Gravity's rainbow
Marcia Bartusiak
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Astronomers are taking advantage of one of nature's tricks — grav

GRAVITY'S

Warrick Couch (University of New South Wales), Richard Ellis (Cambridge University), and NASA

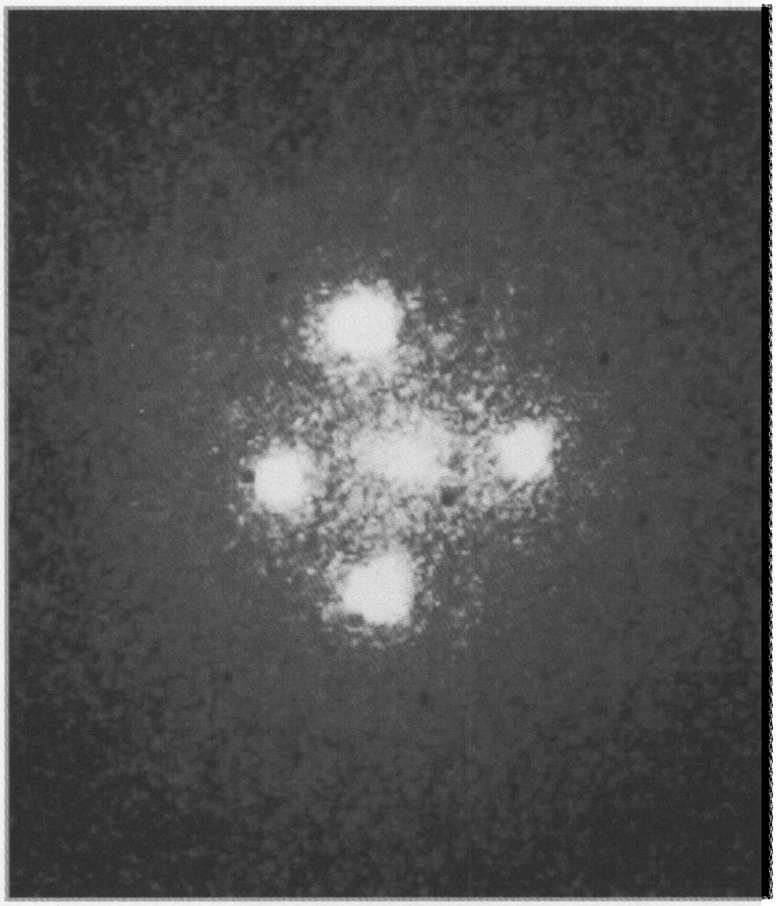
The view is breathtaking. Several bulbous elliptical galaxies sit like contented Buddhas in the middle of Abell 2218, a compact and rich cluster of galaxies situated more than a billion light-years from Earth. A number of bright disks — spiral galaxies most likely — surround them. But there's more. Wispy arcs, 120 in all, encircle the heart of the cluster. The streaks are arranged like the rings of a dartboard. It is one of the universe's most wondrous illusions. The massive cluster is acting like a giant spy glass, only in this case it's the cluster's tremendous gravitational field that is deflecting the light rays passing through it and greatly magnifying the objects that lie far behind Abell 2218. The faint blue arcs are actually the distorted, ghostlike images of distant galaxies that reside some five to ten times farther out than the cluster.

At first, such examples of gravitational lensing were merely cosmic curiosities. But over the last decade, gravitational lenses have evolved into invaluable observational tools, applicable to a host itational lensing — to study the faraway universe. by Marcia Bartusiak

RAINBOW

of key cosmological questions. Astronomers are now using lenses to assess the amount of dark matter in the universe and to pin down the Hubble constant, a measure of the universe's expansion rate (which in turn yields the universe's size and age). And, as witnessed by Abell 2218, lenses can act as telescopic boosters. They take distant galaxies too faint to be seen and bring them into view. In this way, astronomers manage a peek at the universe when it was far younger, a vista difficult to achieve otherwise.

As this Hubble Space Telescope image shows, the massive gravitational clutch of galaxy cluster Abell 2218 acts like a giant zoom lens. The cluster, located 1 to 2 billion light-years away, amplifies and bends the light of more distant galaxies into concentric arcs. Without the lensing effect, the more distant galaxies (which are five to ten times farther than the cluster) would be too faint to be seen even by the most powerful telescopes.



The Einstein Cross is named after the physicist who first predicted gravitational lensing. The bright dot in the center is a foreground galaxy roughly 400 million light-years away. The four surrounding spots are actually a single quasar 20 times farther away, whose light has been gravitationally lensed by the foreground galaxy.

International meetings are now regularly held to discuss the observational uses of gravitational lensing, a sign of the emerging importance of the effect. A special website even keeps track of all the key papers being published. The present count numbers more than 1,500. "It's one of the biggest growth fields in astronomy," says Princeton astrophysicist Edwin Turner, who, over nearly two decades, has witnessed the evolution firsthand.

Progress was a long time coming. Science historians, foraging through Einstein's old notes, recently discovered that the great physicist first thought about gravitational lensing in 1912, three years before completing his momentous theory of general relativity, which serves to explain the effect. General relativity tells us that starlight passing by the sun gets bent — deflected — as it follows the curved warp in space-time carved out by the sun's massive gravitational field. The sun, in effect, acts like a lens. When the glass of an optical lens bends light, it allows the object behind it to be magnified and brightened. A gravitational lens acts in the same way, only now it is gravity doing the work, not a curved piece of glass.

Einstein and others discussed the possibility of lensing occurring farther out in space, as light passed by faraway stars. Depending on the orientation of the "lens" to the background object, the object could be magnified or split into multiple images, as if some giant fun-house mirror were at work. But in 1936 Einstein concluded that "there is no great chance of observing this phenomenon" beyond the sun, since the changes were too small to be detectable.

Lenses Galore

Caltech astronomer Fritz Zwicky had no such qualms. He wrote in 1937 that galaxies offered "a much better chance than stars for the observation of gravitational lens effects." Zwicky was correct, but it would take four more decades before his visionary insight was confirmed. Radio astronomers, while checking the visible counterparts to some radio sources in 1979, chanced upon a close pair of blue objects, identical in every way. It turned out to be a mirage; it was actually two images of the same quasar, known as QSO0957+561. An intervening galaxy, acting as a lens, created the cozy pair, soon labeled A and B. Since then, a couple dozen more systems like 0957 have been discovered. Astronomers also found far away galaxies, not just quasars, being lensed, the galaxies' broader shapes smeared into arcs or rings. Gravity lenses, says Durham University astronomer Ian Smail, are "possibly the cleanest visible signature of the curvature of space-time there is. You can just see it in action."

The Hubble Space Telescope has accelerated the discovery process. Its high resolution allows astronomers to extend their searches to fainter (and hence more distant) lenses. For example, during Hubble's Medium Deep Survey, the telescope imaged two distinctive lenses. They are cross-shaped: Each displays four faint blue images in the form of a cross, around a much brighter and reddish elliptical galaxy.

Cross-shaped, or quadruple, lenses are extremely rare. Previously, only two were known from ground-based surveys of the sky. One, discovered in 1985 and dubbed the "Einstein cross," is a quasar lensed by a nearby bright galaxy. The other, the "clover leaf," is also a multiply imaged quasar. The Hubble crosses hold the promise of allowing astronomers to probe the universe even farther out, although there's a drawback: Telescopes with larger mirrors than Hubble's are needed to obtain useful spectra of the lensed objects — spectra are required to measure distances. "For now, the Keck Telescope is the only instrument powerful enough to get their spectra, but, being ground-based, it may not have sufficient image resolution except on rare days," points out Carnegie-Mellon astrophysicist Kavan Ratnatunga, who helped discover the new crosses. Such spectral studies should be hastened, though, when a new generation of space-borne instrumentation comes on line.

Mapping Dark Matter

One of the most successful uses of gravitational lenses has been mapping the distribution of dark matter in the universe. J. Anthony Tyson, an astronomer with Lucent Technologies' Bell Laboratories in Murray Hill, New Jersey, has devoted a large part of his career to this cause. He takes advantage of the fact that faint galaxies in the far universe are uniformly scattered like grains of sand over the celestial sphere. "And we use these galaxies as 'cosmic wallpaper,'" explains Tyson, "to see them get distorted as their light passes by clusters of galaxies closer in." The ways in which the galaxy images get stretched and smeared depends on the amount of mass in the cluster as a whole. So far, his work is confirming that 90 percent of the mass in clusters is indeed hidden and non-luminous. "Clusters are just whitecaps set within a sea of dark matter," says Tyson.

His best example at the moment is a lens known as CL0024+1654, situated some five billion light-years away. This system was first noticed in 1988, although the Hubble Space Telescope later spotted additional arcs. Based on the positions and distortions of the arcs, Tyson and his colleagues could determine the total mass of the lens, the cluster itself. "It's a gigantic mountain of dark matter, with spikes hanging around the galaxies themselves. It's a bumpy and treacherous terrain. Some forms of dark matter can do that; others can't. Things that wouldn't work would be neutrinos." Those ghostly particles are far too energetic to hang around galaxies in such a fashion. What's needed is something more sluggish, such as WIMPs, weakly interacting massive particles hypothesized in the latest physics theories, or MACHOs — herds of dark, Jupiter-like bodies.

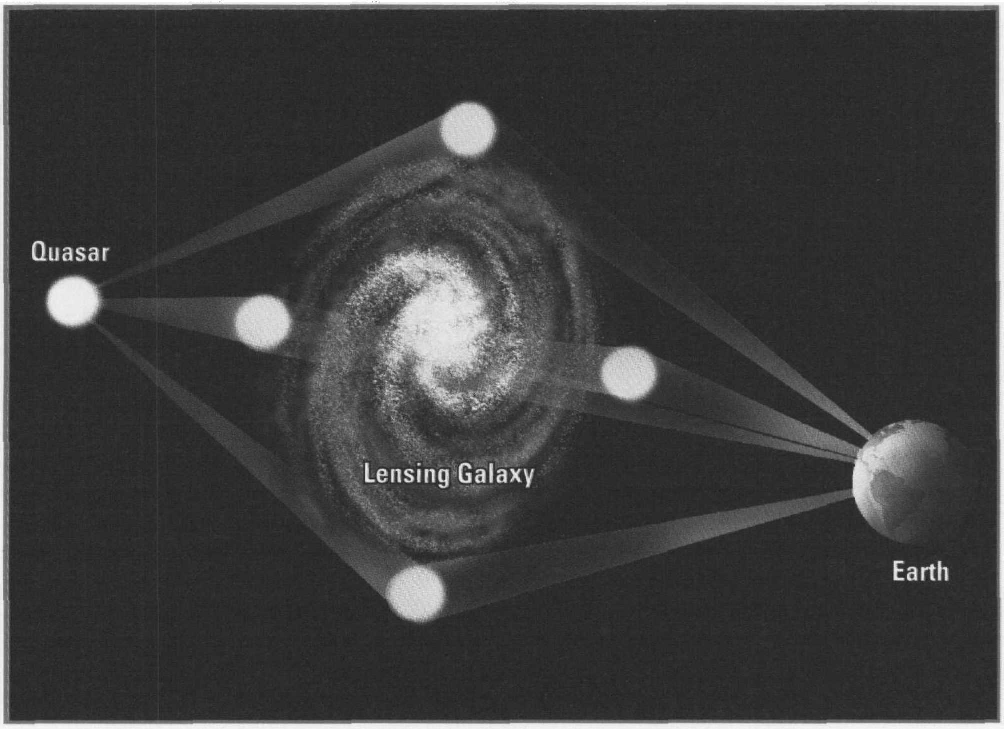
And there's a bonus to such work: With a model of the cluster's size and mass in hand, Tyson and several colleagues were able to reconstruct an undistorted picture of the distant galaxy that 0024+1654 is lensing. The galaxy turns out to be shaped like a ring, a ring that is encrusted with gem-like beads of star formation. It's a glance, perhaps, at a primeval galaxy in the throes of stellar birth. Galaxies such as this tell astronomers what the early universe was like.

Tyson is now concentrating on surveying even larger swaths of sky to see how the dark matter spreads out from cluster to cluster. Is it lumpy? Is it smooth? Answers would provide more clues toward obtaining the proper dark-matter recipe.

Distance Measurements

Ian Smail at Durham, Richard Ellis of Cambridge University, and Jean-Paul Kneib at the Observatoire Midi Pyrenees in France have been using gravitational lensing to estimate a galaxy's redshift, or distance, when the galaxy's spectrum is too faint to be recorded. The more distant a galaxy, the more its light is lengthened — made redder — by the universe's expansion. After obtaining a model of the lens, they assess how the images of distant sources are altered by such a lens. "Basically, the more the galaxy images are distorted — stretched from the galaxy's normal look — the more distant the source," explains Smail. They carried out this procedure on Abell 2218 and determined that the brightest galaxy lensed by the cluster had a redshift between 2.5 and 3.0 (roughly two-thirds of the way back to the Big Bang). A later spectrum found that the true redshift is indeed 2.5. "This was the first time that a redshift, to my knowledge, was predicted from geometry and then confirmed," says Smail. "It was a good day for us." Such a technique, once it's refined, might allow observers to peg distances to objects ten times fainter than currently measured.

It might be argued that the most excitement in this growing field is emanating from those using gravitational lenses to pin down the Hubble constant, the universe's rate of expansion. (For years, the constant has ranged between 50 and 100 kilometers per second per megaparsec, corresponding to an age for the universe between roughly 20 and 10 billion years, respectively; the faster the universe expanded to its current size, the younger it must be.) Astronomers are helped by the fact that quasars often fluctuate in brightness. When the quasar's image is doubled or quadrupled by an



Astronomy: Terri Metzger

intervening cluster or galaxy, the light beams of each image follow slightly different paths, arriving at Earth at different times. The differences in timing, plus a good model of the lens, serves as a tape measure out to the lens. The method itself is complex, but basically, by knowing the different path lengths and the angle of bending, it is possible to obtain a geometric solution, much the way a surveyor on Earth works out distances.

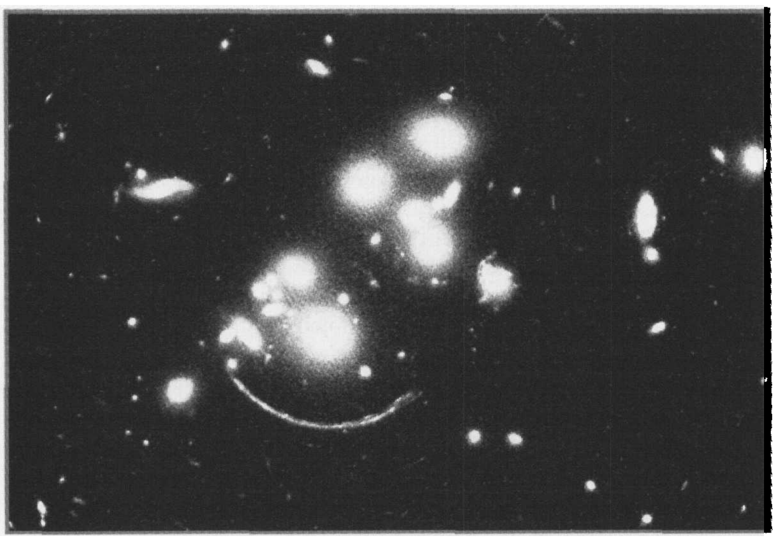
Princeton astrophysicist Turner has been involved in one of the latest tests on the double quasar 0957. Turner and his group first waited for the Apache Point Observatory to open in New Mexico, a state-of-the-art 3.5-meter telescope that allows astronomers to conduct remote observations from their university office computers. That made regular monitoring far easier. "We needed only 10 minutes a night," says Turner. And they looked about every other night for more than a year. "We were lucky," relates Turner. "Within a couple of weeks, the brightness of image A dropped by 15 percent, one of the largest changes observed in that source." About 417 days later, following a longer path, the light of image B dropped, and in the exact same way. From this, the group calculated a Hubble constant of 64, give or take 10 percent. That's a bit lower than more traditional measurements of late. But other gravitational lens groups, in work about to be published, are converging on similar numbers. "Ideally, we want all kinds of techniques to converge on the same answer," cautions Turner.

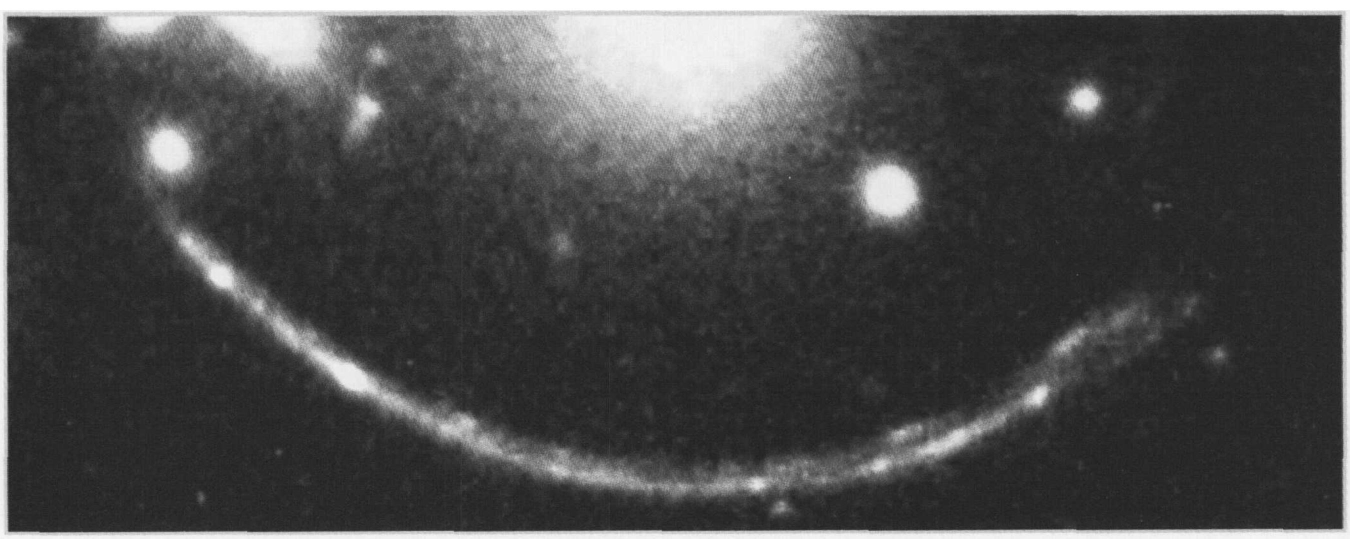
From the standpoint of backyard observing, gravitationally-lensed objects are extremely faint and challenging. One that can be seen with large amateur scopes is 0957+561A and B, which lies in Ursa Major at 10h1m20.7s, +55°53'56". This object is a 17th-magnitude quasar whose light divides into two images due to an intervening galaxy. Spotting it generally requires a 20-inch or larger scope and a black, moonless night.

Yet gravitational lensing does have an edge. Other techniques measure distances in multiple steps, one step outward at a time: from Earth to local stars, stars to nearby galaxies, and from galaxies to clusters. One misstep and all other measurements are off. Lensing, on the other hand, allows astronomers to measure the Hubble constant in one fell swoop across the universe.

Weighing the Universe

Lenses can also test many astrophysical theories, including whether there's an extra "energy" in the cosmos, denoted by a term known as the cosmological constant. Einstein once thought so and incorporated it into his theory of general relativity. But he later took it out. Some cosmologists, though, still like it, because it allows the universe to be a bit older than it looks, so stars don't end up older than the universe. With a cosmological constant, objects are separated by more distance,





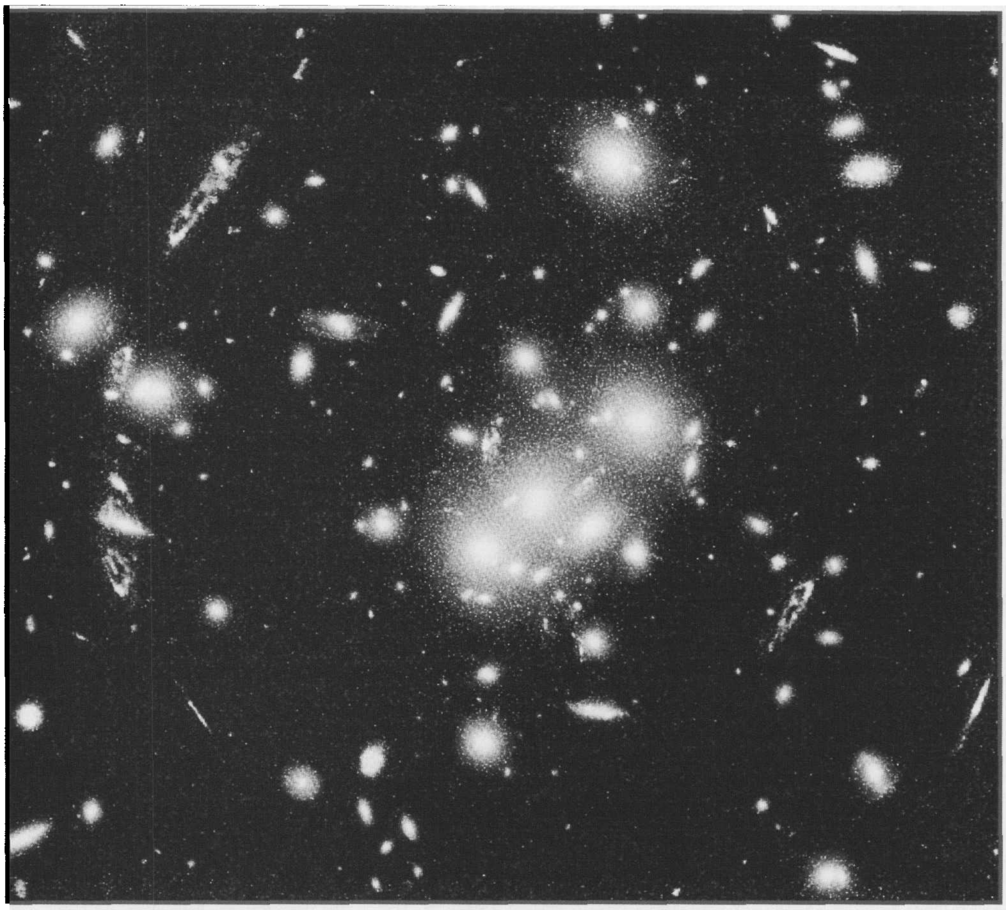
Whether gravitational lensing produces a giant arc or distinct multiple images depends partially upon the exact alignment of the source and lens, but it mostly depends upon the nature of the background object. If it is a point of light, such as a quasar, we will see several distinct images. If it is an extended source, such as a galaxy, the images will usually be merged into a single giant arc.

Bernard Fort (Institut d'Astrophysique de Paris), et al., and NASA/ESA which leads to more lenses per unit volume. But, so far, counts of gravitational lenses seem to rule out a large cosmological constant. If it were large, astronomers would be seeing more gravitational lenses than they do. But a constant hasn't been ruled out entirely; studies continue.

And lenses can be used to "weigh" the universe, to determine whether there's enough hidden mass to cause the universe to collapse someday. Over the last five years, Jeremiah Ostriker and a series of Princeton collaborators have been using supercomputers to build universes filled to the brim with cold dark matter and then predicting how lenses should appear in such universes. In this way, they compare their simulation to the real cosmos and see what matches. Essentially, the more matter there is in the universe, the more chances that lensing can occur. "We numerically shoot rays through this virtual universe to simulate the production of lenses," explains Ostriker. "It's among the biggest numerical simulations ever made. We've recently had one going now [at the Pittsburgh supercomputer center] for about a month." They end up with far too many lenses that are widely separated, ten times more than are seen in the real universe. This may be a strong indicator that the cosmos is fated to expand forever.

Lensing has uses closer to home as well. Einstein would be surprised to learn that lensing by small celestial bodies can indeed be measured right here in the Milky Way's "backyard," thanks to new technologies. The goal is to search for small, dark celestial bodies that might be contributing to the dark matter. A number of programs are being run throughout the world to look at a large stellar population, such as the Large Magellanic Cloud or the galactic bulge, to see if some of the background stars briefly magnify as they are "microlensed" by dark objects passing in front of them.

Awareness of lensing effects is becoming vital, whether an astronomer is a specialist or not. Otherwise, it can lead to some "astronomical bloopers," as Berkeley astronomer James Graham once put it. Take the galaxy FSC 10214+4724. When first discovered in 1991, it was heralded as the most luminous galaxy in the universe. Though bright, it's not as brilliant as previously thought. The Keck Telescope recently revealed that this galaxy is being magnified by a gravitational lens, a foreground galaxy located closer in. Oops, fooled by a gravitational illusion.


Wesley Colley (Princeton University), et al., and NASA

The blue arcs represent the light from a single galaxy located 10 billion light-years away. The galaxy would normally be too faint to be seen, but the lensing effect of the foreground galaxy cluster CL0024+1654, located about 5 billion light-years away, brings it into view. Astronomers can reconstruct the lensed galaxy to find out what galaxies were like in the early universe.

Theorists are even dreaming up new gravitational lens effects. Turner, along with Yun Wang at Princeton, points out that some lensing events could be very extreme, such as tube-like beams of intense radiation coming out of the lens. In a typical globular cluster, for instance, there could be millions of these beams crisscrossing the cluster like celestial spotlights. Each would be strong enough to evaporate dust grains, which might explain the mysterious lack of dust within a globular cluster, says Turner. "I believe gravitational lensing will eventually be seen as one of the major tools for exploring the universe," he says. "If it were a stock, I'd be bullish."

Marcia Bartusiak is a Massachusetts-based science writer and adjunct professor of science journalism at Boston University. Her last article for Astronomy, *"What Makes Galaxies Change?" appeared in the January issue.*