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.

CREDIT: D. APPLEWHITE

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."

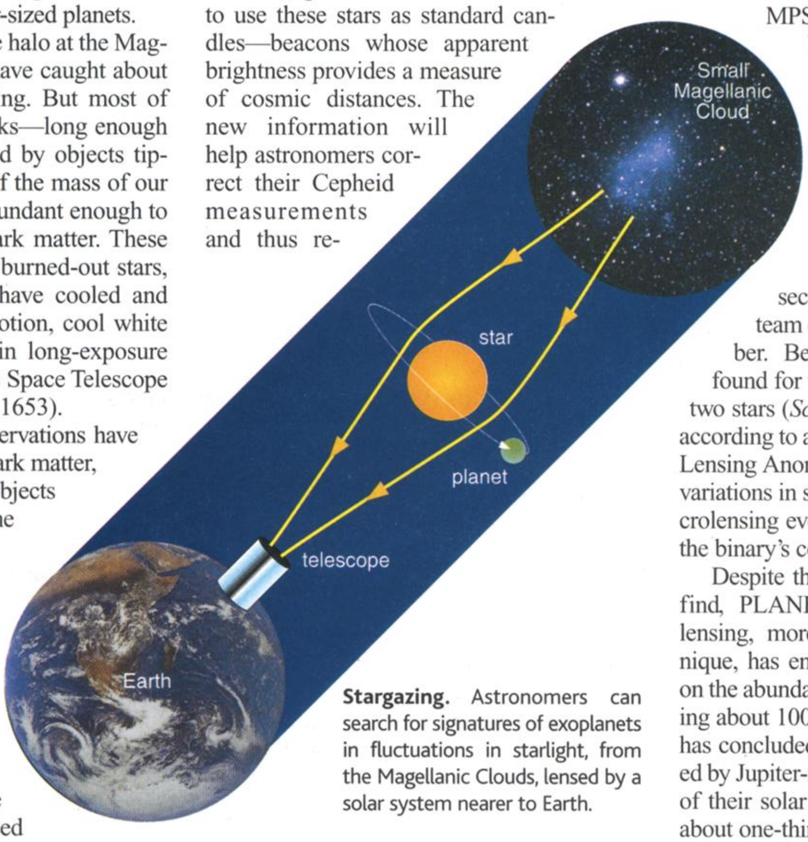
It's a search for needles in a cosmic haystack: At any moment, only about one in a million stars is expected to have its rays sharpened in our line of sight by an object closer to Earth. So the astronomers monitor stars en masse—millions of them, in the Milky Way's central halo as well as in two companion 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, the longer the duration, the heavier the object bending the starlight. When the projects first got going, says MACHO team member David Bennett of the University of Notre Dame in Indiana, "objects weighing less than 10% of the mass of the sun were expected to be the most likely lenses" in the Milky Way's halo, where the population of normal stars is sparse. These so-called MACHOs might be brown dwarfs or wandering Jupiter-sized planets.

After gazing through the halo at the Magellanic Clouds, the teams have caught about 20 instances of microlensing. But most of these events lasted for weeks—long enough that they are best explained by objects tipping the scales at about half the mass of our sun. Nor are they nearly abundant enough to account for most of the dark matter. These heavy MACHOs might be burned-out stars, called white dwarfs, that have cooled and dimmed; supporting this notion, cool white dwarfs seem to show up in long-exposure photos taken by the Hubble Space Telescope (*Science*, 10 September, p. 1653).

Although microlens observations have set limits on the nature of dark matter, the dearth of candidate objects has sent theorists back to the chalkboard to come up with possible new guises for unseen matter in our galaxy (*Science*, 17 July 1998, p. 332). One is small, solitary black holes. Indeed, the MACHO collaboration did see a long-lasting lensing event toward the galactic center, perhaps caused by a black hole a few times more massive than our sun; Bennett says the searches probably miss more such events, because the data analysis programs are not designed to hunt for lensing that lasts for many months. Other scientists, meanwhile, argue that dark matter could be composed of neutrinos or other elementary particles. That would relegate microlens researchers to the sidelines in the dark matter search, leaving the chase to particle physicists.

But just as a fruitless search for one's car keys can turn up a $20 bill, lensing observations have revealed some hidden jewels that search teams hadn't set out to find. For instance, the four projects have amassed a trove of data on stars with intrinsic variations in brightness. "One of our early worries was that the detection of zillions of new variable stars would make it hard to distinguish between an actual microlensing event and a peculiar type of variable star," says Paczyński. "Luckily, that turned out not to be a problem." It's easy to distinguish the two because a variable star's pulsing appears different at different colors, while a lensed star brightens equally at all colors. And by tracking large numbers of Cepheid variables (a common type of pulsating star) in the Magellanic Clouds, microlensing researchers have worked out how the pulsation period of a Cepheid is influenced by the chemical makeup of its host galaxy. Astronomers assume that a Cepheid's period indicates its intrinsic brightness, which allows them to use these stars as standard candles—beacons whose apparent brightness provides a measure of cosmic distances. The new information will help astronomers correct their Cepheid measurements and thus refine estimates of distances in the cosmos.



Stargazing. Astronomers can search for signatures of exoplanets in fluctuations in starlight, from the Magellanic Clouds, lensed by a solar system nearer to Earth.

Telescopes that are pointed in a different direction, toward the heart of the Milky Way, have borne witness to another surprise: hundreds of occasions—far more than anticipated—in which lenses appear to be run-of-the-mill dwarf stars. To account for the seeming abundance of these stars, astronomers have suggested that the central bulge of our galaxy, once thought to be spherical, is shaped more like a bar pointing roughly in our direction. That shape would produce more alignments of background stars and lensing objects than expected. But the data don't yet prove that the Milky Way is a barred spiral. Further lensing observations, says Bennett, "are going to be pretty important in determining the structure of our galaxy."

Perhaps the most thrilling payoffs of the microlensing searches are the apparent discoveries of extrasolar planets. When a lensing star has a companion planet, its light should flicker, either dimming or brightening, if the planet's orbit crosses the line of sight, an effect more pronounced than dimming due to a planet's transit across the face of a star. Measurements of these spikes can yield a rough estimate of a planet's mass and its orbital radius. So far, two serious exoplanet candidates have been found, says Bennett, who leads a project, called the Microlensing Planet Search (MPS), that follows up on alerts from the microlensing programs. Along with collaborators in Japan and New Zealand, MPS in 1998 spotted what appears to be the first low-mass exoplanet orbiting in a parent star's "habitable zone," in which liquid water could exist (*Science*, 1 October, p. 70), says Philip Yock of the University of Auckland in New Zealand.

More controversial is the second candidate, which the MPS team described in *Nature* last November. Bennett's group claims to have found for the first time a planet that orbits two stars (*Science*, 20 August, p. 1191). But according to a competing team called Probing Lensing Anomalies Network (PLANET), the variations in starlight observed during the microlensing event could be attributed solely to the binary's complex pas de deux.

Despite their skepticism about the binary find, PLANET members say that microlensing, more than any other search technique, has enabled astronomers to set limits on the abundance of exoplanets. After observing about 100 microlensing events, PLANET has concluded that the fraction of stars orbited by Jupiter-mass planets in the inner regions of their solar systems cannot be higher than about one-third.

Microlensing's power to peer deep into our galaxy may be nonpareil, but soon only one team will carry the banner for the technique. After using up their allotted funding, DUO is done and MACHO stopped gathering data last month, while EROS is slated for shutdown in 2002. That will leave the field wide open to OGLE, which later this year will be upgraded with a larger camera that's expected to produce an unprecedented 5 terabytes of data per year. The deluge should double the number of cataloged lensing events.

Until astronomers put into orbit a telescope dedicated to microlensing, there should be plenty yet to discover from Earth. "The possibilities of ground-based observations have not yet been fully explored," says Paczyński, who would love to see a continuous, all-sky lensing patrol. "We can still get a tremendous improvement by increasing the number of stars in our surveys." The dark matter may still be at large, but the bright matter of our galaxy is coming into ever-sharper focus.

–GOVERT SCHILLING

Govert Schilling is an astronomy writer in Utrecht, the Netherlands.