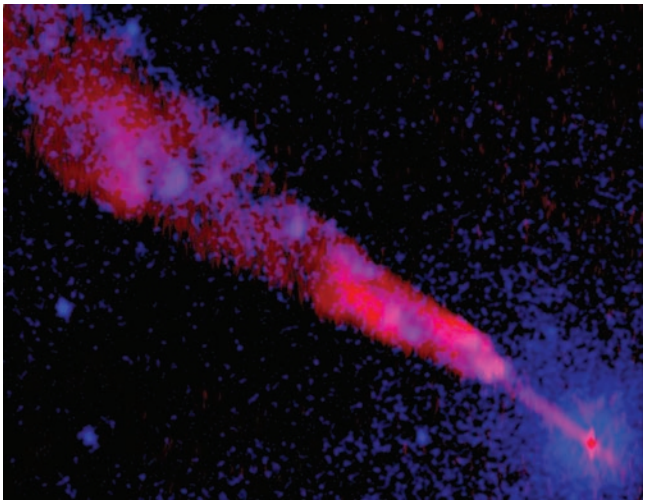
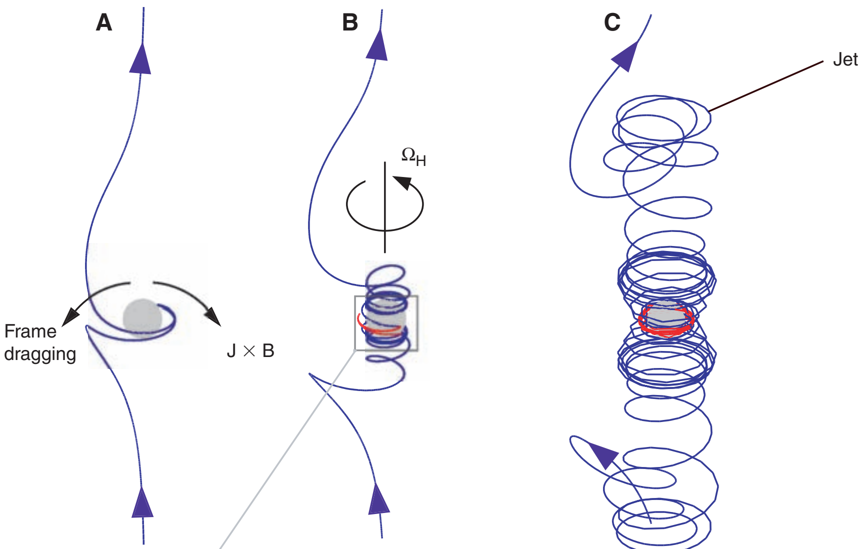


Fig. 3. Composite image of the inner 4000 light years of a jet in the galaxy Centaurus A (*66*). Blue shows x-ray emission as seen by the Chandra X-ray Observatory, and red shows radio emission as measured with the Very Large Array. The jet originates from the vicinity of a supermassive black hole at the center of the galaxy in the lower right of the image. The jet is straight and well-collimated, and has a total length much greater than that seen in the inner region highlighted here.

energy for this outflow comes directly from the rotational energy of the hole rather than from the accreting matter, a possibility that has been discussed for more than 30 years (*41*, *42*).

One physical process by which a jet can be produced by a spinning hole has been cleanly demonstrated in a numerical experiment (Fig. 4) (*43*–*45*). Just outside the horizon of a rotating black hole is a region of spacetime called the ergosphere where matter is not allowed to be at rest, but must rotate along with the hole. Because of this effect of frame dragging, magnetized plasma inside the ergosphere is twisted into corotation with the hole. The twist propagates out along the magnetic field lines as a torsional Alfvén wave, extracting the rotational energy of the black hole and driving an outflow. This is analogous to the mechanism by which outflows are driven from rotating magnetized stars (e.g., pulsars) or accretion disks (*46*, *47*).

Observationally, it is not clear whether the hole or the disk is the source of the outflows seen in accreting black holes (*48*, *49*). X-ray binaries show a strong correlation between the presence of a thick disk and the presence of radio emission from jets (*50*, *51*). There is related evidence in AGN as well, particularly for low-luminosity systems (*52*, *53*). This suggests that the dynamics of the underlying accretion disk is central to the production of jets, either because the outflow originates from the thick disk itself or because the magnetic field structure associated with the thick disk is more conducive to the extraction of energy from the central black hole.



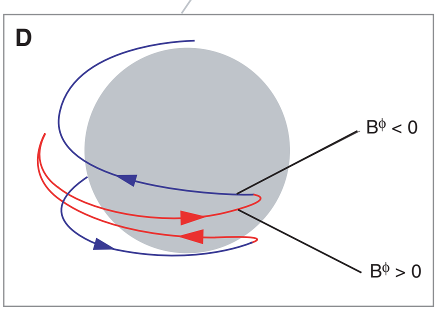


Fig. 4. Illustration of how a spinning black hole with a large-scale magnetic field around it may produce jets. Shown are computer calculations of the evolution of single magnetic flux tubes (*43*). (**A**) The dragging of frames by the black hole causes the field lines in the equatorial region to be pulled forward in the direction of the black hole's spin. (**B** and **C**) The field line becomes progressively more twisted with time, and the twist propagates outward relativistically to form twin jets. (**D**) A closer view of (B). The plasma in the red portions of the field lines has negative energy. As this plasma falls into the black hole, it causes the rotational energy of the hole to decrease. The extra energy comes out in the jet, in a process analogous to the original suggestion of Penrose (*41*) for extracting energy from a spinning black hole. **J**, electric current vector; **B**, magnetic field vector; $\mathbf{B}^\phi$, azimuthal component of **B**; $\mathbf{\Omega}_H$, spin vector of the black hole.

Spinning Holes

Numerical simulations of jets from black holes provide some support for the long-hypothesized connection between relativistic outflows and black hole spin. With the recent progress in measuring the masses of astrophysical black holes, spin is now the sole remaining property required for a full characterization of these objects. There is tantalizing evidence that most massive black holes in galactic nuclei rotate rapidly. The total mass in these black holes in the local universe can be compared with the total radiation produced by accretion over the history of the universe to infer the average efficiency ε of accreting black holes (*54*). This yields efficiencies $\varepsilon > 0.1$ (*55*, *56*), providing suggestive statistical evidence that most holes rotate appreciably, with the spin parameter a_* (*6*) being closer to unity than to zero.

Direct evidence for black hole spin in individual systems is, in principle, possible because spin imparts unique signatures on the structure of spacetime around black holes. Accretion disks around rotating holes extend inside the ergosphere, and the properties of radiation from gas in this inner region should reflect the spin of the hole. Some XRBs and AGN show lines from ionized iron in their x-ray emission. In several cases, the lines are remarkably broad, with a width comparable to the rest wavelength of the line (*57*, *58*). Although the interpretation and analysis are subtle, the line-broadening has been interpreted as being due to the extreme gravitational redshifts and Doppler shifts present in accretion disks around rotating black holes with $a_* > 0.9$ (*59*).

Certain classes of XRBs—both those with black holes and those with neutron stars—show nearly periodic oscillations in their x-ray emission (*60*). These quasi-periodic oscillations (QPOs) have periods similar to the rotation period of matter near the event horizon of the central black hole, which suggests that they arise as matter is just about to plunge through the horizon. Just as earthquakes can be used to study Earth's interior structure, QPOs may provide a means of mapping out the structure of spacetime around black holes, thereby constraining the spin of the hole (*61*).

These methods for estimating the spin are made possible because the gas in an accretion disk probes the relativistic region of spacetime near the black hole. An even more remarkable property of a black hole than the twisting of spacetime by its spin is the fact that it possesses an event horizon. Because the gas in an accretion disk flows into the hole through the horizon, it should, in principle, be possible to test whether black holes do have horizons. Several intriguing differences have been identified between the luminosities and spectra of XRBs with black holes and those with neutron stars. When combined with models of accretion, these differences are found to be consistent with black holes having event horizons and neutron stars having surfaces (*62*, *63*), thus confirming one of the most spectacular predictions of General Relativity.

Ideally, for all these studies, one would like to directly observe gas as it is about to plunge through the horizon of a black hole. In the near future, the most promising technique for doing so is very long baseline interferometry (VLBI), which uses radio telescopes on opposite sides of Earth to create the most detailed images of astronomical objects. At a wavelength of $\sim$0.3 mm, this technique can reach a resolution of $\sim 5 \times 10^{-11}$ rad $\approx 10^{-5}$ arc sec. This would be sufficient to see a coin the size of a U.S. quarter on the Moon. More relevant to observing gas near the horizon of a black hole is that the size of the horizon of the black hole in the galactic center is $\sim 10^{-5}$ arc sec on the sky. VLBI experiments are being planned to try to image the emission from gas close to this black hole (*64*), and there are exciting prospects for seeing General Relativistic effects in such observations, including signatures of black hole spin (*65*). This would represent a remarkable achievement for black hole astrophysics: from theorists' speculations to direct images in $\sim$100 years.

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