REVISITING THE BLACK HOLE

A resurgence of theoretical and observational interest in black holes has given new impetus to the study of these intriguing objects.

Roger Blandford and Neil Gehrels

Twenty-eight years ago, in a celebrated article in PHYSICS TODAY entitled "Introducing the Black Hole," Remo Ruffini and John Wheeler filed a dispatch from the campaign to understand gravity. With hindsight, we now see that they wrote in the middle of a golden age—spanning the mid-1960s and the late 1970s—when remarkable discoveries in the theory of general relativity were made to confront equally stunning developments in observational astronomy.

Thereafter, the study of black holes advanced steadily—though unspectacularly—until about five years ago, when new observational capabilities (exemplified in figure 1) began to demonstrate that the actual behavior of black holes is far more interesting than astrophysicists had imagined, and forced them to reexamine many of their tacit assumptions.

As the century turns, we appear to be in the middle of a second golden age of research on black holes. Eagerly awaited are the launch of several new space missions that, all going well, will test classical general relativity in the strong-field regime and show us how these superb cosmic engines actually work.

Event horizons

In the late 1960s, the term "black hole"—which was introduced by Wheeler in 1968 in a lecture to the American Association for the Advancement of Science and subsequently proved to be a catchphrase—was used to describe a new view of gravitational collapse. No longer was it reasonable to limit our perspective to that of the "observer at infinity," for whom the hole never forms. Instead, we were required to see the black hole on its own terms—that is, to explore the fate of matter falling into the black hole as it crosses its Rubicon, the event horizon, on its way to what Wheeler called the greatest crisis in physics, the singularity, where classical physics offers no help and where quantum gravity has still not provided much enlightenment. (An event horizon is a boundary that separates points in spacetime from which photons can escape to infinity in the future from points where they cannot escape.)

"Black hole" joined the scientific lexicon at a time when it was appreciated just how elementary such objects are. From an astrophysical perspective, black holes form a two-parameter family (note that, in this article, we confine our attention to directly observable phenomena and pay no attention to charged holes, Hawking radiation, D-branes, and so on—all wonderful theoretical constructs, but, so far, of no relevance to the astronomer). One parameter is the mass of the hole, M, which, in effect, is simply a geometrical scale of length, time, and energy. (See box 1 on page 42.) The other parameter is the convenient choice of the black hole's angular velocity, Ω, which also expresses the shape of the spacetime geometry around the black hole and which is measured by a metric tensor discovered in 1963 by Roy Kerr.

Setting aside some technical difficulties that concern us to this day, Kerr's metric appears, remarkably, to be the only *in vacuo* solution of the field equations of general relativity that both reduces to special relativity at large distances and contains an event horizon. (A black hole event horizon is properly a three-dimensional surface in four-dimensional spacetime, but it is permissible to think of it as stationary and axisymmetric, a two-dimensional surface in three-dimensional space.)

Although the event horizon is globally important, it is not locally special. An infalling experimental physicist (sufficiently small in stature so as not to be discomforted by tidal forces) could perform local experiments with the same outcomes as on Earth. However, after crossing the event horizon, he or she would experience an inexorably increasing gravitational stress that would become infinite in a finite proper time at the physical singularity. In short, if general relativity is the correct classical theory of gravity, then we can provide rational and unambiguous answers to essentially all thought experiment–type questions concerning what would happen to rods, clocks, observers, and so on—provided quantum gravity considerations are unimportant.

A black hole is the stage on which great cosmic dramas are enacted, and we understand it well. The challenge to contemporary astronomers is to use observations, obtained throughout the electromagnetic spectrum, to interpret the plays.

Astrophysical black holes

Energy is the key to understanding astrophysical black holes. By the 1970s, it had already been well established theoretically that black holes can be voracious monsters greedily and messily devouring all that they encounter.

Some black holes are extremely luminous and easily outshine their stellar and galactic counterparts that rely on nuclear, as opposed to gravitational, energy for their power. (See box 1.) It was also well understood where they would be most likely to be detected—that is, in stellar binaries of roughly 10 $M_\odot$ ($M_\odot$ denotes the mass of the Sun and is roughly 2×10^{30} kg), and in the galactic nuclei with masses of 10^6–10^9 $M_\odot$.

In the 1960 and 70s, it was expected that, in the standard mode of accretion, in which gas is supplied with enough angular momentum to form an accretion disk, the accreting gas would be steadily converted into energy at a rate of about $0.1c^2 \approx 10^{16}$ J/kg. Central to the power estimates was a benchmark luminosity, called the Ed-

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dington limit ($L_{Edd} \approx 10^{31}$ W / $M_\odot$), which arises when the radiation pressure due to Thomson scattering off electrons counterbalances the tug of gravity. If the luminosity were to exceed the Eddington limit, it was expected that the supply of gas would be shut off.

The archetype of the stellar black hole is Cygnus X-1, whose prodigiously powerful x-ray source varies so rapidly that it has to be a compact star. Only three kinds of compact star are known to astrophysicists: white dwarf, neutron star, and black hole. However, fundamental physics arguments assure us that only the black hole can weigh more than $3\,M_\odot$. Consequently, when Kepler's laws were applied to Cygnus X-1 in 1971 and resulted in an estimated mass for the compact star of $8\,M_\odot$, the source's identity as a black hole was established.

Dynamical arguments like the preceding one have turned out to be the only durable and compelling way to certify black holes, and we now know of nine black holes in stellar binary systems. (See the table in box 2 on page 44.)

For black holes in active galactic nuclei, the story has been somewhat similar. Dynamical investigations, starting with the work of Wallace Sargent, Peter Young, and their collaborators in the late 1970s, established that galaxies, like the giant elliptical galaxy M87 in the Virgo Cluster, contain central dark masses ($3 \times 10^9\,M_\odot$ in the case of M87) that appeared to be too compact to be a central cluster of stars. Originally, the masses were estimated by measuring the velocities of the stars in orbit around the black hole. However, the interpretation of these measurements was controversial because we can only measure directly the component of velocity along the line of sight and have to guess the full three-dimensional velocity distribution.

More recently, these arguments have become much more precise because it has become possible both to look at the stellar distribution in more detail and to measure the speed of gas orbiting black holes in a disk. These two observational feats can be accomplished by taking advantage of the excellent angular resolution of the Hubble Space Telescope or, with even more accuracy, by exploiting a microwave emission line of water molecules observed by means of very long baseline interferometry with an intercontinental array of radio telescopes.

In an observational *tour de force* in 1995, Makoto Miyoshi and his colleagues were able to measure the orbital speed of the gaseous disk around the nucleus of the nearby spiral galaxy NGC 4258. They showed that the gas speed obeys Kepler's laws and, furthermore, that the disk is warped. Since the mass and size of the central object are $4 \times 10^7\,M_\odot$ and half a light year, respectively, all explanations other than a black hole can be confidently ruled out.

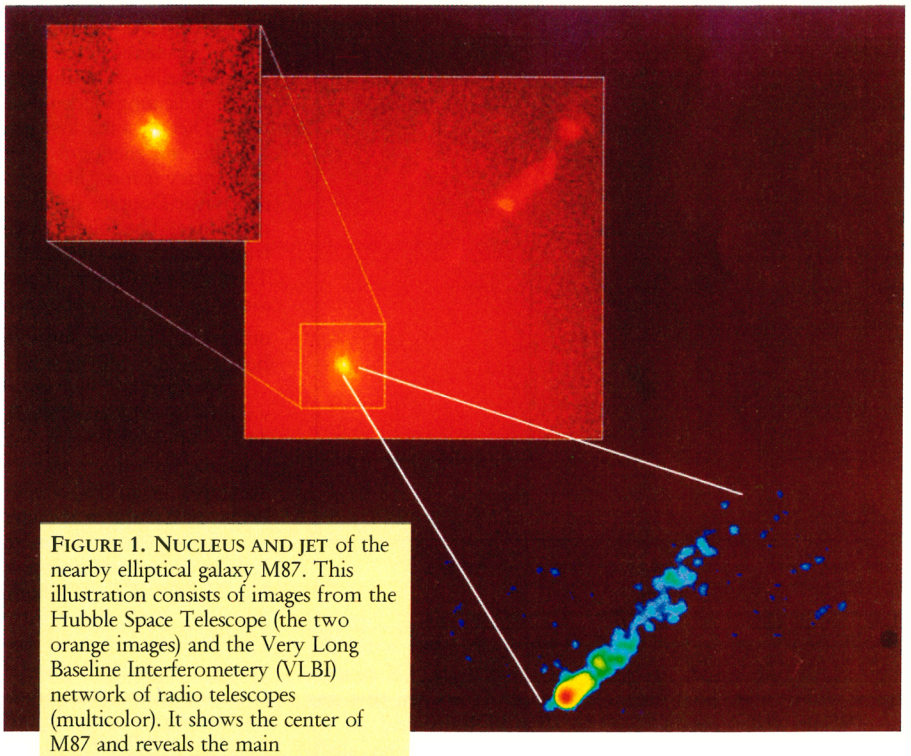


FIGURE 1. NUCLEUS AND JET of the nearby elliptical galaxy M87. This illustration consists of images from the Hubble Space Telescope (the two orange images) and the Very Long Baseline Interferometery (VLBI) network of radio telescopes (multicolor). It shows the center of M87 and reveals the main characteristics of the massive black hole environment—namely, the disk of hot gas orbiting the central source in the HST images, and the jet of relativistic material in the VLBI image. Observations like these, which probe close to the central black hole in galaxies, provide important information on the environment near massive black holes. (Images courtesy of J. Biretta and W. Junor, Hubble Space Telescope Science Institute.)

Exploiting yet another technique, Reinhard Genzel, Andrea Ghez, and their collaborators have been able to measure both the proper motions and the line-of-sight velocities of individual stars in orbit around the center of the Galaxy. They find that the mass of our black hole has a much smaller value, $2.6 \times 10^6\,M_\odot$ (see PHYSICS TODAY, March 1998, page 21).

In total, we have about 15 mass estimates for black holes in the nuclei of nearby galaxies that are quite secure. It appears that the majority of nearby luminous galaxies now contain dormant black holes. However, during earlier epochs, when the black holes were supplied with gaseous fuel at a much higher rate, they were able to outshine their host galaxies—in some cases by a factor of thousands. These ancient objects are the quasars, which we can spot from distances so large that many of them emitted the light we see now when the universe was less than 10% of its present age.

Black holes at the *fin de siècle*

The past five years have seen a remarkable gain in the sophistication of black hole observations with telescopes that span the entire electromagnetic spectrum. No longer is there any serious debate as to whether black holes exist. We know that they must be quite common, and we can now study them in increasing detail.

In addition to masses being measured confidently for the first time, there have been many direct observations of the gas flow close to the event horizon. The Japanese x-ray satellite ASCA has observed several active galactic nuclei, most famously a source known as MCG-6-30-15.

In this object, ASCA has detected a K-shell x-ray emission line of iron, supposedly from fluorescent material on the surface of a disk of accreting gas (see figure 2). Because the line is produced over a restricted range of

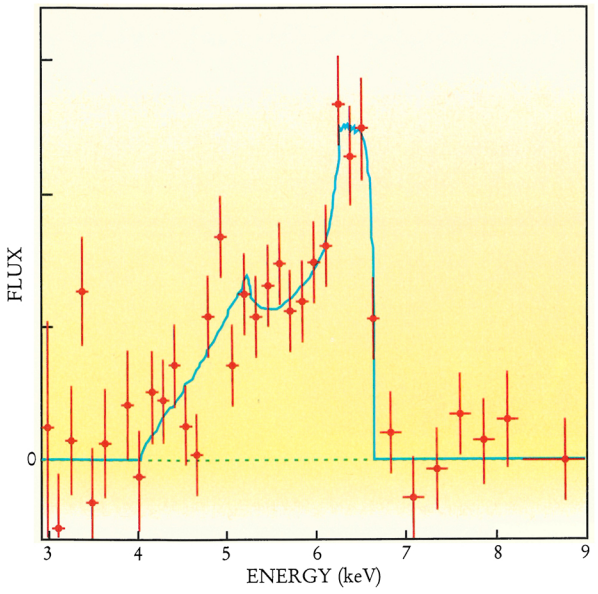


FIGURE 2. LINE PROFILE of iron K-alpha from the active galactic nucleus known as MCG-6-30-15, as observed by the ASCA satellite. The emission line is extremely broad, with a width indicating velocities of order one-third of the speed of light. There is a marked asymmetry toward energies lower than the rest energy of the emission line (6.4 keV). This asymmetry is most likely caused by gravitational and relativistic-Doppler shifts near the black hole at the center of the galaxy. The solid line shows the model profile expected from a disk of matter orbiting the hole. (Adapted from Y. Tanaka *et al.*, *Nature*, volume 375, page 659, 1995.)

disk radii close to the hole, we expect to observe a blueshifted peak in the line profile associated with the side of the disk that is spinning toward us. Of course, there should also be a redshifted peak. However, this gas is moving with speeds close to that of light and so we must include relativistic corrections to the Doppler shift, the gravitational redshift, and beaming or aberrational effects. When these adjustments are made, it is possible to deduce the inclination of the observer and to argue that Ω is close to its maximal value, $m/2$. (Although this result is somewhat controversial, it is remarkable that we are even debating the matter!)

We expect some variation in the emission from a black hole on timescales comparable with the orbital period close to the innermost stable circular orbit, perhaps around $10m$ in geometrical units. Typical periods should be of order a millisecond for a stellar mass black hole and perhaps hours for a black hole in an active galactic nucleus.

In figure 3, we show an example of short-timescale variability observed from the nucleus of the galaxy NGC 4151. Variability studies were one of the reasons for building another x-ray satellite, the Rossi X-Ray Timing Explorer, or RXTE, which has produced wonderful discoveries, particularly concerning Galactic black hole sources.

A well-studied case of variability in a Galactic black hole is the superluminal source GRS 1915 + 105. When we tune in to this remarkable source—that is, if we convert its x-ray light curve into sound, as was done in 1997 by Ed Morgan—we hear the complex rhythms of an avant-garde composition. Snatches of x-ray music with complex time signatures burst out in Fourier space as quasiperiodic variations in intensity with frequencies that range from several millihertz to 67 Hz. The source itself almost certainly consists of a black hole with a stellar companion, which donates material at a rate that greatly exceeds that necessary to sustain emission at the Eddington limit. Unable to accept this copious supply, the black hole expels most of the gas through mechanisms that are not yet understood.

One plausible explanation is that GRS 1915 + 105 could expel material by creating a pair of antiparallel jets—that is, collimated outflows that presumably flow along the spin axis of the hole. In fact, it has been possible to observe these outflows using radio telescopes, and

Box 1: Black Hole Power

An astrophysical black hole with gravitational mass M, measured in units of the solar mass ($M_\odot$, which is about 2×10^{30} kg), defines units of length, time, and energy; they are, respectively

$$m \equiv \frac{GM}{c^2} = 1.5\left(\frac{M}{M_\odot}\right) \text{ km}$$

$$m \equiv \frac{GM}{c^3} = 5\left(\frac{M}{M_\odot}\right) \mu\text{s}.$$

$$m \equiv Mc^2 = 2 \times 10^{47}\left(\frac{M}{M_\odot}\right) \text{J}.$$

In these units, it is found that the hole has a maximum angular velocity of $\Omega < m/2$.

The angular velocity affects the character of the orbits close to the black hole. If we just consider circular orbits in the equatorial plane with the same sense of rotation as the hole, we find that their binding energy (the energy that a particle must lose to get onto these orbits) increases as the orbit shrinks. However, when an orbit becomes too small, it becomes dynamically unstable. The maximum binding energy of a particle of unit mass increases from $0.06c^2$ to $0.42c^2$ as Ω increases from 0 to its maximal value. Therefore, every kilogram of gas that falls into the black hole can release up to 4×10^{16} joules of energy.

In addition to this gravitational mass, defined operationally by measuring the orbit of a distant satellite and using Kepler's laws, there is a second, smaller mass that we can define. Called the irreducible mass, m_0, it is given by

$$m_0 = m(1 + 4\Omega^2 m^2)^{-1/2} \geq 2^{-1/2} m.$$

As its name implies, this is the minimum mass to which we can reduce a black hole in a carefully designed thought experiment in which the hole spins down. The difference $(m - m_0)c^2$ can be considered as the spin energy of the black hole. This energy can be expressed in a pseudo-Newtonian fashion by defining an effective radius r_0 of the black hole from its surface area A:

$$r_0 = \left(\frac{A}{4\pi}\right)^{1/2} = 2m_0$$

The spin angular momentum per unit mass and the rotational speed are then given by $a = r_0^2\Omega < m$ and $\beta = \Omega r_0 < 2^{-1/2}$, respectively. Amusingly, the relation between m and m_0 can then be rewritten in a form familiar from special relativity.

$$m = \frac{m_0}{(1 - \beta^2)^{1/2}}$$

Up to 29% of the rest mass of a black hole is therefore available from the black hole spin for powering cosmic sources.

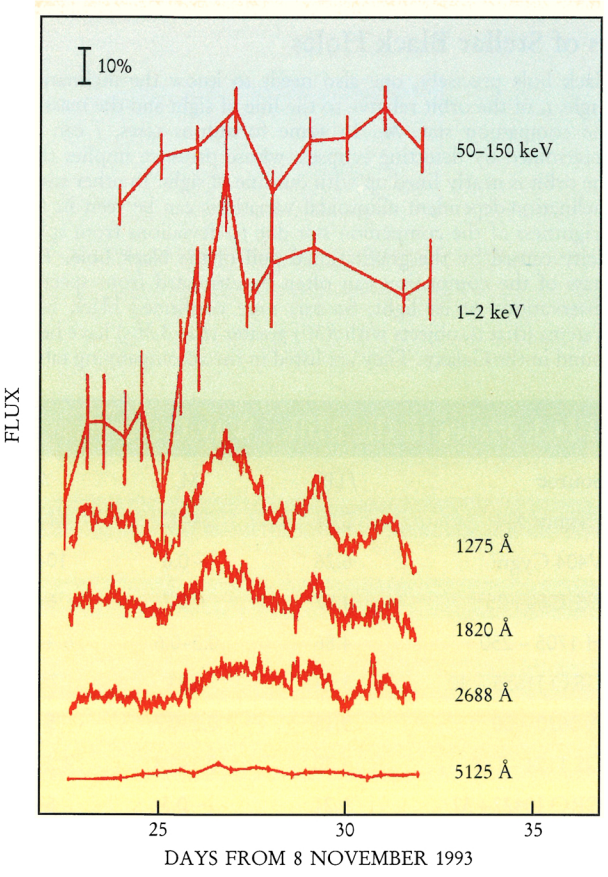


FIGURE 3. LIGHT CURVE OF NGC 4151. A multiwavelength study of this active galaxy shows the variability across a broad range of energies characteristic of accreting black holes. Monitoring such sources over as many wavelengths as possible is key to understanding accretion dynamics. (Adapted from R. A. Edelson *et al.*, *Astrophysical Journal*, volume 470, page 364, 1996.)

features have been found that appear to travel across the sky faster than the speed of light—hence the epithet "superluminal" (figure 4).

The study of jets from black holes has also advanced considerably. There is now little doubt that, on both stellar and galactic scales, jets are created with relativistic outflow speeds close to the black hole. In the case of M87 (figure 1), the emission has been traced down to a scale of $60m$. Speeds in excess of $0.99c$ have been reported. Furthermore, detailed radio studies of moving jet features reveal that these jets often appear to precess, or at least to change their direction of propagation, as is seen in the Galactic dual-jet source SS433.

One of the biggest surprises in extragalactic astronomy in recent years has been the discovery that extragalactic radio jets are often prodigiously luminous gamma-ray sources. Before the launch of the Compton Gamma Ray Observatory (CGRO), it was known that many of the brightest jets observed at radio wavelengths owe their prominence to their relativistic outflow speeds. It is a simple consequence of special relativity that a source of radiation—in this case, synchrotron radiation—will beam its emission along its direction of motion and that, when directed toward us, will appear anomalously bright (by factors that can easily exceed a thousand). This synchrotron radiation is emitted by GeV electrons spiraling in a disorganized magnetic field, and these same electrons can Compton scatter the ambient radiation in the galactic nucleus. In particular, x-ray photons are promoted to GeV photons, which, like the radio emission, are also beamed toward us.

What has surprised astrophysicists is the intensity of these gamma-ray jets—thousands of times more powerful than the radio emission. Indeed, in a couple of nearby sources, TeV gamma rays have been detected. The formation and collimation of black hole jets is clearly an ultra-high-energy process.

Theorists pick up the gauntlet

All these observations have forced us to look at black holes in a new light. As emphasized above, following the flow of energy is essential if we are to understand how black holes actually function. In the extremely luminous quasars and Galactic binary sources, the black holes are rapidly supplied with gas, which spirals in through an orbiting accretion disk at a rate determined by the effective viscosity, a key quantity in the physics of accretion disks.

For decades, attributing an origin and assigning a magnitude to the disk viscosity have been speculative and controversial. If the viscosity is low, the disk is dense and its properties are very different from those of a high-viscosity disk. As well as being viscous, the disk material is also highly ionized, which makes it an excellent electrical conductor. As a result, understanding the flow becomes a problem in magnetohydrodynamics. This characterization, in turn, implies that we can regard the lines of magnetic field as being tied to the moving gas, which quickly twists them up.

Thanks to the efforts of Steven Balbus, John Hawley, and their collaborators, we now have a much more sophisticated view of how disks behave. It is pretty certain that the viscosity is magnetic in origin and that it drives the gas inward toward the hole quite rapidly. This realization is reminiscent of the 1940s, when Hans Bethe and others started to understand how energy was generated inside stars. Nowadays, much work is being done aimed at understanding the analogous internal transport and emission of radiant energy by disks.

We still have to account for the formation and collimation of ultrarelativistic jets by a minority of accreting black holes. Like disk viscosity, these processes are widely suspected of being magnetohydrodynamical in nature. Lines of magnetic field protruding from the surface of the spinning disk could be swung around the axis of rotation and, because these field lines have an effective tension, they could provide a sort of elastic sleeve within which energy released close to the black hole can escape. To determine whether jets really do form in this way, it will be necessary to perform extensive three-dimensional numerical simulations of magnetohydrodynamical flow around black holes. Fortunately, the computing power to meet this daunting challenge is almost within our grasp.

The inflowing accretion disk is not the only source of power. The spin of the black hole provides a second reservoir of energy, which can also be tapped by the magnetic field. Suppose that there is a ring of electrical current flowing in the disk close to the hole. This current will generate magnetic field, and some of the field lines will cross the event horizon, thereby setting up a curious electromagnetic effect. It turns out that we can treat the event horizon as an electrical conductor (with resistance of order 100 ohms), which, because it is moving in an electromagnetic field, will be subjected to an electromotive force.

Under the conditions believed to be present in a quasar, for example, the magnetic flux density may be as high as 1 tesla, and voltages as high as 10^{20} V can be induced, which can cause the flow of currents of a magnitude limited by the total resistance of the circuit. Here,

Box 2: Measuring the Masses of Stellar Black Holes

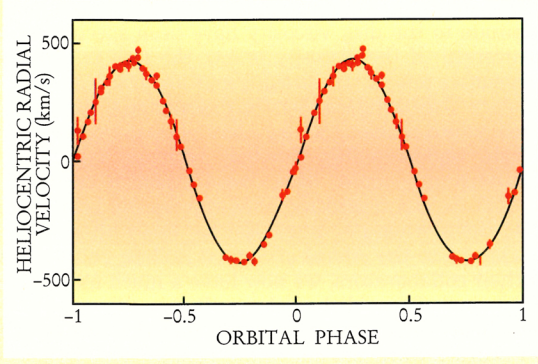
For black holes in binary systems, the component of the orbital velocity of the companion star can be measured from the Doppler shift of its characteristic spectral line frequencies. The accompanying figure from Tom Marsh and his collaborators shows an example of orbital motion for the black hole binary A 0620 – 00.

Using Kepler's laws, we can uniquely determine a quantity called the mass function $f(M)$ of the system,

$$f(M) = \frac{(M \sin i)^3}{(M + M_c)^2} = \frac{PK^3}{2\pi G}$$

$$= 0.1 \left(\frac{P}{1\ \text{day}} \right) \left(\frac{K}{100\ \text{km/s}} \right)^3 M_\odot,$$

by measuring the orbital period, P, and the semiamplitude of the radial velocity, K. The mass function is the *observational* lower limit of the presumed black hole's mass. To weigh the black hole precisely, one also needs to know the inclination angle, i, of the orbit relative to the line of sight and the mass of the companion star, M_c. In some fortuitous cases, i can be determined by detecting eclipses, whose presence implies that the orbit is nearly lined up with our line of sight. In other cases, inclination-dependent ellipsoidal variations can be seen in the brightness of the companion star due to deviations from sphericity caused by the gravitational pull of the black hole. The mass of the companion can often be estimated from spectral observations of its light. So far, nine confirmed black hole systems (that is, objects with $f(M)$ greater than 3 $M_\odot$) have been found in the Galaxy. They are listed in the accompanying table.



Black Holes in the Milky Way Galaxy*

Source	$f(M)$	M_c	M
Cygnus X-1	0.24	24–42	11–21
V404 Cygni	6.26	~0.6	10–15
GS 2000+25	4.97	~0.7	6–14
H 1705 – 250	4.86	0.3–0.6	6.4–6.9
GRO J1655 – 40	3.24	2.34	7.02
A 0620 – 00	3.18	0.2–0.7	5–10
GS 1124 –T68	3.10	0.5–0.8	4.2–6.5
GRO J0422+32	1.21	~0.3	6–14
4U 1543 – 47	0.22	~2.5	2.7–7.5

*All masses given in solar masses.

the total resistance is the sum of the internal resistance of the black hole and that of the effective load, which, under near-vacuum conditions, is related to the impedance of free space and roughly matches the internal resistance. The associated current would then be about 10^{18} A, and the power dissipated in the load—ultimately appearing as photons—would be about 10^{38} W. This current could provide a natural power supply for the nonthermal activity and the jets that distinguish many black hole sources.

Another important recent development has been the realization that black hole accretion can be quite inefficient. The Galactic center provides a striking example. Working from estimates of the density and temperature of the gas close to the Galactic center's black hole, the rate at which material settles onto the black hole could be as small as 10^{19} kg/s. The total power radiated by the accreting gas is no more than 10^{29} W. Although there is some uncertainty in both these estimates, the efficiency of conversion of mass into energy appears to be about 10^{10} J/kg or $10^{-7}c^2$. This represents one-millionth of the fiducial efficiency of accretion onto a black hole and about 10^{-4} of the efficiency of nuclear reactions—hardly an advertisement for gravity power!

There are at least two ways to account for this low efficiency. The first is that the gas falls very rapidly onto the hole and simply does not have time to radiate. This idea, called an advection-dominated accretion flow, has been developed in recent years by Ramesh Narayan and his colleagues (see PHYSICS TODAY, April 1997, page 20). An alternative explanation is that the gas accretes onto the black hole in such a way that the binding energy released by the gas close to the black hole is transported out through the disk by viscous torque and drives an outflow from large radius in such a manner that the amount of gas reaching the hole is only a small fraction of that supplied at large radius.

For simplicity's sake, theorists have often chosen to idealize accretion flows as steady. However, they have always known that the flows are quite variable. Indeed, accretion disks are host to a variety of instabilities that can operate on many timescales. It is possible to understand the quasiperiodic variation in GRS 1915 + 105 and similar sources in these terms, although it is still not clear which instabilities are responsible.

Testing general relativity

Our claim to understand the spacetime geometry around a black hole depends on general relativity being the true, classical theory of gravity. Perhaps the greatest challenge to black hole astrophysics is to provide a clean, quantitative test of the theory of relativity in this domain.

Over the past year, some of the observed quasiperiodic variability in black holes has been attributed to a peculiarly relativistic effect first described in 1918 by Hans Lense and Joseph Thirring. Called inertial frame dragging, this effect induces a gravitational precession of the accretion disk and might be related to the apparent precessional motion seen in many extragalactic and Galactic sources, such as SS433. However, there are alternative explanations for these variations and we should defer regarding precession as a quantitative test of general relativity, although it may become one when we get a better understanding of gas flow around the hole.

Looking far into the future, a most compelling test of general relativity is the promise of a phenomenon that is believed to happen quite often in the universe—the merg-

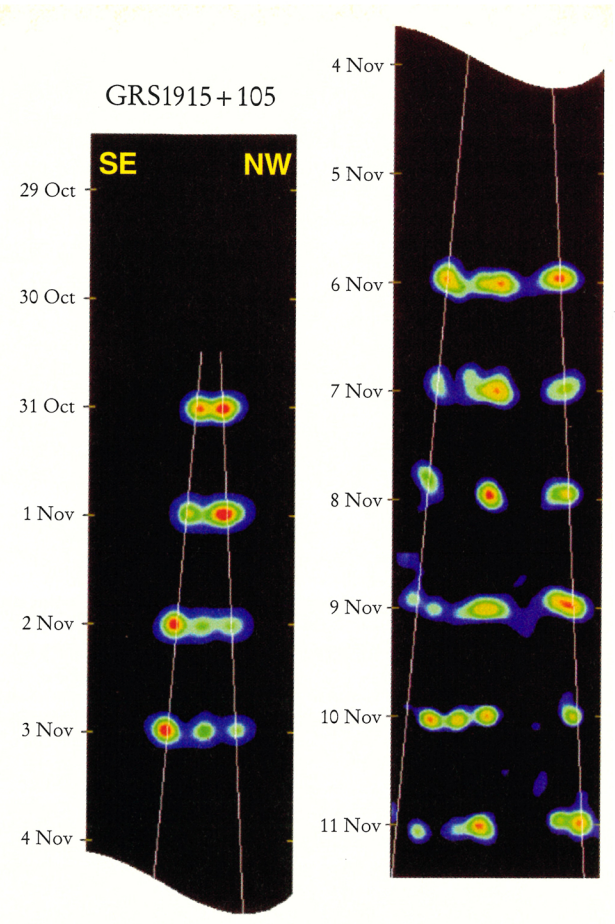


FIGURE 4. RADIO JET MAP of GRS 1915 + 105. This time history of the radio-emitting material ejected in the autumn of 1997 from the center of GRS 1915 + 105 reveals the source to be a microquasar—a small-scale Galactic version of an active galactic nucleus complete with a relativistic jets, which appear to traverse the sky faster than the speed of light. The observations were made by the Multi-Element Radio Linked Interferometer Network (MERLIN), an array of radio telescopes in the UK. (Illustration courtesy of Rob Fender, University of Amsterdam.)

ing of two black holes, which occurs most often when two galaxies collide. The final cataclysm is accompanied by a powerful burst of gravitational radiation, lasting from minutes to hours and so intense that it can be detected on Earth—even when the sources are cosmologically distant. At present, computing the profile of this gravitational pulse turns out to be a formidable problem in numerical general relativity, but if theory and observation can ever be brought to a satisfactory state, the result would provide an impressively powerful test of Albert Einstein's theory.

How to image a black hole

Much of the appeal of contemporary astronomy, felt by the general public and professional astrophysicists alike, stems from the power of the images that modern telescopes can produce. Revealing worlds undreamt of in anyone's philosophy, the images often provide the firmest evidence for settling the claims of competing astrophysical theories.

However, black holes, being small, cannot be imaged directly. We therefore have to make use of indirect techniques to try to understand the flow of gas near an event horizon. Such an approach is not so unusual. The seismologist, the scanner of magnetic resonance images—even the observational cosmologist—all have to analyze enormous multidimensional data sets before they can measure the three-dimensional structure of their respective targets.

Since we cannot make a big enough telescope to resolve a black hole directly, we must be cunning and use spectroscopy, time variability, and imaging of structures on scales much larger than the size of the black hole if we want to figure out how gas flows into a black hole, why black holes operate with such impressive radiative efficiency (despite the inefficiency of accretion), and how jets are actually launched and collimated.

Fortunately, in conjunction with the rapid advances we are currently making in our understanding of black hole astrophysics, matching technological advances are now being developed. Among the technologies of high promise are the following:

▷ Nested thin-shell mirrors that provide much larger collecting areas for x-ray astronomy.

▷ Multilayer reflecting surfaces that make possible large, focusing, hard x-ray telescopes.

▷ Gamma-ray instrumentation—based on advances in solid-state gamma-ray detection drawn from particle physics—that is over 30 times more sensitive than CGRO and that can observe a large fraction of the sky simultaneously.

▷ Space-based very long baseline radio astronomy that will improve angular resolution tenfold—maybe even a hundredfold—over the current Earth-based systems, which are limited to angular resolutions of order the ratio of the wavelength to Earth's diameter—that is, about 100 microarcseconds, which corresponds to a few light years in distant sources. Such space-based observatories are

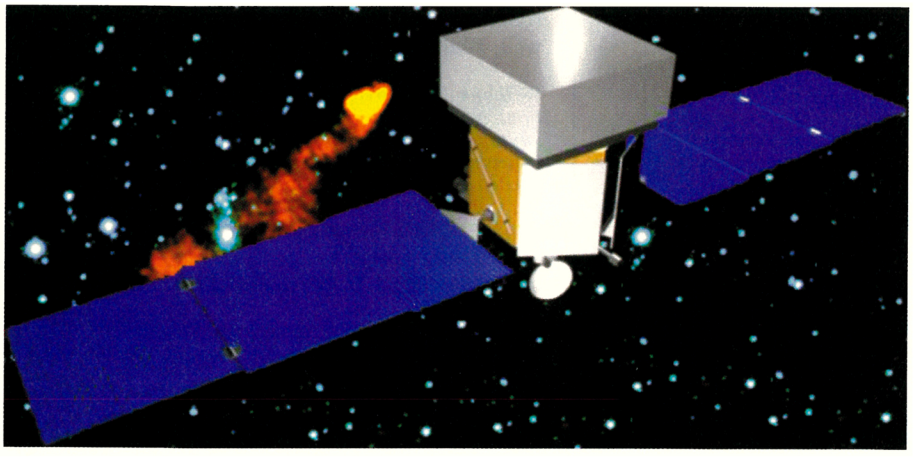


FIGURE 5. ARTIST'S CONCEPTION of the GLAST mission, whose large-area gamma-ray instrument is shown as the gray box mounted on the spacecraft. GLAST will observe sites of particle acceleration in the universe, such as jets from black holes. In the background, is a radio image of jets from the active galaxy PKS 2356 – 61 obtained by the Australia National Telescope Facility. (Radio image courtesy and copyright of A. M. Koekemoer, R. T. Schilizzi, G. V. Bicknell, and R. D. Ekerscredit.)

Box 3: Future Space Missions to Study Black Holes

The missions listed here will provide more and better information on a larger sample of black holes than their predecessors. (Several of the later missions are in the planning stages and are not fully funded for flight.)

▷ **Chandra** (formerly AXAF, or the Advanced X-Ray Astrophysics Facility). X-ray imaging mission. Launch date: 1999.

▷ **XMM** (X-Ray Multimirror Mission). X-ray spectroscopy mission. Launch date: 2000.

▷ **Astro-E.** X-ray spectroscopy mission. Launch date: 2000.

▷ **GP-B** (Gravity Probe B). Orbiting gyroscope mission to test general relativity. Launch date: 2000.

▷ **INTEGRAL** (International Gamma-Ray Astrophysics Laboratory). Gamma-Ray mission. Launch date: 2001.

▷ **Spectrum X.** X-ray and gamma-ray mission. Launch date: 2003.

▷ **GLAST** (Gamma-Ray Large Area Space Telescope). High-energy gamma-ray mission. Launch date: 2005. (See figure 5 on page 45.)

▷ **SIM** (Space Interferometer Mission). Optical interferometry mission. Launch date: 2005.

▷ **Constellation X.** X-ray spectroscopy mission. Launch date: 2007.

▷ **NGST** (Next Generation Space Telescope). Large infrared telescope. Launch date: 2007.

▷ **ARISE** (Advanced Radio Interferometry between Space and Earth). Future radio interferometry mission.

▷ **LISA** (Laser Interferometer Space Array). Future gravitational wave mission

▷ **OWL** (short for Orbiting Wide-Angle Light Collectors). Future high-energy cosmic ray mission.

▷ **XEUS** (X-ray mission for Evolving Universe Spectroscopy). Future large-aperture x-ray spectroscopy mission under study.

already a reality, as demonstrated by the Japanese orbiting radio telescope, HALCA (see PHYSICS TODAY, September 1997, page 23).

Ambitious plans are currently being hatched in the US, Europe, and Japan for a new generation of orbiting telescopes that will harness these technologies and be capable of assembling just the sort of picture we have described. (See box 3 above.) Detailed studies of Galactic and extragalactic black holes will become possible over an incredibly large energy range. Photons will not be the only diagnostics of black hole environments, however. Gravitational waves and cosmic-ray particles will contribute as well. Black hole astrophysics has a bright future.

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Further reading

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