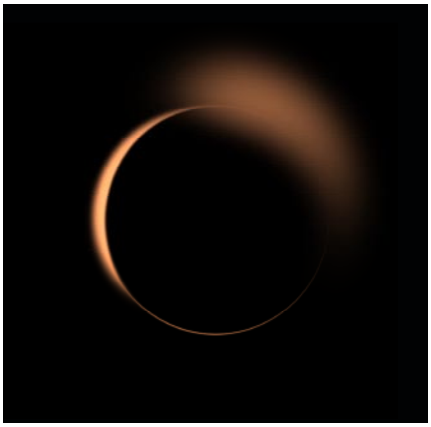
Portrait of a BLACK HOLE

By Avery E. Broderick and Abraham Loeb



By adapting a global network of telescopes, astronomers will soon get their first look ever at the dark silhouette of a black hole

You have probably seen the TV commercial in which a cell phone technician travels to remote places and asks on his phone, "Can you hear me now?" Imagine this technician traveling to the center of our Milky Way galaxy, wherein lurks a massive black hole, Sagittarius A* (Sgr A*), weighing as much as 4.5 million suns. As the technician approached within 10 million kilometers of the black hole, we would hear his cadence slow down and his voice deepen and fade, eventually turning to a monotone whisper with diminishing reception. If we were to look, we would see his image turn increasingly red and dim as he became frozen in time near the black hole's boundary, known as the event horizon.

The technician himself, however, would experience no slowing of time and would see nothing strange at the location of the event horizon. He would know he had crossed the horizon only when he heard us say, "No, we cannot hear you very well!" He would have no way of sharing his last impressions with us—nothing, not even light, can escape from gravity's extreme pull inside the event horizon. A minute after he crossed the horizon, the gravitational forces deep inside the hole would tear him apart.

In real life we cannot send a technician on such a journey. But astronomers have developed techniques that will soon allow them, for the first time, to produce images of a black hole's dark silhouette against a backdrop of hot glowing gas.

Wait, you say. Haven't astronomers reported lots of observations of black holes, including all sorts of pictures? That is true, but the pictures have been of gas or other material near a black hole, with the hole itself an invisible speck, or of huge outpourings of energy presumed to come from a black hole. In fact, we do not even know for sure whether black holes really exist [see "Black Stars, Not Holes," by Carlos Barceló, Stefano Liberati, Sebastiano Sonego and Matt Visser; SCIENTIFIC AMERICAN, October].

Astronomers have detected objects in the sky that are sufficiently massive and compact that, if Einstein's general theory of relativity is correct, they must be black holes, and it is customary to talk of them as if they were (as we do in this article). But until now we could not tell if these objects had the defining characteristic of a black hole—a horizon through which material can flow only one way. This question is not merely a matter of esoteric curiosity, because such horizons are at the heart of one of the deepest puzzles in theoretical physics. And images showing the dark silhouettes of black holes' event horizons would help us understand the extraordinary astrophysical processes taking place in their neighborhood.

Driving Questions

Event horizons are a source of fascination because they represent a fundamental inconsistency between two great triumphs of 20th-century physics: quantum mechanics and general relativity. Time reversibility is an essential fea-

MENACINGLY DARK DISK of the Milky Way galaxy's central black hole and hot gas caught in its gravity could look like these computer simulations (*left*) when a network of radio telescopes begins observing next year. Interstellar gas will, however, blur the finer details (*above*).

COURTESY OF AVERY E. BRODERICK

KEY CONCEPTS

- Black holes are among the most mysterious objects in the universe. So far astronomers have observed them only indirectly, from their gravitational effects on stars and from the radiation emitted by hot gas spiraling toward them.
- Astronomers are adapting a network of radio telescopes to produce images of the supermassive black holes that lie at the center of the Milky Way and M87 galaxies.
- Better studies of black holes not only would help explain unusual phenomena produced by the holes but also could test Einstein's theory of general relativity and provide vital insights into the nature of gravity in extreme situations.

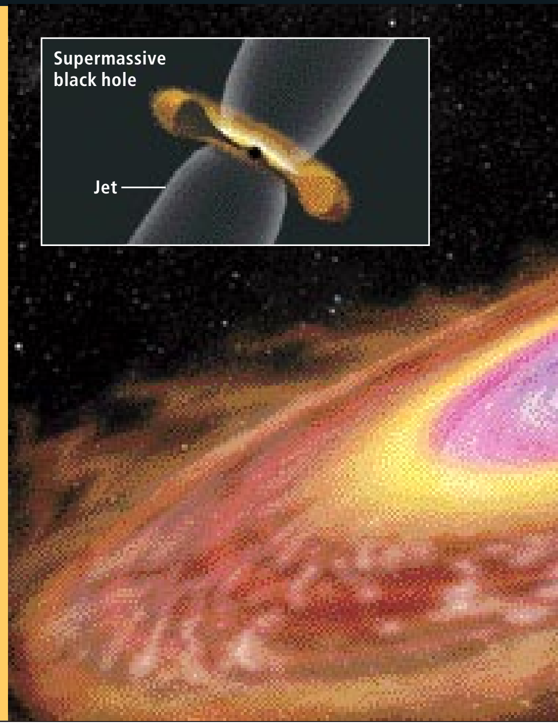
—The Editors

[BASICS]

LAIR OF A MONSTER

A black hole's defining feature is its event horizon, a sphere in space within which nothing can overcome the black hole's gravity and emerge. Gas, dust and other matter accrete in a hot, luminous disk orbiting the black hole. Transitory bright spots may appear in the disk, similar to solar flares. Many supermassive black holes emit bright jets of material at almost the speed of light.

The accretion disk's inner edge is believed to be near a circle called the innermost stable circular orbit (ISCO). Any matter that strays closer to the hole than the ISCO will find itself in an unstable orbit and will quickly plunge into the hole. At the photon orbit, light could in principle circle the black hole in a permanent orbit. In practice, however, the photon orbit is also unstable—the tiniest disturbance would send the light spiraling in or out.



ture of the quantum-mechanical description of physical systems; every quantum process has an inverse process, which may be used, in principle, to recover any information that the original process may have scrambled. In contrast, general relativity—which explains gravity as arising from the curvature of space and predicts the existence of black holes—admits no inverse process to bring back something that has fallen into a black hole. The need to resolve this inconsistency between quantum mechanics and gravitation has been one of string theorists' primary motivations in their quest for a quantum theory of gravity—a theory that would predict the properties of gravitation as arising from interactions following the laws of quantum mechanics.

On a more basic level, physicists would like to know if Einstein's general relativity really is *the* theory of gravity, even where it predicts shocking deviations from classical, Newtonian theory—such as the existence of event horizons. Black holes have the twin virtues of corresponding to extraordinarily simple solutions to Einstein's equations of gravity (a black hole is completely characterized by just three numbers—its mass, charge and spin), as well as being places where gravity differs the most from Newtonian theory. Thus, black holes are prime locations for seeking evidence of deviations from Einstein's equations under extreme conditions, which could provide clues toward a quantum theory of gravity. Conversely, the equations' success near black holes will dramatically extend the regime in which we know general relativity works.

Pressing astrophysical questions about what happens in the vicinity of black holes also demand answers. Black holes are fed by infalling material such as gas and dust. The matter gains vast quantities of energy as it falls closer to the hole's horizon, producing heat 20 times more efficiently than nuclear fusion, the next most potent energy generator known. Radiation from the hot, spiraling gas makes the environment near black holes the brightest objects in the universe.

Astrophysicists can model the accreting material to some extent, but it is unclear how gas in the accretion flow migrates from an orbit at a large radius to one near the horizon and how, precisely, it finally falls into the black hole. Magnetic fields, created by charged particles moving in the accretion flow, must play a very important role in how the flow behaves. Yet we know little about how these fields are structured and how that structure affects black holes' observed properties. Although computer simulations of the entire accreting region are becoming feasible, we theorists remain decades away from true ab initio calculations—input from observations will be vital for inspiring new ideas and deciding among competing models.

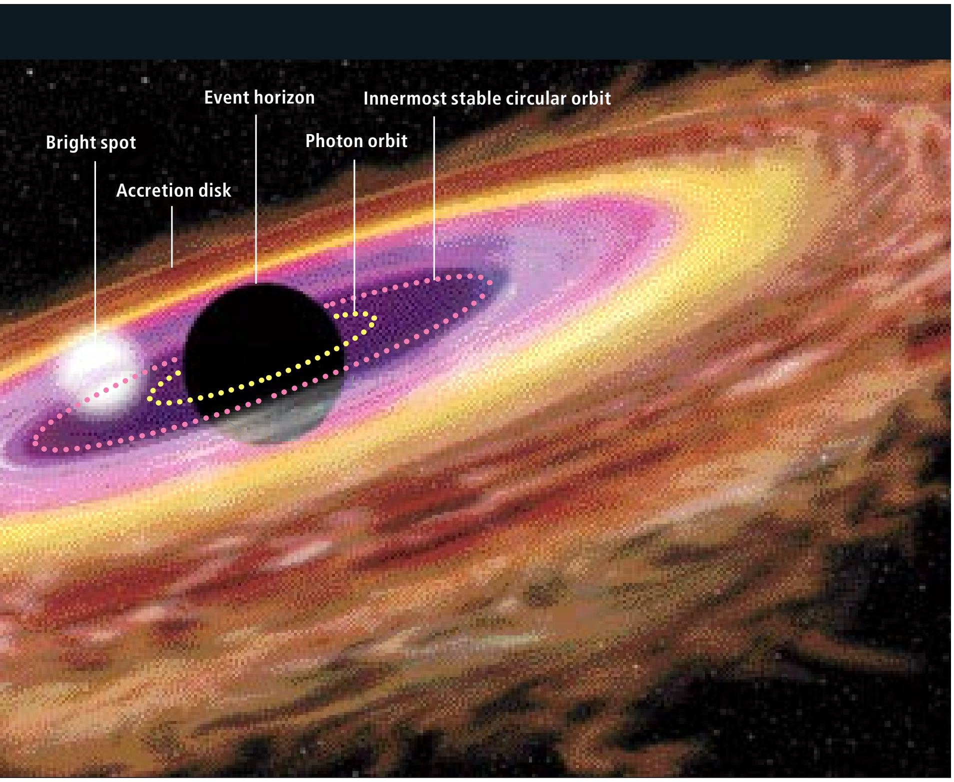
More embarrassing to astrophysicists is our lack of understanding of black hole jets—phenomena in which the forces near a supermassive black hole somehow conspire to spew out material at ultrarelativistic speeds (up to 99.98 percent of light speed). These amazing outflows traverse distances larger than galaxies, yet they originate near the black hole as intense beams collimated tightly enough that they could thread the solar system—the eye of a galactic needle. We do not know what accelerates these jets to such high speeds or even what the jets are made of—are they electrons and protons or electrons and positrons, or are they primarily electromagnetic fields? To answer these and other questions, astronomers desperately need direct observations of the gas in a black hole's vicinity.

Black holes are prime locations for seeking evidence of deviations from Einstein's equations of general relativity under extreme conditons.

Stalking the Behemoth from Afar

Unfortunately, such observations are difficult for several reasons. First, black holes are extremely small by any astronomical measure. They appear to come in two main varieties: stellar-mass black holes, the remnants of dead massive stars, with typical masses of five to 15 suns,

DON DIXON



and supermassive black holes, located at the centers of galaxies and weighing millions to 10 billion suns. A 15-solar-mass black hole's event horizon would be a mere 90 kilometers in diameter—far too tiny to be resolved at interstellar distances. Even a one-billion-sun monster would fit comfortably inside Neptune's orbit.

Second, a black hole's small size and intense gravity make for extremely fast motion—matter very near a stellar-mass black hole can complete an orbit in less than a microsecond. It takes highly sensitive instruments to observe such rapid phenomena. Finally, only the small subset of black holes that have large reservoirs of nearby gas to accrete are visible at all; the vast majority of black holes in the Milky Way are, as yet, undiscovered.

Rising to these challenges, astronomers have developed a variety of techniques that, short of providing direct images, have provided information about the properties and behavior of matter orbiting close to suspected black holes. For instance, astronomers can weigh a supermassive black hole by observing stars near it, much like using planets' orbits to weigh the sun. In distant galaxies, individual stars near a supermassive hole cannot be resolved, but the spectrum of their light indicates their distribution of velocities, which yields a mass for the hole. The supermassive black hole Sgr A* at the center of the Milky Way is close enough for telescopes to resolve individual stars near it, producing the best mass estimate of any black hole to date [*see box on page 37*]. Unfortunately, these stars are far outside the region that interests us most, where general relativistic effects become significant.

Astronomers also search for signatures of general relativity in the way that radiation emitted near a black hole varies over time. For example, the x-ray emissions of some stellar-mass black holes fluctuate in luminosity in a nearly periodic manner with periods similar to that of orbits expected to be near the inner edge of the accretion disk.

Thus far the most fruitful avenue for probing supermassive black holes has exploited the fluorescence of iron atoms on the surface of the accretion disk. The fast motion of the accretion disk carrying the iron atoms and the strong gravity of the hole combine to shift the characteristic wavelength of the fluorescence and spreads it over a band of wavelengths. Near a rapidly spinning black hole, the accretion disk itself orbits the hole faster (thanks to a general relativistic effect that drags space around with the hole's rotation), and the emission will have a telltale asymmetry. The Japanese satellites ASCA and Suzaku have observed just such emissions, which astronomers interpret as direct evidence of rapidly spinning black holes, with orbital velocities as high as one third of light speed in the accretion disks.

Information about how much spin stellar-mass black holes have has come from binary systems in which a black hole and an ordinary star orbit each other close enough for the hole to slowly feed on its companion. Analysis of the x-ray spectra and orbital parameters for a handful of such systems indicates that the holes have 65 to 100 percent of the maximum spin permitted by general relativity for a hole of a given mass; very high spin seems to be the norm.

Light (ranging from radio waves to x-rays) and energetic jets are not the only things emitted by black holes. When two black holes collide, they shake the fabric of spacetime around them, producing gravitational waves that propagate out like ripples on a pond. These ripples of spacetime should be detectable at vast distances, albeit requiring incredibly sensitive instruments. Although observatories already operating have yet to detect any, gravitational waves, the method offers a revolutionary new way to study black holes. [see "Ripples in Spacetime," by W. Wayt Gibbs; Scientific American, April 2002].

[THE AUTHORS]

Avery E. Broderick and **Abraham Loeb** began collaborating in 2005 at the Institute for Theory and Computation, which Loeb now directs, at the Harvard-Smithsonian Center for Astrophysics. Broderick is currently a senior research associate at the Canadian Institute for Theoretical Astrophysics at the University of Toronto. He has been a leader in pushing for horizon-resolving imaging of supermassive black holes. Loeb is professor of astronomy at Harvard University and visiting professor at the Weizmann Institute of Science in Rehovot, Israel. He has conducted pioneering theoretical studies of the first stars, supermassive black holes and gamma-ray bursts.

COURTESY OF ALYSSA BRODERICK (*Broderick*); PUBLIC AFFAIRS OFFICE OF THE HARVARD-SMITHSONIAN CENTER FOR ASTROPHYSICS (*Loeb*)

A Window with a View

None of the observations we have described thus far, however, offer an image of a black hole's event horizon. Now, thanks to very recent advances in technology, direct imaging of a black hole's horizon is imminent. The black hole to be imaged is the behemoth in our backyard, Sgr A*. At a distance of only 24,000 light-years, Sgr A* occupies the largest disk on the sky of any known black hole. A 10-solar-mass black hole would have to be 1/100th as far away as the nearest star to appear as big. And although supermassive black holes much larger than Sgr A* exist, they are millions of light years away.

The dark silhouette of a distant black hole is more than doubled in apparent size thanks to the bending of light rays by the hole's gravity. Even so, Sgr A*'s horizon will appear to span a mere 55 microarcseconds—as small as a poppy seed in Los Angeles viewed from New York City.

The resolution of all modern telescopes, as impressive as they are, is fundamentally limited by diffraction, a wave-optics effect that occurs as light passes through the finite aperture presented by the size of the telescope. Generally, the smallest angular scale resolvable by a telescope can be decreased by making the telescope larger or by capturing shorter wavelength light. At infrared wavelengths (which, conveniently, pass through dust clouds that hide Sgr A* at visible wavelengths), an angular scale of 55 microarcseconds would require a telescope seven kilometers across. The shorter wavelengths of visible or ultraviolet light would somewhat reduce this gargantuan requirement but not by enough to be any less ridiculous. Considering longer wavelengths might seem pointless—millimeter radio waves, for instance, would require a telescope 5,000 kilometers across. But it just so happens that Earth-size radio telescopes are already operating.

A technique called very long baseline interferometry (VLBI) combines the signals detected by an array of radio telescopes sprinkled around the globe to achieve the angular resolutions that an Earth-size radio dish would achieve. Two such arrays of telescopes have been operating for more than a decade—the Very Long Baseline Array (VLBA), with dishes in the U.S. as far afield as Hawaii and New Hampshire, and the European VLBI Network (EVN), with dishes in China, South Africa and Puerto Rico, as well as Europe. You may remember seeing a much smaller system, the Very Large Array in New Mexico, in movies such as *Contact* and *2010*.

Unfortunately, the VLBA and EVN are suitable only for radio wavelengths above 3.5 millimeters, corresponding to resolutions of at best 100 microarcseconds, too large to resolve Sgr A*'s horizon. Moreover, at these wavelengths, interstellar gas blurs the image of Sgr A*, just as dense fog blurs the streetlights overhead. The solution is to implement an interferometer at shorter wavelengths of millimeters and below.

These shorter wavelengths, however, suffer yet another problem: absorption by atmospheric water vapor. For this reason, millimeter and submillimeter telescopes are placed at the highest, driest sites available, such as atop Mauna Kea in Hawaii, in the Atacama Desert in Chile, and in Antarctica. When all is said and done, two useful windows generally remain open, at 1.3 millimeters and at 0.87 millimeter. An Earth-size array at these wavelengths would provide resolutions of about 26 and 17 microarcseconds, respectively, good enough to resolve the horizon of Sgr A*.

A number of millimeter and submillimeter telescopes that could be incorporated in such an array already exist—in Hawaii, scattered throughout the southwestern U.S., and in Chile, Mexico and Europe. Because astronomers built these telescopes for other purposes, adapting them for VLBI involves many technological challenges, including development of extraordinarily low-noise electronics and ultrahigh bandwidth digital recorders.

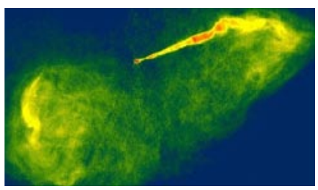
Nevertheless, a collaboration led by Sheperd S. Doeleman of the Massachusetts Institute of Technology solved these problems in 2008. The group studied Sgr A* at 1.3-millimeter wavelengths with an array of just three telescopes, in Arizona, California and on Mauna Kea. Such a small number of telescopes is insufficient to generate an image, but the researchers successfully resolved Sgr A* in that their data indicated that it had bright regions only 37 microarcseconds in size, two thirds of the horizon's size. Additional telescopes should make it possible to produce images of the event horizon's dark silhouette.

Already the recent millimeter-VLBI observations make it exceedingly difficult for Sgr A* not to have a horizon. Accretion onto a black hole and onto horizonless objects differ in a fundamental way. In both cases the accreting material accrues vast amounts of energy during its infall. In the absence of a horizon, this energy is converted to heat where the accreting material finally settles and is subsequently emitted as radiation, producing a characteristic thermal spectrum visible to outside observers. In contrast, for black holes, infalling material can carry any amount of ener-

DISTANT SIGNS OF BLACK HOLES

Astrophysicists believe that black holes—too small and far away to be seen—are responsible for phenomena ranging from x-ray emissions to huge jets of material ejected from galaxy centers.

Centaurus A galaxy imaged in x-rays by the Chandra satellite shows a 13,000-light-year jet emitted by its suspected supermassive black hole. Starlike spots are stellar-mass holes consuming matter from companion stars. Red, green and blue indicate three bands of x-ray wavelengths.



Supermassive black hole presumed to be at the center of the M87 galaxy is surrounded by lobes of gas about 15,000 light-years across and shoots an ultrarelativistic jet toward us. An unseen counterjet may be sending material in the opposite direction. The Very Large Array in New Mexico took this image at two-centimeter radio wavelengths. The colors represent intensity of the signal.

SCIENCE SOURCE (*Centaurus A*); NATIONAL RADIO ASTRONOMY OBSERVATORY/NATIONAL SCIENCE FOUNDATION (*M87*) gy across the horizon, which will hide it forever.

For Sgr A*, we can use its total luminosity to estimate the infall rate of accreting material. The millimeter-VLBI observations place a tight limit on the maximum possible size of the accretion flow's inner edge and thus on how much energy has been liberated in the flow's fall to that point. If Sgr A* does *not* have a horizon (and so is not a black hole), the surplus energy must be radiated when the accreting material comes to rest, emitting primarily in the infrared. Despite careful observations, astronomers have not found any thermal infrared emission from Sgr A*. The only way to reconcile this discrepancy without a horizon is for the material to radiate away all the excess energy as it plummets inward, but that would require absurdly high radiative efficiencies.

Portrait of a Monster

We, among other theorists, have been very busy trying to predict what observers might see when VLBI produces images of Sgr A* in the next few years. Generically, a black hole casts a silhouette on the wallpaper of emissions by nearby accreting gas. This "shadow" arises because light rays from along that line of sight come only from the accretion in front of the black hole. Meanwhile the bright region around the "shadow" is supplemented by emission from behind the black hole, carried by light waves that just miss the horizon. Strong gravitational lensing bends light rays so that even material directly behind the black hole will contribute to the light around the dark region. The resulting silhouette is what is meant by a "portrait of a black hole," a fitting picture in which the black hole truly is black.

This shadow will not be a circular disk, primarily because of the extreme orbital velocities of the gas, which approach the speed of light. The emission from such fast-moving matter will be Doppler shifted and concentrated in a narrow cone in the direction of motion, which substantially brightens the emission from the approaching side of the orbiting gas and dims the receding side, producing a bright crescent instead of a full, bright ring around a disklike silhouette. This asymmetry disappears only if we happen to be looking along the disk's axis of rotation.

The spin of the black hole itself, which may have a different axis of rotation than the accretion disk, has a similar effect. Such images will therefore allow astronomers to determine the direction of the black hole spin and the inclination of the accretion disk relative to it. Equally important for astrophysics, the data will provide invaluable observational input into accretion theory, settling once and for all the gas's density and the geometry of the accretion flow's inner edge.

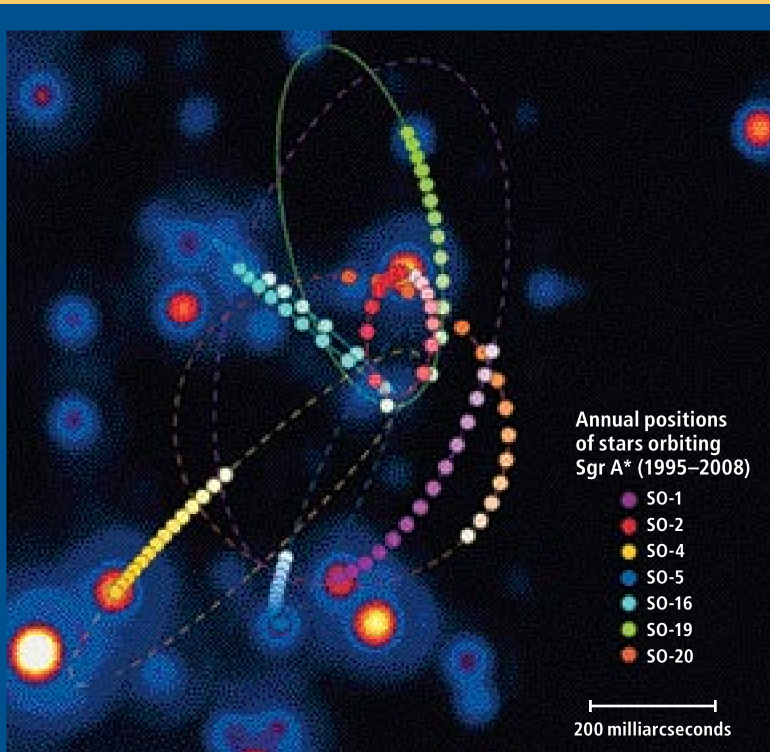
Sgr A* is the only supermassive hole close enough that telescopes can resolve the individual stars nearest to it.

Other supermassive black holes should also be within range of VLBI and can be compared with Sgr A*. We recently showed that the second-best target is the black hole believed to lie at the center of the giant elliptical galaxy M87. This black hole is 55 million light-years distant, and until recently astronomers' standard estimate of its mass was about three billion suns, giving it an expected silhouette somewhat less than half the size of Sgr A*'s. In June of this year, however, Karl Gebhardt of the University of Texas at Austin and Jens Thomas of the Max Planck Institute for Extraterrestrial Physics in Garching, Germany, used the most recent data and updated models of M87's distribution of stars and dark matter to determine a black hole mass of 6.4 billion suns—enough to make its silhouette about three-

[SAGITTARIUS A*]

CLOSING IN ON THE GIANT

Until recently, observations such as measurements of the motions of stars near the Milky Way's center have been the closest that astronomers have come to observing the event horizon of the black hole Sgr A*. The stars' orbits (*dashed lines*) reveal that they are in the thrall of a very compact object with a mass of 4.5 million suns. Colored dots mark the stars' positions each year from 1995 to 2008. The background is a 2008 infrared image of the stars (and others). The star S0-16 comes closest to Sgr A*—within seven light-hours—but even that distance remains 600 times larger than the event horizon's radius.



ANDREA GHEZ *U.C.L.A. Galactic Center Group;* DATA SETS OBTAINED WITH THE W. M. KECK TELESCOPES

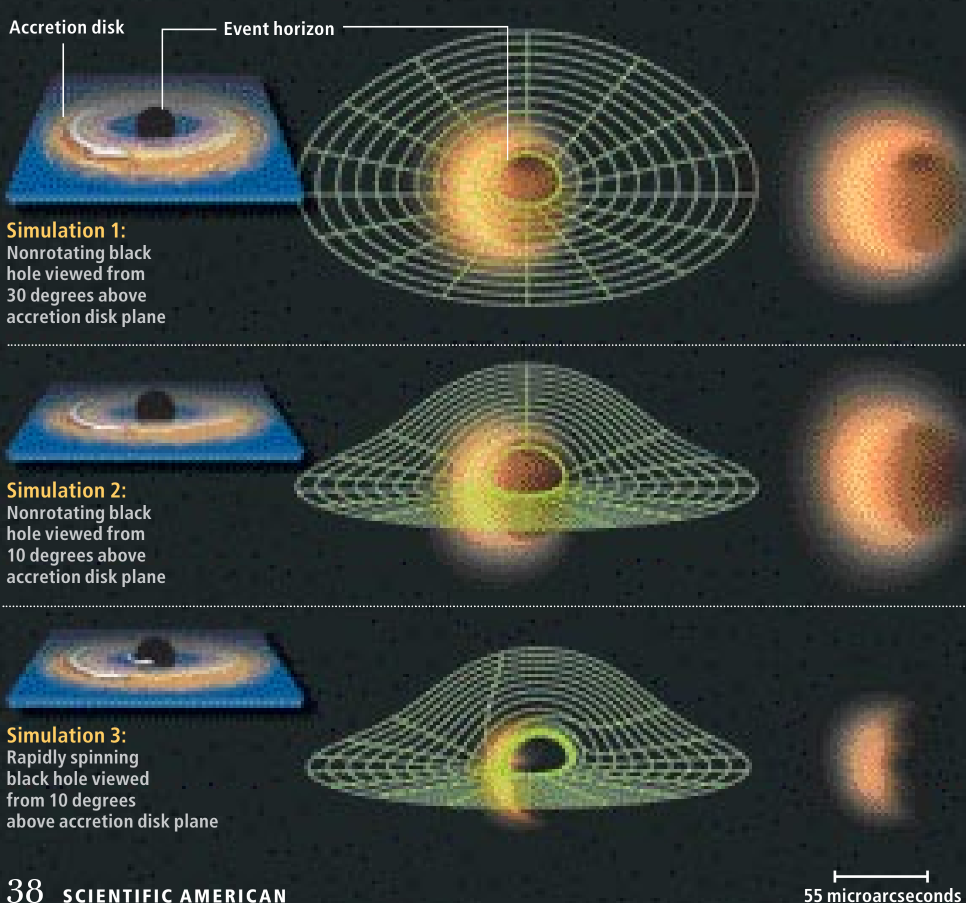
[IMAGING]

Shooting the Beast

Astronomers are developing several radio telescope arrays to form a globe-spanning network of observatories (*right*) that can observe Sgr A* and its immediate surroundings at wavelengths near 0.87 and 1.3 millimeters—two "windows" that are not excessively absorbed by Earth's atmosphere or scattered by interstellar gas. The size of the network will permit observations with sufficient resolution to produce images of Sgr A*'s event horizon.

The appearance of Sgr A* should reveal information about the orientation of the black hole's accretion disk along our line of sight and how fast the black hole is spinning—two of the most basic facts to be learned about the Sgr A* system and vital for understanding whatever else is observed about it (*below*). On occasions when a bright spot flares up in the accretion disk, gravitational lensing by the black hole will form multiple subimages of the spot (*opposite page*). If these subimages can be resolved, they will provide detailed information about the gravitational field near the black hole, which will stringently test the predictions of general relativity.

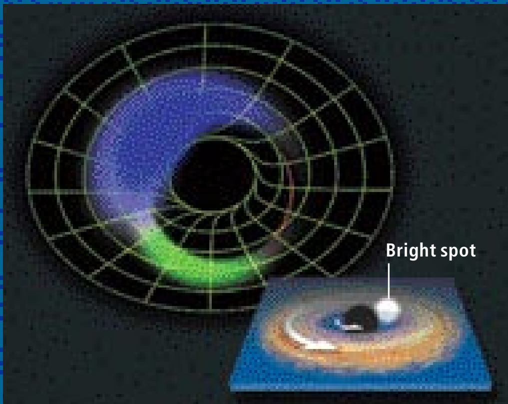
COLLECTING DATA
The Combined Array for Research in Millimeter-Wave Astronomy (CARMA; *above*), located at Cedar Flat, Calif., is one of several radio telescope arrays astronomers are developing to observe Sgr A*'s event horizon. A network of such observatories (*left*) separated by baselines thousands of kilometers long (*lines*) can exploit a technique called very long baseline interferometry to produce images with resolutions as fine as those that would be possible with a radio dish the size of Earth. Four arrays (*green*) are ready to be used together, two (*pink*) are under development, and the last (*blue*) needs only to be adapted for observations at submillimeter wavelengths.



WHAT THE SILHOUETTE CAN REVEAL
Simulations show how an accretion disk around Sgr A* would appear depending on the orientation of its accretion disk and the magnitude of its spin. The rightmost trio of images includes the blurring effects of interstellar gas.

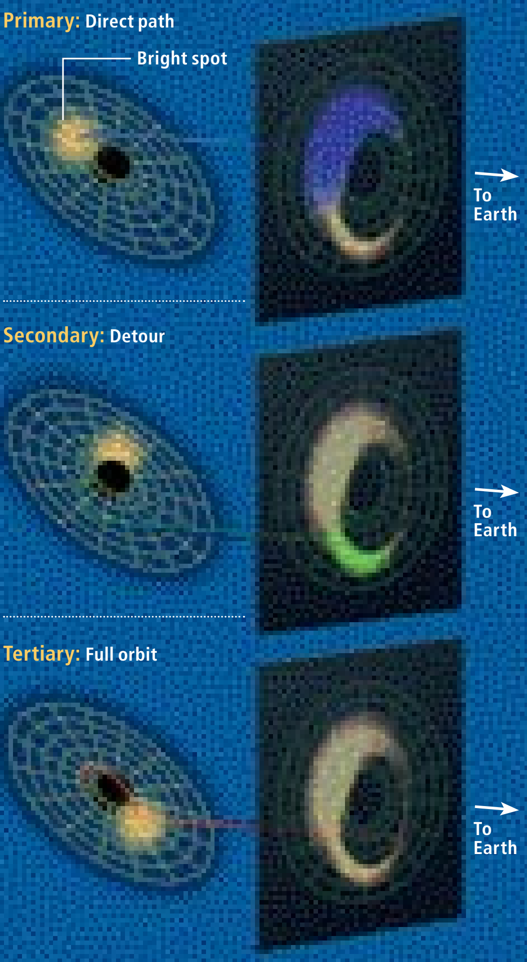
The green coordinate grid is in the plane of the accretion disk, centered on the black hole. The grid's innermost ring is at the black hole's event horizon. Bending of light rays by the hole's gravity, known as gravitational lensing, distorts the grid's appearance and also magnifies the hole's silhouette. Because the accretion disk orbits the hole at velocities approaching the speed of light, special relativistic effects come into play, making it much brighter on the side moving toward us (*here, on left of hole*). In the bottom image, the black hole's large, angular momentum causes additional deflection of light, further distorting our view of the equatorial plane and dramatically changing the appearance of the accreting gas.

Thus, comparing images of Sgr A* with simulations can reveal the system's orientation and the black hole's spin and can also provide—from the silhouette's size—a new measurement of the hole's mass.



MEASURING GRAVITY WITH LENSED IMAGES
Astronomers can measure gravity very near a black hole by analyzing multiple subimages (produced by gravitational lensing) of a bright spot in an accretion disk. Shown above is a simulated image of a bright spot near a moderately rotating black hole, colored to mark its three constituent subimages, which are explained below.

The primary image (*blue region*) forms from radio waves that traveled from the spot along the most direct path to Earth (*blue line*). Thanks to the hole's intense gravity, some rays the spot emitted earlier take a detour around the hole (*green line*) and reach Earth at the same time, forming the secondary subimage (*green region*). Rays that were emitted even earlier and execute a full orbit around the black hole (*red line*) generate the barely visible tertiary subimage (*red region*). Because the positions and shapes of the subimages depend on how gravity bends light in a variety of locations very close to the hole, analysis of the full image can reveal if general relativity correctly describes gravity there.



TOM LOWE *Timescapes.org* (CARMA); COURTESY OF AVERY E. BRODERICK (*computer simulations*); JEN CHRISTIANSEN (*illustrations*)

quarters the diameter of Sgr A*'s.

In many respects, M87 is a more interesting and promising target than Sgr A*. It has a vigorous jet that extends 5,000 light-years; resolving the jet-launching region will provide critical information for theorists' efforts to understand these ultrarelativistic outflows. Unlike Sgr A*, M87 lies in the Northern Hemisphere sky, making it more amenable to VLBI using existing observatories, relatively few of which are in the south. Furthermore, with the M87 black hole being 2,000 times the size of Sgr A*, dynamical changes will occur on timescales of days instead of minutes. The orbital period near the accretion disk's inner edge will be 0.5 to five weeks (depending on the black hole's spin). Obtaining sequences of images of unfolding events should be much easier with M87. Finally, high-resolution images will most likely suffer less blurring of the kind inflicted by interstellar gas between us and Sgr A*. To date, the best VLBI images of M87, taken at wavelengths of two to seven millimeters, have a resolution of about 100 microarcseconds, more than double the size of the expected silhouette.

For both Sgr A* and M87, an exciting prospect in the long run will be the possibility of imaging flare-ups that are seen in their emission from time to time. If some of these flares are caused by bright spots in the accretion flow, as most theorists expect, they can be exploited to map out the spacetime around the horizon in greater detail. The main image of each spot will be accompanied by additional images, corresponding to light rays that reach the observer by circuitous routes around the hole [*see box at left*]. The shapes and positions of these higher-order images encode the structure of the spacetime near the black hole. They will, in effect, provide independent measurements of that structure at the different locations traversed by each image's bundle of light rays. Taken together, this data will sternly test general relativity's predictions for the behavior of strong gravity near black holes.

Black hole observations are entering a new golden era. Almost a century after Einstein conceived of general relativity, we are finally in a position to test whether this theory correctly describes gravity in the extreme environments of black holes. Direct imaging of black holes will provide a new test bed for comparing Einstein's theory with its alternatives. When images of Sgr A* and M87 become available, we will be able to investigate the spacetime near black holes in detail, without sacrificing cell phone technicians. ■

Thanks to gravitational lensing, even material directly behind the black hole will contribute to the light around the silhouette.

➥ MORE TO EXPLORE

Event-Horizon-Scale Structure in the Supermassive Black Hole Candidate at the Galactic Centre. Sheperd S. Doeleman et al. in *Nature*, Vol. 455, pages 78–80; September 4, 2008.

Imaging the Black Hole Silhouette of M87: Implications for Jet Formation and Black Hole Spin. Avery E. Broderick and Abraham Loeb in *Astrophysical Journal*, Vol. 697, pages 1164–1179; June 1, 2009.

The Event Horizon of Sagittarius A*. Avery E. Broderick, Abraham Loeb and Ramesh Narayan in *Astrophysical Journal*, Vol. 701, pages 1357–1366; August 20, 2009.

Imaging an Event Horizon: Submm-VLBI of a Super Massive Black Hole. Sheperd S. Doeleman et al. in *ASTRO2010 Decadal Review*. Available at **arxiv.org/abs/0906.3899**

Inside Black Holes. Andrew J. S. Hamilton. Includes animations of descent into a black hole. Online at **http://jilawww.colorado.edu/~ajsh/insidebh**

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