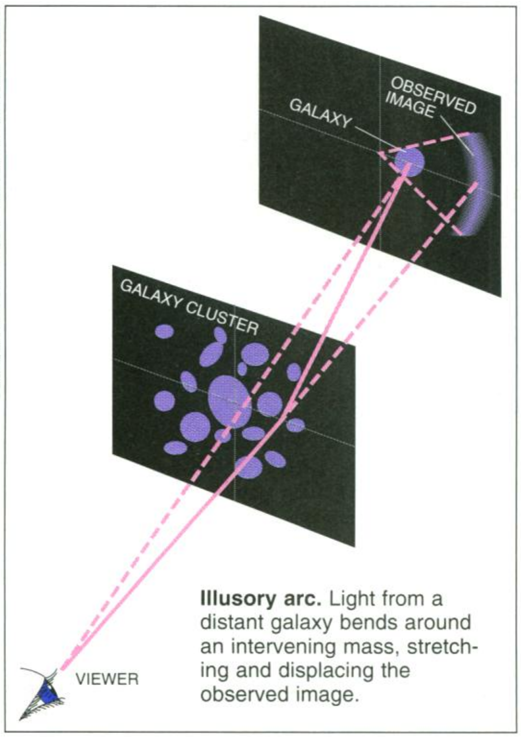
Putting a Cosmic Illusion to Work

Warps in the fabric of space called gravitational lenses are helping astronomers track down the secrets of quasars, survey cosmic distances, and map dark matter

When astronomer Jacqueline Hewitt and her colleagues at the Massachusetts Institute of Technology (MIT) wanted to measure the distance to a quasar at the very outskirts of the universe, they used a lens to match—one that stretched across thousands of light-years. That may sound excessive in this time of tight funding, but in fact the lens cost nothing. It was a gravitational lens—nature's own magnifier, consisting not of glass but of the very fabric of space, warped by the mass of an intervening galaxy. Aligned by chance along the line of sight to the quasar, the lens split the quasar into a double image that gave the astronomers a new trick for measuring distance to this faraway object.

In the past 13 years astronomers have discovered many such gravitational lenses, which were first predicted by Einstein in his theory of relativity. Like flaws in a sheet of glass, these space warps can take a faint point and blow it up many times its original size, distend it into an oblong or arc, or shatter it into multiple images. Though the resulting illusions have fooled astronomers in the past, today's star-gazers are mastering the medium—exploiting lenses to study otherwise hard-to-see objects.

In some cases, like Hewitt's, astronomers try to use the lenses to learn more about the quasars and galaxies whose images are distorted before they get to Earth. In others, it's the lens itself that fascinates them. Cosmologists believe that as much as 99% of the mass of the universe is hidden in the form of invisible "dark" matter, but some of it is revealing itself by creating gravitational lensing that distorts more distant objects. True, astronomers have to take gravitational lenses where they find them, and lensing can be tricky to interpret, but give us time, says Harvard astronomer Ramesh Narayan: "The big advances are still in the future."



Illusory arc. Light from a distant galaxy bends around an intervening mass, stretching and displacing the observed image.

SOURCE: ANTHONY TYSON ILLUSTRATION: JULIE CHERRY

Astronomer Duncan Walsh of Manchester University in England and his colleagues were the first to spot a gravitational lens when, in 1979, they observed a "twin" quasar that was too good a match: The two images had exactly the same spectra, indicating they actually came from the same quasar. Since then, astronomers have found other quasars split into two, three, and even four separate images. In the following years scientists found mysterious arcs that they later realized were galaxies distorted by lensing, and one unlikely example where the alignment of objects was so perfect that a galaxy was dilated into a ring. And while most lenses seem to be created by vast concentrations of mass—a galaxy or more—even a passing star can act as a "microlens," temporarily focusing and brightening the image of a more distant star or quasar.

Hewitt and her colleagues were among the first to put these lenses to work, when they reasoned that the flickering of a certain "double quasar" could signal its distance. The trick was in the timing. Flickers in one image tended to lag behind those in the other by about a year-and-a-half, suggesting that the two different paths the signals are following from the quasar to Earth differ in length by about one-and-a-half light-years. By combining that path difference with the approximate size and shape of the lensing galaxy and applying some simple geometry, the workers got a measure of the quasar's distance.

It was only a rough measure, they admit, but this was the first time astronomers have had any direct gauge of such great distances. As a result, it has helped to calibrate the overall distance scale of the universe—and hence its age. Astronomers traditionally estimate distances to galaxies or quasars from the amount by which their light gets shifted toward the red end of the spectrum as a result of the expansion of the universe. But to convert those red shifts into absolute distances, astronomers need a constant of proportionality known as the Hubble constant. The Hubble constant is currently known only to within a factor of 2—between 50 and 100. And this confusion has left astronomers arguing whether the universe is close to 20 billion years old, or a mere 10.

To pin down the Hubble constant, astronomers need an independent measurement of distance to an object of known red shift. The Hewitt group's result, published last summer in *Nature*, helps, but it won't resolve the longstanding dispute: The quasar distance could only confine the constant to a value of less than 85. The problem, Hewitt explains, is that "the lenses are complicated—you have to understand the mass distribution of the lens to make the connection between the time delay and the Hubble constant." Even so, Hewitt's result was a proof-of-principle that is inspiring other astronomers to apply lenses to the study of quasars and other mysterious objects.

Peeping through a microlens

Take Princeton astrophysicist Bohdan Paczynski and Harvard's Narayan, who are using lenses to measure quasar diameters. Clues for them aren't in multiple quasar images, though, but in the microlensing that results when an individual star eclipses a quasar, causing its image to brighten for several days. So far, the team has seen only one case of microlensing, says Narayan: a blip in one of the triple images of an already-lensed quasar.

If, as he and Paczynski believe, the blip resulted when a single star in the same galaxy responsible for the split image passed across the line of sight, the amount of brightening should reveal the quasar's diameter. The larger the quasar, Narayan says, the less a passing star should perturb it. The researchers' size estimate—10^{13} meters, or about the size of our solar system—is consistent with the theory that quasars are powered by massive black holes.

The microlensing also yielded a bonus, according to Narayan: a figure for the mass of the intervening star, given by the duration of the blip. The result, about one-tenth the mass of our sun, "is the first time anyone has done a mass measurement on a star in another galaxy," he says.

And Narayan has yet another ambition: He is hoping to spot lensing in the mysterious, fraction-of-a-second explosions of gamma rays called gamma-ray bursts. Astronomers can't say whether the bursts come from the far reaches of the universe or originate right in the backyard of our own galaxy. One way to resolve the issue, Narayan says, would be to find an example of a lensed burst, visible as a set of multiple gamma-ray "images" that all showed the same spectral fingerprint. Such lensing would mean that the burst could not have originated in our neighborhood; it would have to lie far enough away for an intervening galaxy or cluster of galaxies to bend its signal.

ANTHONY TYSON

Through a dark lens. This giant cluster of galaxies, heavy with dark matter, distorts more distant galaxies into faint arcs.

"The great hope is that we can see dark matter."
–Ramesh Narayan

Making darkness visible

Besides using gravitational lensing to examine mystery objects, astronomers are trying to learn about the lensing matter itself. If the vast majority of the matter that makes up the universe is unseen, as astronomers believe, the dark matter should distort the images of distant galaxies and quasars—and thereby reveal something of its own nature and distribution. Says Narayan: "The great hope is that we can see dark matter."

Astronomers believe that clusters of galaxies are rich in dark matter, and AT&T Bell Laboratories astronomer Anthony Tyson is using gravitational lensing to track it down. He is seeing the fingerprint of dark matter in the faint "arclets" that pattern images of galaxy clusters. Each arclet is a "background" galaxy, even more distant than the cluster itself, whose image is stretched into crescent-moon shape by the mass of the cluster. A given cluster may sport hundreds of arclets—enough for Tyson to map the amount and distribution of matter, dark and light, doing the lensing.

The resulting maps confirm that the clusters are suffused with more than 10 times as much matter as is visible; take the dark matter away, and you'd see a much weaker lensing effect. The maps also show that dark matter is distributed fairly evenly around the cluster, not clumping too much around the individual galaxies. That finding in turn offers a clue to the nature of the dark matter. Physicists have proposed that it consists of everything from vast numbers of the particles called neutrinos, which travel at nearly the speed of light, to hypothetical "cold" particles, which would move very slowly. Tyson says his map casts doubt on both extremes: Neutrinos move too fast for enough of them to have collected around the cluster to explain the lensing, and cold particles would form subclumps within clusters that he doesn't observe.

To glean more clues about the nature and role of dark matter, Tyson and others would like to know whether all of it huddles close to galaxies and clusters of galaxies, or whether dark matter also looms in the loneliest voids of space. In that search, too, gravitational lensing has yielded clues—though nothing definitive. In 1988 and 1989, astronomers found two lensed quasars with no visible intervening galaxy or cluster of galaxies doing the lensing. The objects bending the light, says Caltech astronomer Roger Blandford, could be some massive and compact form of dark matter—perhaps entire dark galaxies.

Tyson plans to extend the search for such isolated clumps of dark matter by mounting a survey for lensed galaxies where nothing seems to lie along the line of sight. Blandford, meanwhile, would like to go even further and map the distribution of dark matter on the very largest scales. Over the past 10 years, astronomers have found that visible matter is distributed through the universe in vast filaments and walls, separated by empty space. By looking at large-scale patterns in the gravitational lensing of distant galaxies, Blandford hopes to learn whether dark matter is organized on the same grand scale. If so, the dark matter may have acted as a scaffolding for the universe's vast visible structure.

On the trail of MACHOs

While Blandford, Tyson, and other workers are using gravitational lensing to plumb the far reaches of the universe, other astronomers are applying it closer to home, in our own galaxy. The Milky Way has its own complement of dark matter, which some researchers think may be hiding in the galaxy's vast halo in the form of MACHOs—massive compact halo objects. These might include brown dwarfs—stars too small to catch fire—or little black holes, or even stray planets.

The best way to catch one of these invisible objects, says Princeton's Paczynski, is to watch for microlensing of individual stars. The longer the brightening of the lensed star, the bigger the MACHO that is eclipsing it. So far, says Paczynski, no one has ever seen a microlensed star in our galaxy—but he notes that no one has really looked hard yet. What's more, even if the galaxy is teeming with MACHOs, they would eclipse only one in a billion stars observed at any one time. Until recently, he says, the idea of searching for such a rare phenomenon was "science fiction."

But with modern silicon detectors, says Paczynski, "we can look at 100,000 stars at a time." Two groups are now planning a MACHO search: Paczynski's own, working at the Las Campanas Observatory in Chile, and another group observing from Australia. "I would be surprised if we don't discover a case in the next 2 years," says Paczynski. And considering how hard it is to see the effect, he adds, "if you see one, you know there could be many of them."

Paczynski's maxim is a good metaphor for the entire subfield of gravitational lensing. Hewitt and her MIT colleagues saw one application of this celestial tool, and now just about everyone is finding more. And astronomers apparently discovered lensing just in time. "We've really blunted all our other tools that apply to those problems," says Princeton cosmologist Edwin Turner. But lensing is no simple tool, he says. It will take new advances in observing technology to realize its promise. "There's no shortage of ideas for things you might possibly do with gravitational lensing," he says. "The hard part is figuring out which ones to spend all your time on, and then making them work."

–Faye Flam