Visions of Black Holes

A menagerie of black holes—forming, colliding, evaporating—is romping though the minds and computers of theorists, testing their command of Einstein's theory and hinting at new physics

CHICAGO—When the talk is of black holes, everyone has a Chandra story. One of Kip Thorne's favorites comes from a cross-country drive he took in 1966 from Princeton University, where he had recently finished his graduate studies, to the California Institute of Technology, where he now specializes in general relativity. On the way, Thorne stopped at the University of Chicago to see the great astrophysicist Subrahmanyan Chandrasekhar—the man universally known as Chandra—who died two summers ago at the age of 84. Thorne says he drove out of his way simply because "I had a question for Chandra." Thorne was studying an exotic concept, remote from anything ever observed: black holes. He made his pilgrimage to ask whether he might be wasting his time.

Chandra had been in that situation himself. On a voyage from Bombay to England in 1930, he had realized that old, burnt-out white dwarf stars can't support themselves against gravity when they exceed 1.4 times the mass of the sun. Above what came to be called the Chandrasekhar limit, he declared, they collapse into denser and more exotic objects or blow apart completely. The idea met with disbelief at the time and even in 1966 had little observational support. "Chandra reassured me that [research on black holes was] at least as likely to make contact with observation as his white-dwarf work had been," recalls Thorne.

The advice was prescient. "Neutron stars were found a year later," says Thorne—compact balls of matter, billions of times denser than ordinary stars, that are one endpoint of stellar collapse. Their discovery not only vindicated Chandra's ideas; it primed astrophysicists to accept the even more drastic vision of gravitational collapse that Thorne and others were exploring. "It was Chandra who started things off," says Stephen Hawking.

Thirty years later, black-hole theorists are still following Chandra's example, as a conference* here showed: They are leaving present observations far behind as they create and study strange new beasts, confident that observers will eventually catch up. While the observational case for real black holes is firming up (see sidebar), theorists have already moved on to study the details of the holes' behavior. "There's an incredible level of activity," says Ed Seidel of the Albert Einstein Institute in Potsdam, Germany. Lately, theorists have conjured up donut-shaped black holes, discerned clues to a fundamental graininess of space-time in the properties of black holes, and—thanks to Hawking's latest brainstorm—contemplated the possibility that invisible black holes might be gobbling information right under our noses.


INDIAN ACADEMY OF SCIENCES

Showing the way. The late Subrahmanyan Chandrasekhar.

The exploding power of supercomputers is responsible for some of this frenzy, says Seidel. But the real spur is the intellectual challenge of trying to understand the purest creatures of general relativity, Einstein's theory representing gravity as curvature of space-time. In a black hole, that curvature is so extreme that it forms an "event horizon," from which light itself can't escape. To theorists trying to master the many-armed complexity of Einstein's equations, says Matthew Choptuik of the Center for Relativity at the University of Texas, Austin, understanding violent interactions between black holes is the ultimate test.

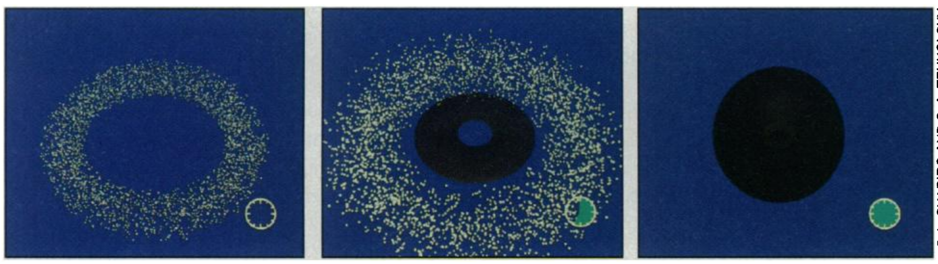
Hole in a hole

One current goal is to simulate the interactions of two spinning black holes as they orbit around each other, gradually spiraling in and coalescing while spraying out gravitational waves. Tracing the process will eventually take a trillion bytes of memory and a week of computation time on a machine hundreds of times faster than most of today's supercomputers, says Choptuik, but "it's a watershed problem for general relativity."

Even before computational physicists get close to wrapping up that problem, the exercise has yielded unexpected theoretical insights. A year ago, a team including Seidel and Saul Teukolsky of Cornell University published the solution to a simplified version—the head-on collision of two nonspinning black holes—and got their first close look at how two event horizons could merge into one (*Science*, 10 November 1995, p. 941).

The process can be visualized as a pair of pants stretched out in space-time, in which two "legs" merge at a "crotch." The legs show the history of the converging event horizons, which are themselves traced out by the space-time trajectories of light rays that don't quite fall into the black holes but can never escape. The puzzle is how the light rays converge at the crotch, where two separate event horizons become one. The computer model showed that the rules of space-time don't allow light on the inseam of the pants to ride up the crotch onto the new event horizon. Instead, the simulation showed, some of the light rays trapped on the new boundary arrive from someplace else in the universe, flashing onto the event horizon during collision.

Later, Teukolsky and Stuart Shapiro, of the University of Illinois, Urbana-Champaign, created what some mathematicians thought they had proved could not exist: a toroidal—or donut-shaped—black hole. Teukolsky and Shapiro did this by replacing the original "two-car collision" of black holes with an entire torus of collapsing matter, crashing inward like dozens of Renaults smashing together simultaneously in one of Paris's multistreet intersections. "We were unaware of these theorems, so we just tried to


S. L. SHAPIRO AND S. A. TEUKOLSKY

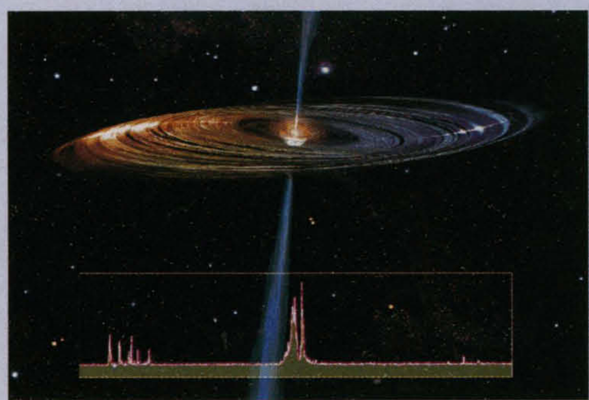
Loophole. In a computer simulation, matter collapses into a donut-shaped black hole, contrary to predictions. The clock in each frame shows the fraction of time elapsed.

* "Black Holes and Relativistic Stars: A Symposium in Honor of S. Chandrasekhar," sponsored by the University of Chicago, 13–15 December 1996.

Black-Hole Observations: The Gathering Darkness

Black holes are flourishing in theorists' computers and on their blackboards, as a recent symposium held in honor of the late Subrahmanyan Chandrasekhar showed (see main text). But these objects—the children of Einstein's theory of gravity—are also alive and well in the universe, observers are finding: They are detecting increasingly strong signs of black holes at the centers of galaxies and, closer to home, in turbulent x-ray beacons. These new observations indicate that "the entities to which Chandra devoted so much of his life have a real, concrete existence and are not just theoretical constructs," said Martin Rees of the University of Cambridge at the symposium.

What Rees calls "the most convincing case for a black hole" comes from microwave measurements of a whirling, gaseous disk at the center of a galaxy called NGC4258, about 20 million light-years away. Two years ago, a team including Makoto Miyoshi of the National Astronomical Observatory in Japan and James Moran of the Harvard-Smithsonian Center for Astrophysics (CfA) in Cambridge, Massachusetts, observed NGC4258 with the Very Long Baseline Array, a far-flung set of radio telescopes. They found that as water molecules in the disk become excited by, say, starlight, they can amplify certain frequencies and act as a maser—the microwave equivalent of a laser. As the disk's material whirls toward or away from Earth, the maser's microwaves are shortened or lengthened. The magnitude of these Doppler shifts, along with other images of the galaxy, indicated that the gas is whirling around a compact, dark object with a mass of about 36 million suns.



PREPARED FOR MAKOTO INOUE BY JOH KAGAYA

It's got that spin. An artist's impression shows the disk of gas at the heart of galaxy NGC4258. Frequency shifts in maser signals *(bottom)* from the disk suggest it is whirling in the grip of a giant black hole, which also drives the two jets.

"It's dark, and the scale is so small"—less than half a light-year across—"that you could not conceivably hide a star cluster in that region," says Rees. Moran, who presented new measurements at the 18th Texas Symposium on Relativistic Astrophysics, held just after the Chandra conference, says the team now has two more "solid candidates" for galaxies showing similar Doppler patterns.

Similar observations of stars have pointed to black holes at the hearts of other galaxies, although stars—being scattered points—can't trace out a gravitational field with the smooth continuity of a disk of gas. Still, what Mitchell Begelman of the University of Colorado, Boulder, considers the next-best case for a black hole comes from stellar measurements close to home: at the center of the Milky Way. Doppler shifts in starlight from the Milky Way's core had suggested that a small, massive attractor resides there. But skeptics could argue that if some asymmetry led to slower velocities, on average, across the plane of the sky than along the line of sight to Earth, the mass of the central object might not be so great. In a paper in the 3 October issue of *Nature*, however, A. Eckart and Reinhard Genzel of the Max-Planck-Institut für Extraterrestrische Physik in Garching, Germany, "tightened the noose on the galactic nucleus," says Begelman.

Eckart and Genzel followed 39 stars near the galaxy's core across the sky for several years and showed that their velocities are roughly the same in all directions. The speeds indicate that they are orbiting a dark mass of several million suns somewhere within a fraction of a cubic light-year around the center—a density that strongly implies a black hole.

What's true of our ordinary galaxy may be true of most others. During a 13 January press conference at an American Astronomical Society meeting in Toronto, for example, a team led by Douglas Richstone of the University of Michigan described a black-hole census of 15 nearby galaxies using the orbiting Hubble Space Telescope. Doppler measurements showed that at the centers of nearly all of the galaxies, stars are swirling at a frenzied pace, apparently rallied by the gravitational pull of giant black holes with anywhere from millions to billions of times the mass of the sun.

Still, says Rees, all of this work begs the deeper question of "whether these black holes really have the properties that Einstein's theory says they have." Here again, he says, "there's been progress." One advance comes from an international team that used the Japanese x-ray satellite ASCA to collect data from "active" galaxies, which have mysterious, brilliant cores. X-ray spectra of the cores seem to show an imprint of the warped space-time that Einstein's theory predicts close to a black hole, in the form of peculiar frequency shifts that can be caused only by strong gravity.

First reported 2 years ago, the signature has now been seen in more than a dozen new objects, says Richard Mushotzky of Goddard Space Flight Center in Greenbelt, Maryland, who did the work with a team including Andrew Fabian at Cambridge, Paul Nandra at Goddard, and Yasul Tanaka, recently retired from the Institute of Space and Astronautical Science in Japan. Says Mushotzky, "We think these [data] are the strongest evidence for the missing component in black holes—strong gravity."

But another set of ASCA observations described at the Toronto meeting may have trumped this claim. A team at the CfA announced uncovering possible evidence of the "event horizon" shrouding black holes. According to Einstein's equations, nothing—neither light nor matter—that passes within the event horizon ever emerges again. The CfA team looked at x-ray emissions from nine objects called x-ray novae, which are powered by gases peeled from a companion star and sucked toward a superdense object—either a neutron star or perhaps a black hole.

X-ray novae don't drag in material at a steady pace, and theoretical models suggested that when the infalling material is especially tenuous, it should be slow to lose energy, because there are too few collisions for the atoms to radiate much. In fact, it should be unable to shed most of its energy until after it has made the plunge. The energy should still be able to escape from a neutron star, but it would be lost behind the event horizon of a black hole. And the team did find that the suspected black holes were unusually dim compared to the neutron stars during these periods of slow accretion. "We think we are seeing, for the first time, direct evidence that the event horizon really exists," says Ramesh Narayan of CfA, who did the analysis with CfA's Jeffrey McClintock and Michael Garcia. Comments Yale University astronomer Charles Bailyn, "This moves some very exotic behavior into observational astronomy."

–J.G.

make [toroidal black holes]," says Teukolsky. "We succeeded"—although the donut hole always closed up soon after the collapse.

Hot and cold black holes

Another group of theorists is using the weirdness of black holes as a clue to physics beyond Einstein's equations entirely. No one has yet merged quantum mechanics—which describes the small-scale graininess of matter and energy—and relativity to make a successful theory of "quantum gravity" that would extend this graininess to space and time. One possible route could lie in the esoteric mathematics known as string theory (*Science*, 15 September 1995, p. 1511). But striking parallels between the mechanics of black holes and classical concepts of temperature and entropy—a system's degree of randomness—could also end up showing the path to quantum gravity, says Robert Wald of the University of Chicago and the principal organizer of the Chandra symposium.

A century ago, he reminded his listeners, the second law of thermodynamics—the inevitable increase of entropy of a system such as gas in a piston's chamber—helped persuade physicists that all matter consists of atoms. By accounting for atomic motions, they found, they could actually prove the law. Lately, says Wald, theorists are finding resemblances between the textbook mechanisms and the workings of black holes that are "just too amazing, I think, to be some mathematical curiosity."

In this analogy, the area of the event horizon takes the place of entropy. Just as total entropy always increases when parcels of gas merge or get pushed around mechanically, the event horizon always expands when, say, two black holes interact or more matter is added to a black hole. Black holes have a temperature, too, as Hawking showed in 1974 when he found that black holes should radiate particles. This radiation is fed by the normally undetectable pairs of particles that, according to quantum mechanics, constantly pop in and out of existence throughout space: Near the event horizon, one member of a pair can get sucked into a black hole while the other flies away. And he and others have shown that this Hawking radiation should have a "thermal" spectrum of energies, shaped exactly like the spectrum of radiation from an object glowing at a particular temperature. The stronger a black hole's gravity at the event horizon, the higher its "temperature" would be.

Physicists hope that such correspondences will let them understand the rest of the story. Working backward from the black hole's entropy, says Rafael Sorkin of Syracuse University in New York and ICN-UNAM in Mexico City, shows that "it's just as if the black-hole horizon was made out of many pieces of about the Planck size"—what would be the smallest imaginable dimension in quantum gravity. Sorkin is still sorting out exactly how that graininess might arise. But he thinks that ultimately, black-hole entropy may "[lead] us to the atoms of space-time itself."

Physicists acknowledge, however, that the analogy comes with deep mysteries, such as how the horizon area could ever take the place of the entire volume, the natural setting for classical thermodynamics. Even more distressing to some traditionalists is a black hole's apparent disregard for "real" information such as the kind of material that falls into it, which can figure in the standard kind of entropy. The Hawking radiation allows black holes to slowly "evaporate" and disappear without yielding any information about what they had swallowed up. That's uncomfortable for some physicists who, Hawking says, "seem to have a strong emotional attachment to information."

Hawking's talk only deepened this discomfort by proposing that the process could be ubiquitous: Microscopic pairs of black holes could be forming and evaporating throughout space, consuming small-scale order like Pac-Mans. Such black holes might, for example, eat one kind of particle and emit another as they evaporate, violating some of the most hallowed conservation laws of particle physics.

But this mind-bending vision was also a fitting conclusion to the symposium, said Hugo Sonnenschein, president of the University of Chicago, where Chandra spent nearly 6 decades as a faculty member. "It's an amazing juxtaposition to call yourself a wanderer"—one of Chandra's favorite descriptions of himself—"and be in so many ways unsure, and yet feel that you can solve mysteries that are beyond imagination."

–**James Glanz**

PLANETARY SCIENCE

An Icy World Looks Livelier

WASHINGTON, D.C.—The latest images of Jupiter's moon Europa, released here last week at a NASA press conference, reveal a landscape in turmoil. To team members poring over images returned by the Galileo spacecraft, the wild jumble of ridges, grooves, pits, ice flows, and chaotic terrain shows ever more signs that heat forged Europa's icy surface. Even to a nonscientist, it's clear that this moon's surface is—or was—mobile. Pope John Paul II, who was shown images of the satellite last week after a scientific meeting in Italy, said simply, "Wow!"

"These new images demonstrate that there was enough heat to drive [ice] flows on the surface," says Galileo imaging team member Ronald Greeley of Arizona State University. And where there's water and enough heat, there might once have been life, he says. "Europa thus has a high potential" as a place where life could have gotten started.

Space scientists had already raised the notion that Europa might at some time have been warm enough to support a water ocean, thanks to Voyager images taken in the 1980s and Galileo images from an earlier, more distant flyby (*Science*, 20 December 1996, p. 2015). Now, images showing details up to 20 times finer—as small as 36 meters—add weight to that possibility. Greeley points to several features in the accompanying image that he suspects depict various stages in the rising of plumes of warm ice or a wet, icy mush. The plume first bulges the surface and cracks it (middle of top block). Then, some unearthly geologic process takes over, and the broken terrain collapses into a chaotic jumble of ice blocks (right side of middle image blocks). Greeley speculates that sublimation of small amounts of ammonia or methane ice from the water ice weakens the terrain, and so it crumbles. In other images, rising water or icy mush appears to have burst through the surface like an ice volcano, flowing as 100-meter-thick lobes of ice for hundreds of kilometers.


JPL/NASA

Heat waves? Europa's chaotic terrain *(center)* may suggest a heat-driven plume from below.

Even these features don't prove that an ocean lurks beneath the surface. Icy volcanism could be driven by scattered hot spots in a solid layer of ice rather than an actual ocean. Or an ocean may have existed in the moon's youth and frozen solid since, squeezing out these few dribbles of ice with its last gasp. But it's also possible that there may still be a warm, liquid sea—perfect for life—hidden below the ice. Galileo's future close encounters with Europa may tell.

–**Richard A. Kerr**

For more images of Europa's surface, see the Jet Propulsion Laboratory's Web page at: http://www.jpl.nasa.gov:80/galileo/status970117.html