NEWS

Into the Lair of The Beast

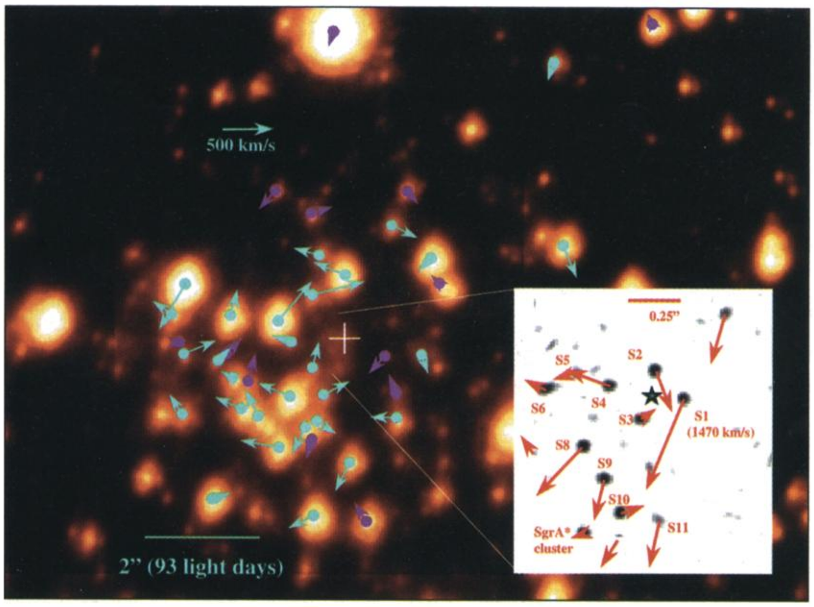
After charting swift stars in the heart of our galaxy, scientists are convinced that a supermassive black hole is pulling the strings. Now they are striving to glimpse the monster's shadowy point of no return

VINCENT: Captain, the ship has been programmed. I don't have the information to override.

PIZER: You mean we're going into the black hole?

HOLLAND: Yup.

Aside from the crew who went down with their ship millions of light-years from Earth in Disney's 1979 cult classic *The Black Hole*, nobody has peered into the maw of one of the most awesome forces in the universe. Such terrors, it turns out, lie in wait much closer to home than Hollywood could have ever imagined. Just 26,000 light-years from Earth, in the center of our own galaxy, broods a behemoth that would snack as readily on stars as on spaceships. In the last 2 years, scientists have firmed up evidence for this supersized black hole, which has swallowed enough gas and dust to equal the mass of more than 2 million suns.



Main attraction. Dozens of stars are known to be kept in orbit by the gravity of a supermassive black hole at the center of our galaxy.

The quest to pierce the dusty veil that shrouds the heart of the Milky Way—and track down the black hole there—has taken more than a decade. It has pushed telescope technology to its limits. But astronomers have glimpsed stars whirling around our galaxy's inner sanctum at speeds up to 1500 kilometers a second, 50 times faster than Earth circles the sun. Only the relentless grip of a supermassive black hole could keep these frenzied stars locked into orbit within the galactic center.

With the beast's identity now known, astronomers hope next to better understand its feeding habits. "We have a unique laboratory in our galaxy," says Andrea Ghez of the University of California, Los Angeles (UCLA). "It's the only place to see a supermassive black hole influencing its neighborhood." Smaller black holes, about the mass of our sun, dot our galaxy by the millions, and observations of stars and gas dashing around the centers of distant galaxies have betrayed other supermassive black holes. But none is as accessible as our superheavyweight, whose combination of mass and proximity to us gives astronomers a chance to study the workings of a black hole like they can no other. Scientists are also raising the tantalizing prospect of viewing, for the first time, an event horizon—the eldritch boundary beyond which nothing can escape a black hole's gravity. Spotting this point of no return would be "the first direct, conclusive evidence" for an effect of extremely strong gravity as predicted by general relativity, says Fulvio Melia, an astronomer at the University of Arizona in Tucson. "That would be extremely exciting."

Star search

The notion that a supermassive black hole squats in the galactic center, an area spanning 30 light-years, was first proposed by Martin Rees and Donald Lynden-Bell in 1971. Seeking to explain the tremendous energy—equal to 100 million suns—pouring from the center, the two astronomers suggested that vast amounts of turbulent gas and dust were reaching fierce temperatures during their plunge into a black hole. That idea has fallen by the wayside. Much of the heat, it turns out, comes from the millions of stars packed into the galactic center.

By the early 1980s, however, a new line of evidence for a titanic black hole had emerged: observations of a powerful radio beacon at the galactic center, called Sagittarius A* (Sgr A*). The radio waves, astronomers speculated, are shed by electrons energized by a black hole's gravity. However, other phenomena, such as matter falling onto clusters of neutron stars, can also emit powerful radio waves. "Everyone has expected for 20 years that our galaxy would have a [supermassive] black hole," says Rees, who is with the University of Cambridge in the United Kingdom. "But the evidence was depressingly slim."

A stronger argument emerged from investigations of the galactic center in the 1980s. A team led by Charles Townes of the University of California, Berkeley, used infrared telescopes to track the movements of gigantic gas clouds, spanning up to trillions of kilometers, in the innermost 3 light-years of the galactic center. Because clouds nearest the center seemed to move faster than ones farther out, the team suggested the clouds were all being tugged by a massive black hole as heavy as 3 million or 4 million times the mass of the sun. "We thought we had clinched the case," recalls Reinhard Genzel, who is now at the Max Planck Institute for Extraterrestrial Physics in Garching, Germany. "But the community at the time didn't believe us." Other scientists suggested that it was possible the gas clouds were being distorted by internal magnetic fields or buffeted by stellar winds.

A more reliable way to hunt for large dollops of hidden mass is to track individual stars. Unlike wispy clouds, stars don't veer from their orbits unless pulled by strong gravity. But it's hard to see pinpricks of starlight deep inside the nimbus of stars and light-blocking dust that cocoons the galactic center. What does escape this shroud is electromagnetic radiation at longer wavelengths, such as infrared and radio, that undulates through the dust.

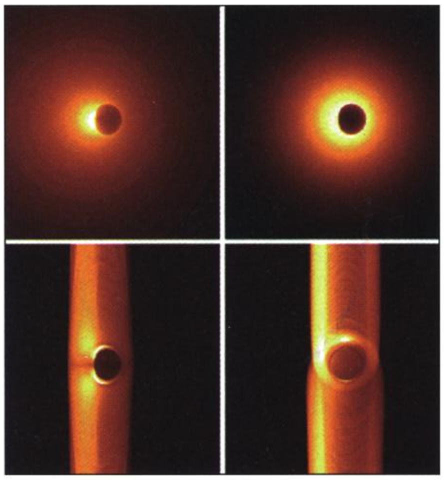
By 1990, infrared detectors had advanced to the point that they might be sensitive enough to make out emissions from stars in-

CREDIT: R. GENZEL

side the galactic center. Genzel's team attached just such a detector to the European Southern Observatory's 3-meter New Technology Telescope in La Silla, Chile. The stars they could discern were awfully fuzzy, partly because the few infrared rays that made it out of the cloud and all the way to Earth were getting knocked around by our own atmosphere. To reduce this distortion, Genzel and his colleague Andreas Eckart, now at the University of Köln in Germany, used a trick called speckle imaging, in which they took many short exposures—like a sports photographer snapping photos of a twirling ice skater. A computer compared the pictures and extracted a true image from the shimmer. But the data were so heavily processed, says Genzel, that when the team members insisted they could make out the motion of stars, "people weren't inclined to believe us."

They kept at it, and by 1996, they had seen enough stellar motions to piece together the orbits of 39 stars. (To view an animation, see www.mpe-garching.mpg.de/www_ir/GC/prop.html) Meanwhile, a group led by UCLA's Ghez had started to make similar measurements with the higher resolution 10-meter Keck telescope on Mauna Kea, Hawaii. At a 1996 conference in La Serena, Chile, the teams compared notes and found they were witnessing similar darts and dashes. "That's when we began to believe these changes were real," says Genzel.

He and his colleagues calculated that the puppet master must have a mass about 2.45 million times that of our sun. The finding was quickly backed up by Ghez's team, which is now taking even finer snapshots of the galactic center using newly installed adaptive optics—a system of pistons that fine-tune the shape of a mirror to cancel out atmospheric turbulence (*Science*, 19 November, p. 1504). The crucial point is that all this mass—recent estimates put Sgr A* at up to 2.6 million solar masses—must fit inside the orbits of the rapidly moving stars, a gap about 16 light-days across. That implies a density so high that only a black hole could explain it. "This is a very important and very beautiful result," says Rees. "It rules out anything we can plausibly propose except for a black hole," adds Leo Blitz of the University of California, Berkeley.



Danger zone. Views of Sagittarius A*'s event horizon as pictured by computer models.

Indigestion

As supermassive black holes go, ours is puny. Other galaxies house the true heavyweights, such as the 3-billion–solar-mass black hole in M87, a galaxy 50 million light-years away. But the behavior of Sgr A* is peculiar. When most black holes at galactic centers suck in matter, they pump out streams of radio waves, x-rays, and gamma rays. Sgr A* is surrounded by an ample supply of gas, yet the only certain signal detected from this region has been radio waves. The leading explanation is that Sgr A* gulps its food without chewing it up much.

The idea—generally called advection dominated accretion flow—is that infalling gas heats up but radiates inefficiently. Instead, the particles grow stupendously hot as they plummet faster and faster toward the black hole. Some heat escapes as infrared radiation, while the accelerating electrons emit radio waves; however, most energy disappears with the particles when they cross the event horizon. "It's an elegant solution," says Andrew Fabian, an astronomer at the University of Cambridge.

Exactly how this disappearing trick works is still being debated. One idea, proposed by Arizona's Melia, is that the magnetic fields spun by the infalling gas are weak. If so, this would lead to inefficient synchrotron radiation, the way in which electrons give off energy when they are accelerated by a magnetic field. That could explain why the observed radio emissions are many hundreds of times weaker than predicted. Alternatively, Rees proposed in 1982 that the ionized gas near Sgr A* might come in two temperatures, its protons warmer than its electrons. The radio emission that does escape from Sgr A* might come from

Biography of a Recluse

If the everyday life of our galaxy's central black hole is cloaked in mystery, its past is even murkier. Where did Sagittarius A* come from? The most plausible model, says theorist Scott Tremaine of Princeton University, is that a huge gas cloud near the center of the young Milky Way collapsed under its own gravity, spawning a black hole. No birth record exists, however: The black hole could be almost as old as the universe, some 15 billion years, or it may be much younger.

As a toddler, the black hole would have weighed no more than a few hundred thousand solar masses. Throughout its life it has probably been grazing quietly on wisps of gas, gradually swelling to more than 2 million solar masses. Punctuating this routine every 10,000 years or so, models suggest, are weeks-long gorges in which Sagittarius A* may sink its gravitational fangs into a star that drifts too close and rip it to shreds. During such a meal, the black hole might belch enough radiation to flare as bright as a supernova, briefly outshining all the stars in the Milky Way. Although much of this outburst would be sopped up by dust in the galactic center, today's infrared, radio, and x-ray telescopes would be able to discern such a flash.

Our own solar system, however, is safe from being munched. Like other supermassive black holes, Sagittarius A* cannot engulf the bulk of its galaxy: It lacks the gravitational brawn to influence matter much more than a few tens of millions of kilometers beyond its boundary. "There is no great sucking going on," notes Julian Krolik of The Johns Hopkins University in Baltimore. Matter that orbits a black hole must lose angular momentum to approach, just as a satellite has to be slowed by atmospheric drag before it falls to Earth. Our solar system has far too much momentum to get pulled toward the galactic center, says Tremaine.

Instead, Sagittarius A* has a date with another hulking black hole. In a few billion years or so, the Milky Way is likely to crash into the Andromeda galaxy (see p. 62), which harbors a supermassive black hole perhaps 50 times bigger than our own. The two black holes will spiral together in a violent tango, releasing surges of gravity waves, and ultimately merge. The galactic smashup will refuel the titanic black hole and also trigger new star formation, dramatically brightening Andromeda–Milky Way for a few hundred million years.

Eventually, the gravy train will end. Little nourishment will remain for the black hole, as matter—in our galaxy and throughout the universe—gets locked up, out of reach, in dead stars. The galaxy "will get darker and darker and less and less interesting," says Tremaine. Hundreds of trillions of years from now, when the last lights in the Milky Way have winked out, all that will remain will be a graveyard of stellar corpses—and a silent, hungry black hole. –E.S.

CREDIT: H. FALCKE

these cooler electrons. But the protons, being poor radiators, silently carry the bulk of the infalling matter's energy with them to the grave—a scenario since refined by theorists such as Ramesh Narayan of the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts.

The latest models suggest that much of the black hole's prey may elude it. In a paper published last February in the *Monthly Notices of the Royal Astronomical Society*, Roger Blandford of the California Institute of Technology in Pasadena and Mitchell Begelman of the University of Colorado, Boulder, propose that most of the hot matter spurts out as high-speed winds. Propelled by heat or magnetic fields, these gusts would tend to blow gas away from the black hole. The winds themselves would radiate a bit, but this would also reduce the amount of matter sucked in. The nature of this outflow is unclear. The winds might stir the gas and keep it circulating, like roiling water. Or they may blast the gas away in a tightly focused jet, similar to a model developed by Heino Falcke of the Max Planck Institute for Radio Astronomy in Bonn, Germany.

So far, radio astronomers haven't been able to vet these detailed ideas about black hole feeding. But data from new x-ray telescopes may help. NASA's Chandra X-ray Observatory, launched last July, will be able to spot objects in the galactic center that are 10 times fainter than those any previous x-ray satellite could spot. Chandra may also be able to spot high-energy radiation cast off by matter falling into our homegrown black hole. And if it turns out that Sgr A* is swallowing matter without churning out radiation, other black holes hidden in distant galaxies may be doing the same thing. The visible universe could be losing far more matter than scientists had estimated—and those elusive black holes might not be bulking up as slowly as they seem to be.

Shadow world

Perhaps the ultimate observation of our galaxy's black hole would be a glimpse of its boundary—the point of no return. According to Falcke, the event horizon should be visible as a shadow outlined by radio waves. Falcke, Melia, and Eric Agol of The Johns Hopkins University in Baltimore, Maryland, estimate that this gloom should extend up to five times the width of the event horizon itself, as any radiation skirting the black hole would be pulled out of our line of sight. If astronomers spotted an event horizon, they would have direct evidence for a bizarre phenomenon predicted only by general relativity. The horizon's shape may also reveal whether the black hole is spinning, which ought to twist the fabric of space-time.

But it may be a few years before that sort of view is possible, says Falcke. About 300 light-years away from the galactic center is a mysterious swath of ionized gas that blocks our vision by scattering radio waves. Trying to tune in radio emissions from Sgr A* is "like looking through frosted glass," says Geoff Bower of the National Radio Astronomy Observatory in Socorro, New Mexico. "The only thing we see is a smeared-out blob." The scattering decreases with shorter wavelengths; astronomers accustomed to 7-millimeter radio waves are now pushing to resolve 1- to 3-mm wavelengths. That's a tough job, because existing antennas perform poorly at shorter wavelengths, a problem exacerbated by atmospheric turbulence. If these issues can be solved, Falcke says, the event horizon may come into focus at about 0.85 mm.

Reaching that target will allow scientists to see "all the way down to the bottom of the falling gas," says Melia. That will be just as thrilling as riding a spaceship into a black hole—and unlike the fate of the Disney vessel, this voyage would be only the beginning.

–ERIK STOKSTAD

NEWS

A Magnifying Glass for the Milky Way

By watching stars for rare flickers, astronomers hoped to glean clues to the nature of dark matter; instead, they have gained a richer knowledge of other beasts in our galactic menagerie

About a decade ago, Bohdan Paczyński of Princeton University hit upon an ingenious approach to probing one of astronomy's biggest mysteries: the nature of the dark matter, invisible to telescopes, whose gravity keeps our own Milky Way from flying apart as it spins. His idea was to mount a search for dark matter based on the principle that a massive object's gravity can act as a lens, bending light from other stars. If large chunks of dark matter—planets or the failed stars called brown dwarfs—are floating in the galaxy's spherical halo, every so often one of them should float across our line of sight to a background star. Its gravity should briefly boost the star's brightness, a phenomenon called microlensing. In the early 1990s, Paczyński and others set out to catch the dark matter by monitoring millions of stars at once for the telltale flickers.

Dark thoughts. Paczyński thought microlensing observations might give clues to the nature of dark matter.

Ten years later, Paczyński and his colleagues remain stumped by the riddle of dark matter. But far from being a bust, microlensing has opened a new window on the Milky Way, including possible discoveries of extrasolar planets and insights into curious variable stars. Observations of the rare lensing events have also forced astronomers to ponder a new structure for our galaxy: that rather than being a perfect pinwheel, it seems to have a bar-shaped clot of stars at its center. The study of microlenses, says Roger Ferlet of the Institut d'Astrophysique de Paris in France, has become "a completely new way of doing astronomy."

It's a search for needles in a cosmic haystack: At any moment, only about one in a million stars is expected to have its rays sharpened in our line of sight by an object closer to Earth. So the astronomers monitor stars en masse—millions of them, in the Milky Way's central halo as well as in two companion galaxies, the Large and Small Magellanic Clouds, that cling to our galaxy. Four teams have pursued the search. First off the blocks was the French collaboration Expérience de Recherche d'Objets Sombres (EROS); hot on its heels were the Optical Gravitational Lensing Experiment (OGLE), run by Paczyński and colleagues at the University of Warsaw in Poland, the U.S.–Australian Massive Compact Halo Objects (MACHO) project, and a smaller French effort called Disk Unseen Objects (DUO). All four have relied on ground-based telescopes, equipped with charge-coupled device detectors, plus computers to sift through stacks upon stacks of brightness measurements. "It was the very first time that astronomers handled such huge amounts of data," says Ferlet, an EROS team member.

The telltale flickers last anywhere from a few hours to a couple of months; generally,

CREDIT: D. APPLEWHITE