

CRAZY ILLUSIONS can be created by the power of gravity. Objects can be multiplied manyfold—as in this case of a certain magazine's logo acted on by a computer program that simulates the effect of gravity on light. Or they can be magnified and mangled—like the galaxies distorted by the galaxy cluster Abell 2218 (*opposite page*). The large yellowish galaxies belong to the cluster; the thin bluish curves are the images of galaxies five to 10 times farther away from us.

The most massive telescopes known to humanity sit not on earthly mountaintops but in deep space. They are gravitational lenses, once mere curiosities, now one of the most important tools in astronomy

By Joachim Wambsganss

Gravity's Kaleidoscope



To many people, the universe seems like a hall of mirrors—filled with objects that are beyond bizarre and phenomena that challenge our very understanding of reality. Little do they realize how apt this metaphor is. The skies are riddled with fun-house illusions: quasars that appear in quadruplicate, galaxies that are

squished from their usual pinwheel or beehive shape into long, skinny threads, stars that fade in and out like streetlamps on a foggy night. Just as psychologists prize optical illusions for what they reveal about the brain, astronomers find that the heavenly mirages show a universe they might not otherwise see.

Usually light from an astronomical object goes straight from the object through the depths of space into our telescopes. But if a second object is located exactly in between, its gravity can deflect the light, much as a glass lens does. We see a distorted, magnified or multiplied image. Analysis of that image can shed light both on the background object and on the lens itself.

The study of gravitational lensing is still a young field, having just finished its teenage years as an observational science. A decade or so ago astronomers knew of just a few examples of lenses [see “Gravitational Lenses,” by Edwin L. Turner; SCIENTIFIC AMERICAN, July 1988].

They have since detected and explored entire new manifestations of lensing: the so-called microlensing of quasars and stars; arclets and weak lensing in galaxy clusters; and, last year, the subtle shearing caused by very weak lensing of the large-scale structure of the universe. Anything that possesses mass can serve as a lens; it does not need to emit light of its own. For this reason, gravitational lensing is one of the few ways that astronomers can map out the invisible dark matter of the universe. Lensing can also probe the internal structure of quasars, spot black holes traipsing through interstellar space and detect Earth-mass planets around other stars.

Credit for gravitational lensing is often given to Albert Einstein, but he was not, in fact, the first person to predict it. As early as 1801, Berlin astronomer and geographer Johann Georg von Soldner argued that the attractive force of the sun could

MARK CLEMENS, USING ADOBE PHOTOSHOP; GRAVITATIONAL LENS FILTER BY PETE KERNAN
Case Western Reserve University (theory2.phys.cwru.edu/~pete) [opposite];
ANDREW FRUCHTER Space Telescope Science Institute and NASA (Abell 2218)

bend the light rays of distant stars. According to Newtonian gravity theory, the position of a star seen near the edge of the sun should shift by 0.84 arcsecond relative to its position measured half a year later, when the sun is elsewhere in the sky.

According to general relativity, however, the angle is twice as large. As Einstein wrote, “Half of this deflection is produced by the Newtonian field of attraction of the sun, and the other half by the geometrical modification (‘curvature’) of space caused by the sun.” During the now famous solar eclipse of May 1919, British astrophysicists Arthur S. Eddington and Frank W. Dyson measured this effect and confirmed the relativistic estimate (although, in retrospect, the experimental precision was probably insufficient to distinguish the two estimates beyond a reasonable doubt).

Einstein dealt again with gravitational light deflection in the 1930s, when he predicted that a foreground star could magnify the image of a background star. But he was skeptical that such an illusion could ever be seen. More optimistic were Swiss-

THE AUTHOR

JOACHIM WAMBSGANSS often compares gravitational lensing to looking through the bottom of a wineglass. Both produce the same type of distortion. But what makes the comparison so apt is that Wambsganss comes from a family of winemakers; his uncles, cousins and parents own vineyards in the Rhine Valley. He says he became interested in cosmology when a high school teacher gave him a copy of *Scientific American*. [No, we didn't bribe him to say that.] Today he is a physics professor at Potsdam University.

American astrophysicist Fritz Zwicky, who predicted the lensing effects of galaxies and galaxy clusters, and American Henry Norris Russell, who suggested that this light deflection could be used to visualize and popularize relativity [see “A Relativistic Eclipse,” by Henry Norris Russell; *SCIENTIFIC AMERICAN*, February 1937]. It was not until 1979, however, that astronomers actually saw evidence of lensing. The following pages review the progress since then.

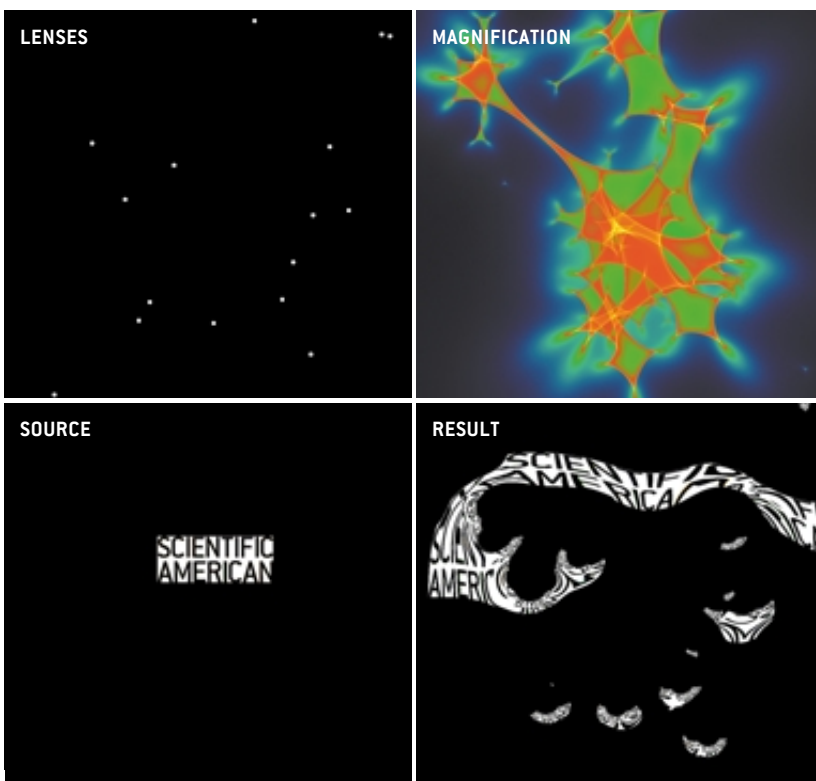
FOUR CONSEQUENCES OF GRAVITATIONAL LIGHT DEFLECTION

■ **CHANGE OF POSITION** The deflection shifts the apparent location of a star, galaxy or quasar in the sky. In most cases, this makes little difference to observers, because they do not know where the object would have been in the absence of lensing. But if the source-lens alignment changes—for instance, if either is moving—astronomers can directly measure the displacement.

■ **MAGNIFICATION AND DEMAGNIFICATION** The deflection and focusing of light rays affect the apparent brightness of the background star or quasar. Although most cosmic sources are demagnified slightly, some are magnified by varying degrees. Observers have measured magnifications of more than 100 times.

■ **DEFORMATION** Extended cosmic objects (such as galaxies) often appear stretched along a circle centered on the lens, producing banana-shaped arcs. Point sources (such as stars and quasars, which are either too small or too distant to see in detail) typically remain points.

■ **MULTIPLICATION** Strong gravitational lensing can produce multiple images. Additional images always emerge in pairs, and one of these images is mirror-inverted. Although the number of images must be odd, one image is usually obscured, so observers see an even number.



SIMULATED DISTORTION demonstrates the lensing effects of a cluster of stars (top left). Whenever a lens is not a single object but a collection of objects, the outcome can get rather complicated. Astronomers visualize this by preparing a color map (top right) that shows magnification as a function of position. The cluster magnifies a source of light to a small [blue], moderate [green] or large [red] degree. The yellow lines are so-called caustics, where the magnification is extremely high. The uneven magnification distorts a perfectly respectable magazine logo (bottom left) into a phantasmagoria (bottom right).

I. How Lensing Works

Stars, galaxies or black holes can deflect light rays from the straight and narrow

A gravitational-lens system comprises four ingredients: a distant source of light (star, galaxy or quasar), an intervening mass that acts as the lens (anything from a planet to a black hole), an observer on Earth, and the space in which all three are embedded. The line that connects lens and observer is called the optical axis.

Light always follows the shortest possible route between two points. But Einstein showed that the shortest connection between two points can be curved, just as the shortest path between two points on the surface of Earth is part of a great circle. As light rays approach the curved space near a cosmic body, they will bend. The degree of deflection depends on how close the rays get to the body and how massive this body is. The deflection angle is directly proportional to the mass and inversely proportional to the closest distance.

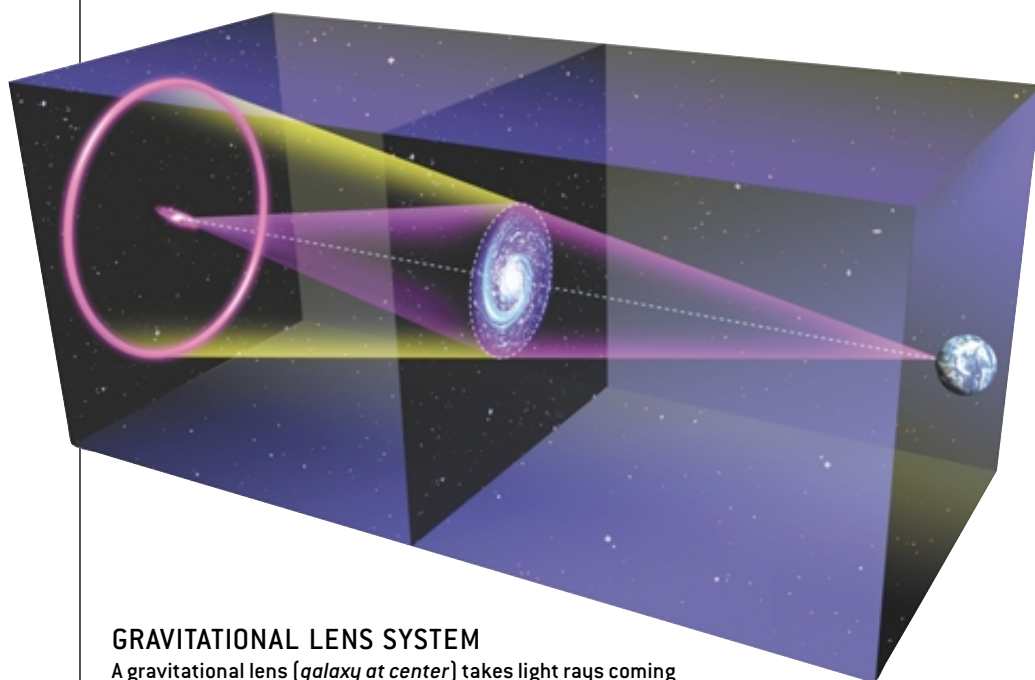
In many ways, gravitational lenses act like ordinary glass lenses. One of the major differences is that ordinary lenses have a well-defined focal point, whereas the gravitational varieties produce focal lines or surfaces. The convex shape of an ordinary lens ensures that the deflection angle is directly proportional to the distance from the optical axis. All incoming parallel rays meet at the same point behind the lens—the focus. The typical gravitational lens, however, causes light rays to experience smaller deflections the farther they are from the optical axis. For this reason, parallel rays deflected by gravity meet at different locations behind the lens, depending on how far away

from the optical axis they originate. Certain glass lenses have the same effect; a good example is the bottom of a wineglass.

Another difference between gravitational lenses and ordinary glass lenses is that the former affect all wavelengths of light equally. In other words, gravitational lensing is achromatic. For glass lenses, the degree of deflection depends on the wavelength of the light. Gravitational-lensing effects have been measured throughout the electromagnetic spectrum, even in x-rays, which cannot be focused by glass optics.

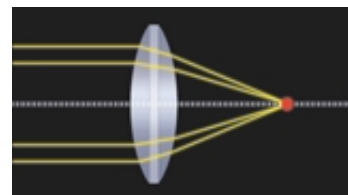
If the lens system is perfectly symmetric—source, lens and observer are in alignment, and the lens is a point or sphere—the rays converge somewhere along the optical axis and the resulting image is a ring (*below*). But if the system is asymmetric—if the alignment is slightly off or the lens has an oblong mass distribution—the ring breaks up into discrete variegated images. The lens magnifies different parts of the source by different amounts. The highest magnification occurs for parts of the source that happen to be on a curve known as the caustic. An everyday example of caustics is the lacework of bright lines you see on the bottom of a sunlit swimming pool; the ripples on the surface of the water act as irregular lenses.

If the alignment is very far off or the lens mass distribution is very spread out, the lensing is weak. Images are barely distorted or magnified. Although in this case the effects are difficult to discern for a single object, they can often be detected statistically by looking at large populations of objects.



GRAVITATIONAL LENS SYSTEM

A gravitational lens (*galaxy at center*) takes light rays coming from a distant galaxy and focuses some of them (*purple cone*) on Earth. To observers, the light appears to have followed a straight line (*yellow cone*), giving the illusion that it emanated from a ring.



CONVEX GLASS LENS

Light near the edge of a glass lens is deflected more than light near the optical axis. Thus, the lens focuses parallel light rays onto a point.



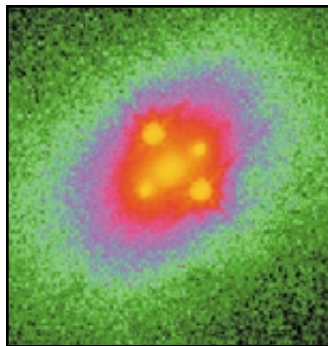
GRAVITATIONAL LENS

Light near the edge of a gravitational lens is deflected less than light near the center. Thus, the lens focuses light onto a line rather than a point.

II. Quasars

As mighty as quasars are, they appear as mere dots in most telescopes. Gravitational lensing can peer inside them

MULTIPLE QUASARS

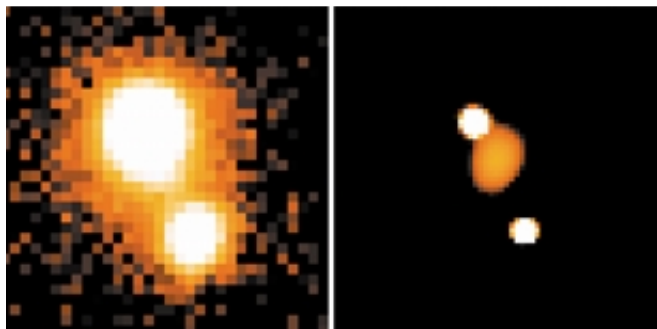


QUADRUPLE QUASAR Q2237+0305

Gravitational lensing became an observational science in 1979, when Dennis Walsh of Jodrell Bank Observatory in England and his colleagues discovered the double quasar Q0957+561, a pair of almost identical quasars right next to each other in the sky. Today astronomers know of 64 double, triple and multiple quasars separated by a few arcseconds or less. They are rare, accounting for roughly one out of every 500 observed quasars. The most comprehensive attempt so far to determine their prevalence was the CLASS (Cosmic Lens All-Sky Survey) project, which mapped more than 10,000 radio sources and found 17 multiply imaged systems.

To make sure a grouping is an illusion rather than a real cluster of quasars, observers go down a checklist: Do the quasars lie at the same distance, as determined by measuring the redshift? Are their spectra, which are as characteristic for quasars as fingerprints are for humans, identical or at least very similar? Is there a galaxy—a potential lens—between us and the quasar? Finally, does the brightness of each quasar fluctuate in exactly the same way?

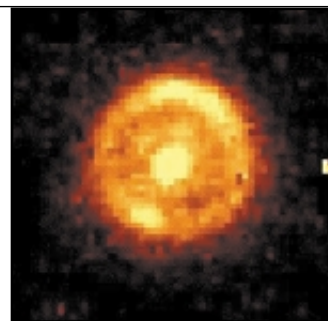
The third of these criteria, the detection of a lens galaxy, is not rigid, because it is possible that the galaxy is either very faint or even completely dark. For instance, it may be a lump of gas in which no stars have formed. The lens may not even be a galaxy but rather an isolated black hole with a comparable mass. But in every well-studied case of multiple-quasar images, astronomers have been able to detect a more or less normal galaxy. One implication is that the universe does not contain large numbers of dark galaxies or isolated supermassive black holes.



DOUBLE QUASAR HE1104-1805, straddling a faint lensing galaxy

EINSTEIN RINGS

When a lens galaxy is spherically symmetric, it can redistribute the light of a background quasar or galaxy into a complete circle. The diameter of the ring is proportional to the square root of the lensing mass—providing a very elegant way of determining the mass of the lens galaxy. About a dozen Einstein rings are now known.

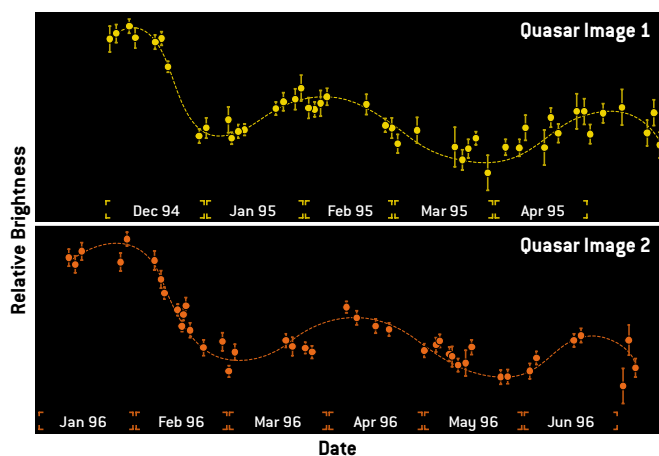


EINSTEIN RING B1938+666

HUBBLE CONSTANT

One of the most powerful applications of quasar lensing, first suggested by Sjur Refsdal of Hamburg University in Germany in 1964, is to gauge the Hubble constant, a measure of the size and present expansion rate of the universe. Most other techniques to determine this value rely on a long ladder of distance measurements, but the gravitational-lens method leaps to the answer in a single bound.

When one of the images in a double quasar changes its brightness, the other one usually does, too—but not at exactly the same time. A delay is introduced by two effects: lensing asym-



MATCHING BRIGHTNESS VARIATIONS of the double quasar Q0957+561

metry (which forces the light rays that produce each image to take paths of slightly different lengths) and the gravitational field of the lens (which, according to relativity theory, reduces the apparent velocity of light). From models of the shape and mass distribution of the lens, astronomers can estimate the time delay as a fraction of the total light-travel time. Then, by measuring the time delay and dividing by this fraction—typically about one ten-billionth—they can calculate the total light-travel time from the quasar, hence its distance. Because the redshift measures the receding speed, the constant of proportionality between

ROBERT SCHMIDT University of Cambridge, SPACE TELESCOPE SCIENCE INSTITUTE AND NASA (quadruple quasar); LINDSAY KING University of Bonn and Class Team (ring); SARA CHEN, SOURCE: TOMISLAV KUNDIC Renaissance Technologies (graph); FREDERIC COURBIN Pontificia Universidad Católica, Chile (double quasar)

distance and velocity, the Hubble constant, can be calculated.

The technique was first applied to the double quasar Q0957+561 (*diagram on opposite page*). Flickers in one of the quasar images (*blue*) appear in the other (*red*) about 417 days later, which implies that the quasar is about 14 billion light-years away. Astronomers have now measured time delays from seven multiple-quasar systems. The inferred value of the Hubble constant is lowish but matches those arrived at by other techniques, within the error bars. The biggest uncertainty is the complicated mass distribution in the lenses.

COSMOLOGICAL CONSTANT

Multiple quasars can also give insight into another infamous cosmological parameter, the cosmological constant. This constant, or something like it, is needed to explain why the expansion of the universe appears to be accelerating [see “The Quintessential Universe,” by Jeremiah P. Ostriker and Paul J. Steinhardt; *SCIENTIFIC AMERICAN*, January]. The acceleration relates to lensing because it makes the universe larger, which increases the probability that a quasar will be lensed. The more the expansion has accelerated, the bigger the volume of space and the more likely it is that an alignment between a galaxy and a distant quasar occurs (*below*). Therefore, the number of multiple quasars can put an upper bound on the cosmological constant.

In 1998 Emilio E. Falco, Chris S. Kochanek and Jose A. Muñoz of the Harvard-Smithsonian Center for Astrophysics concluded that the cosmological constant cannot account for more than 62 percent of the energy density of the universe. If the constant were larger than this value, then observers should find many more multiple quasars than they do. This analysis favors smaller values of the constant than do such cosmological measurements as the brightness of distant supernovae, but the

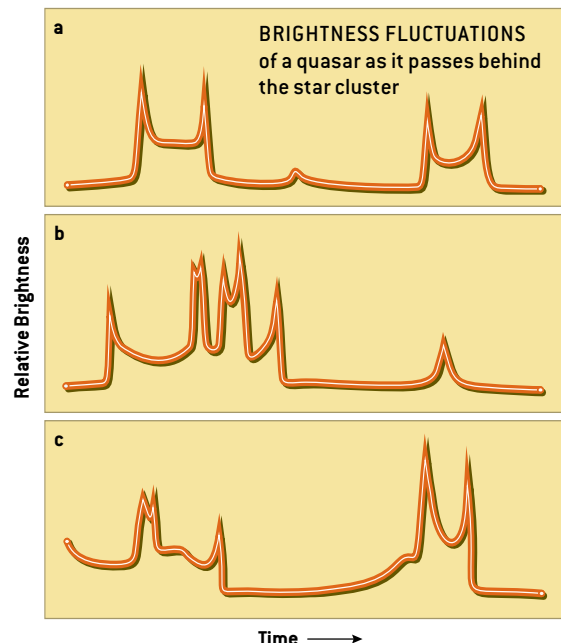
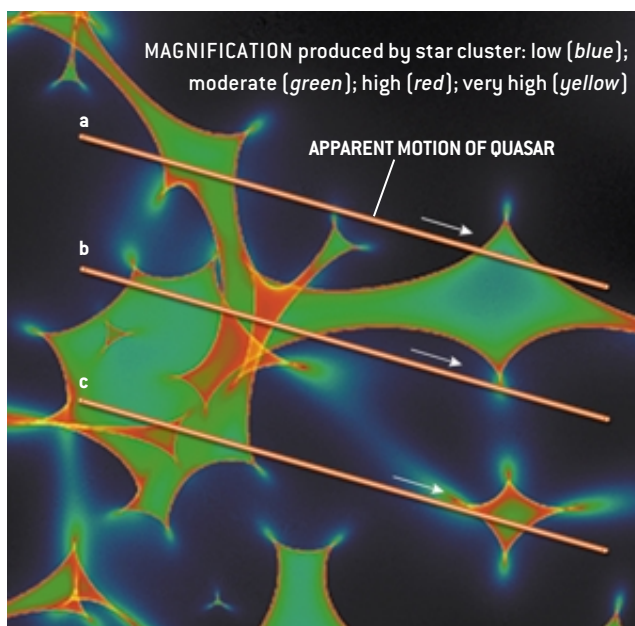
difference is not statistically significant, and more recent studies have loosened the constraint a bit.

MICROLENSING OF QUASARS

Lensing is not always as obvious as in the examples above. If a star does the lensing, for example, the images are so close together that even the best telescopes cannot resolve them. This so-called microlensing effect is nonetheless measurable. Because the star is moving, the lens configuration—and therefore the magnification—changes over time. If observers see a quasar brighten and then dim in a particular way, they can infer that a star passed in front and briefly magnified its image.

The problem is that quasars are unsteady; they tend to brighten and dim on their own. To distinguish microlensing fluctuations from the quasar’s intrinsic variability, astronomers monitor multiple-quasar systems. If one of the images flickers while the others do not, it may be because a star within the lens galaxy has passed into the line of sight and temporarily added an extra brightening to the effect already produced by the galaxy as a whole. Intrinsic changes, on the other hand, will show up in all the images. Since 1989 astronomers have confirmed microlensing in five multiple-quasar systems.

The brightness of the quasar increases smoothly until it hits a caustic, and then it undergoes an abrupt drop. The effect depends on the size of the quasar: the smaller it is, the more abruptly the brightness varies. These patterns provide a way to measure the size of the quasar and probe its internal structure. The brightness varies more abruptly in blue light than in red light. Consequently, researchers conclude that the innermost parts of a quasar are hotter and bluer than the outer parts. By monitoring caustic crossings using various color filters, astronomers can reconstruct the brightness profile of the quasar.

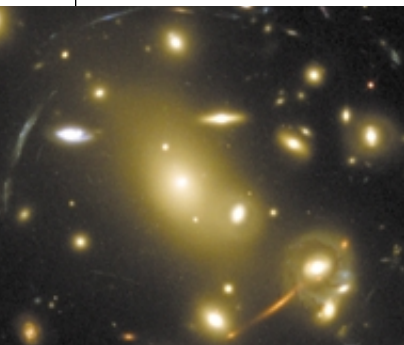


III. Galaxies

The lensing of galaxies betrays the presence of dark matter

GIANT LUMINOUS ARCS

If the lens is not a single galaxy but an entire cluster of galaxies, the image can be a kaleidoscope of strongly distorted arcs and arclets. The first giant luminous arcs were discovered in 1986 independently by Roger Lynds of National Optical Astronomy Observatory with Vahé Petrosian of Stanford University and by Genevieve Soucail of Midi-Pyrénées Observatory in France and her colleagues. Almost 100 such arc clusters have been identified so far, one of the most dramatic being cluster Abell 2218 (*left*).

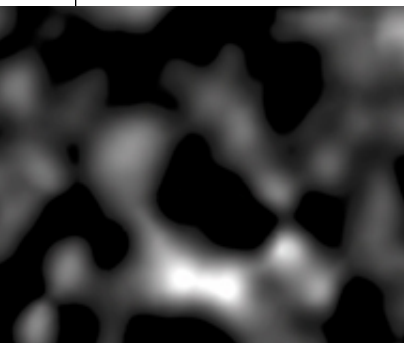


CLUSTER Abell 2218 distorts images of more distant galaxies.

With the help of these images, astronomers can reconstruct the mass distribution inside the cluster. The results, like those of other techniques for measuring cluster masses, imply that clusters are dominated by unseen dark matter. In addition, like multiple quasars, arcs can provide estimates of cosmological parameters such as the cosmological constant. In 1998 Matthias Bartelmann of the Max Planck Institute for Astrophysics in Garching, Germany, and his colleagues used the number of observed arc systems to measure the cosmological constant and came up with a lower value than have scientists using other methods. This discrepancy has not yet been resolved.

COSMIC SHEAR

On extremely large scales, vaster even than galaxy clusters, agglomerations of matter tend to be too broad and smooth to act as powerful lenses. Any distortion of galaxy images tends to get lost in the natural variation of galaxy shapes. But when astronomers analyze thousands of galaxies, they can use statistical methods to look for tiny but systematic distortions. Last year four teams—led by David J. Bacon of the University of Cambridge, Nick Kaiser of the University of Hawaii Institute for Astronomy, Ludovic van Waerbeke of the Canadian Institute for Theoretical Astrophysics and David M. Wittman of Lucent Technologies in Murray Hill, N.J.—independently discovered this very weak lensing effect. The widespread shearing of galaxy images supports the view that the universe is a giant cobweb of matter interspersed with voids.



RECONSTRUCTION of dark matter distribution using weak lensing

IV. Stars

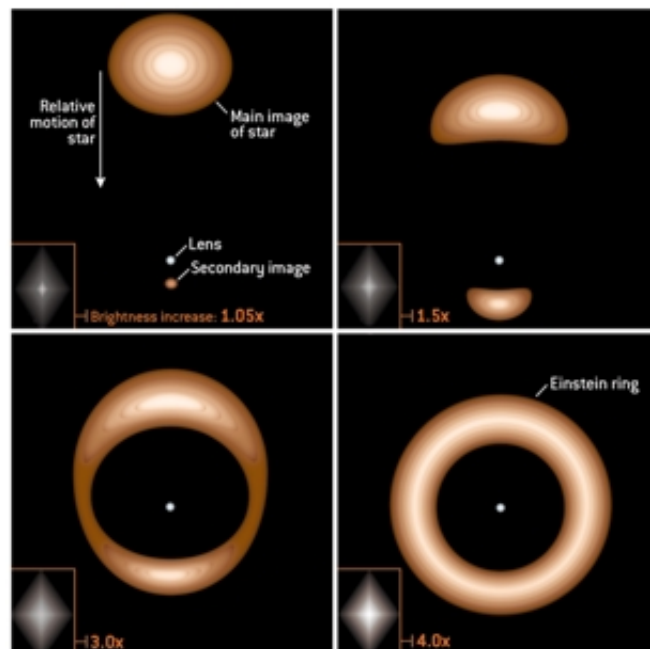
The distortion of stars is too subtle to see directly but shows up as a slow waxing and waning

MICROLENSING OF STARS

Lensing is an ideal way to ferret out the dark matter that lurks in the outermost part of our galaxy, the halo. Some of this dark matter may be exotic elementary particles, but some may comprise macroscopic objects that telescopes, for whatever reason, cannot see directly: rogue planets, dead stars or black holes. In 1986 Bohdan Paczyński of Princeton University suggested a technique to search for such objects, collectively known as MACHOs, or massive compact halo objects.

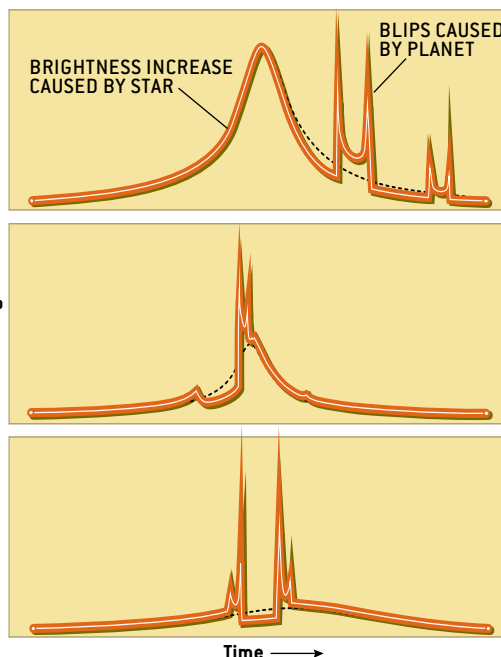
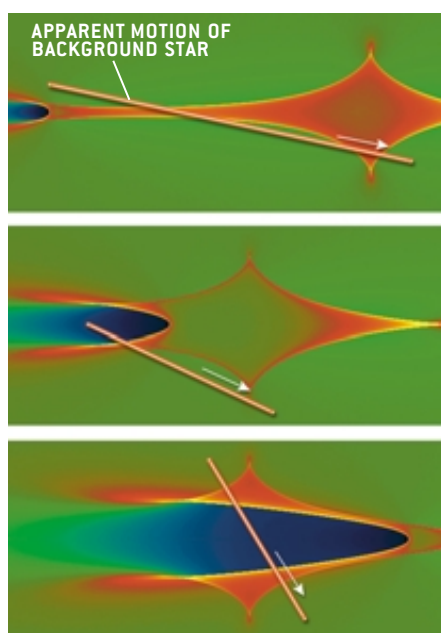
If a MACHO drifts in front of a background star, it will magnify that star and create a second image (*below*). Observers will not be able to resolve the images, but they will notice a temporary brightening. The duration of the event is proportional to the square root of the lens mass. This microlensing effect is relatively easy to distinguish from the other ways in which stars vary in brightness. At any given moment, the chance of such an alignment is only about one in a million. But if observers monitor millions of stars at a time, they should occasionally see a microlensing event.

In the early 1990s several scientific teams, going by a slew of contrived acronyms—notably the French EROS, the American-Australian MACHO and the Polish-American OGLE—started to apply this method. Monitoring stars in the Large Magellanic Cloud, a small satellite galaxy of the Milky Way, the teams saw a total of almost two dozen microlensing events over seven years. These events lasted from a few weeks to several months, implying that the objects had approximately half



IF TELESCOPES HAD high enough resolution, a microlensing event would look like this. In practice, observers see only that the star got brighter.

ANDREW FRUCHTER Space Telescope Science Institute and NASA (Abell 2218); YANNICK MELLIER Institute of Astrophysics of Paris (dark matter); SARA CHEN (microlensing)



SIMULATED STAR-PLANET
microlensing event shows how a little planet can have a big effect on brightness. The color maps (*left*) show how magnification varies with position; the three diagrams correspond to three different distances between planet and star. As a background star moves through one of these maps, it is magnified to a small (*blue*), moderate (*green*), high (*red*) or very high (*yellow*) degree. Consequently, the brightness appears to fluctuate (*right*).

the mass of the sun. The number of events, however, was too low to explain more than a small fraction of the dark matter. Analogous techniques for other galaxies suggest that their dark matter cannot be made entirely of MACHOs, either.

The same teams also monitored stars toward the center of our Milky Way and observed more than 500 microlensing events in that direction, many more than expected. In this case, the lenses were not MACHOs but most likely normal stars with low mass. A small percentage appeared to be double stars, which caused the brightness to vary abruptly because of caustic crossings. Monitoring such caustic crossings can reveal the properties of stellar atmospheres and surfaces—the only way that astronomers have been able to discern such fine detail on distant stars. A few of the microlensing events may have been caused by stellar-mass black holes.

EXTRASOLAR PLANETS

Stellar microlensing can even detect planets. Several teams of observers—the PLANET (Probing Lensing Anomalies Network) group led by Penny D. Sackett of the University of Groningen in the Netherlands, the MPS (Microlensing Planet Search) group headed by David P. Bennett of the University of Notre Dame, and the MOA (Microlensing Observations in Astrophysics) group led by Philip Yock of Auckland University in New Zealand—have taken a detailed look at some of the events seen by the dark matter searches. In two cases, the observers saw a blip—an extra burst of brightening that might have been caused by a planet orbiting the lens star. Typically the blip lasted a few hours and boosted the brightness by a few percent.

Although these planet detections have not been independently confirmed, the principle is sound. It is only a question of time until gravitational lensing reveals an entire list of con-

vincing planet candidates. Most other techniques look for the planet's effect on its parent star, which depends strongly on planet mass or size. But with the lensing technique, even a low-mass planet produces a caustic that leads to high magnification of the background star (*above*).

Five months ago a team of scientists headed by Kailash C. Sahu of the Space Telescope Science Institute detected the flickering of a handful of stars in the central part of the Milky Way. They tentatively interpreted it as microlensing by free-floating planets in the globular cluster M22—an exciting claim that, if confirmed, would have profound implications for the frequency of planetary-mass objects in the galaxy. Prior to this announcement, most astronomers had assumed that planets would be found only orbiting a star, not off on their own in deep space. It is yet another example of how scientists sometimes come closest to the truth when they are studying “illusions.” **SA**

MORE TO EXPLORE

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