National Aeronautics and Space Administration

Einstein Rings: Nature's Gravitational Lenses

Leonidas Moustakas and Adam Bolton

Taken from: Hubble 2006 Science Year in Review

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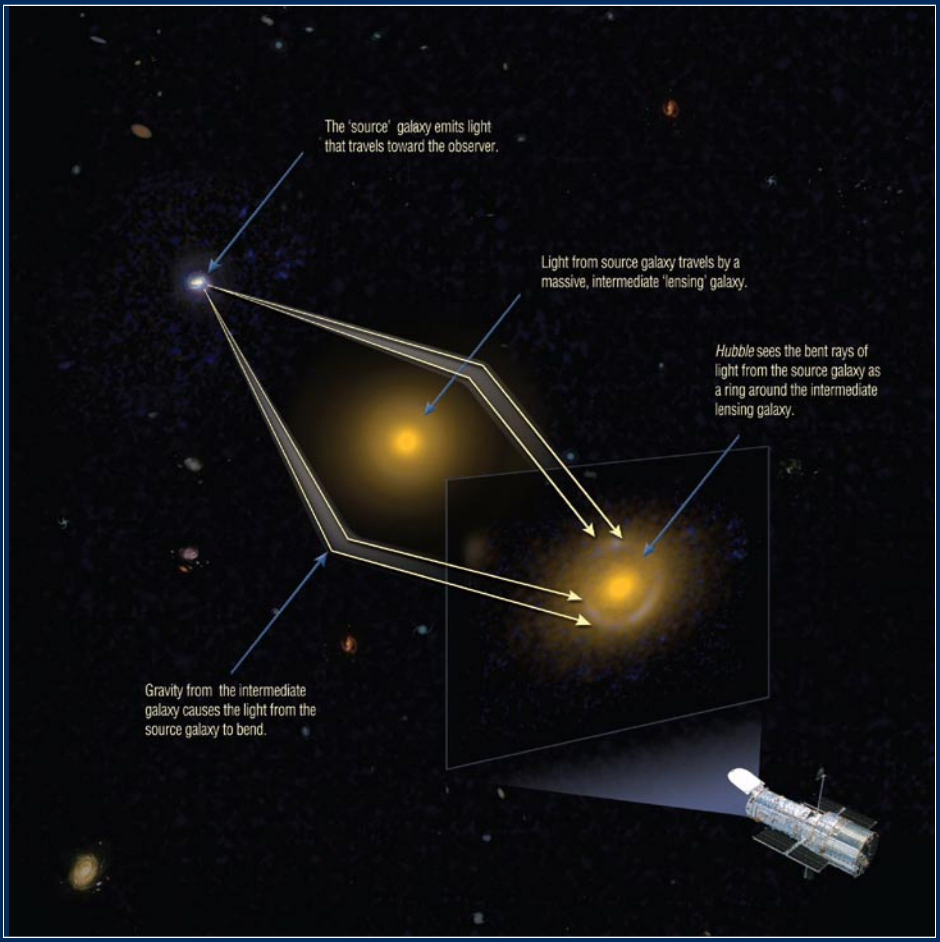
In his General Theory of Relativity, published in 1915, Albert Einstein proposed that gravity bends the path of light. In 1936, at the urging of an amateur scientist, he wrote a brief paper about an optical illusion due to this bending: multiple images of one astronomical source located behind another. With near-perfect alignment, a full "Einstein ring" should appear around the intermediate, lensing object. "Of course, there is no hope of observing this phenomenon directly," Einstein wrote. In his cover letter, he thanked the editor of *Science* for his "cooperation with the little publication, which Mister Mandl squeezed out of me. It is of little value, but it makes the poor guy happy."

Today, the elegant phenomenon of "strong" gravitational lensing—the case when multiple images can occur—makes many astronomers happy. Even though such gravitational lenses are uncommon, many have been found and studied, with *Hubble* playing an important role. Furthermore, lenses are proving to be much more than curiosities. When the lens and source are galaxies, the illusion can teach us about nonluminous and hence unseen "dark matter," hidden structure, and the processes by which galaxies form and evolve.

The angular size of the Einstein ring is determined by the amount of mass—both stars and dark matter—enclosed within it. By virtue of their stronger gravity, more massive foreground galaxies produce larger Einstein-ring images of galaxies in the background. Measuring the mass of galaxies is a difficult, but fundamental, task of astronomy. Lensing, when it occurs, is perhaps the most direct method.

Though gravitational lensing has been studied previously by *Hubble* and ground-based telescopes, this phenomenon has never been seen before in such detail. The Advanced Camera for Surveys image of Abell 1689 reveals 10 times as many arcs as would be seen by a ground-based telescope. It is five times more sensitive and provides pictures that are twice as sharp as the previous *Hubble* cameras; it can see the very faintest arcs with greater clarity.



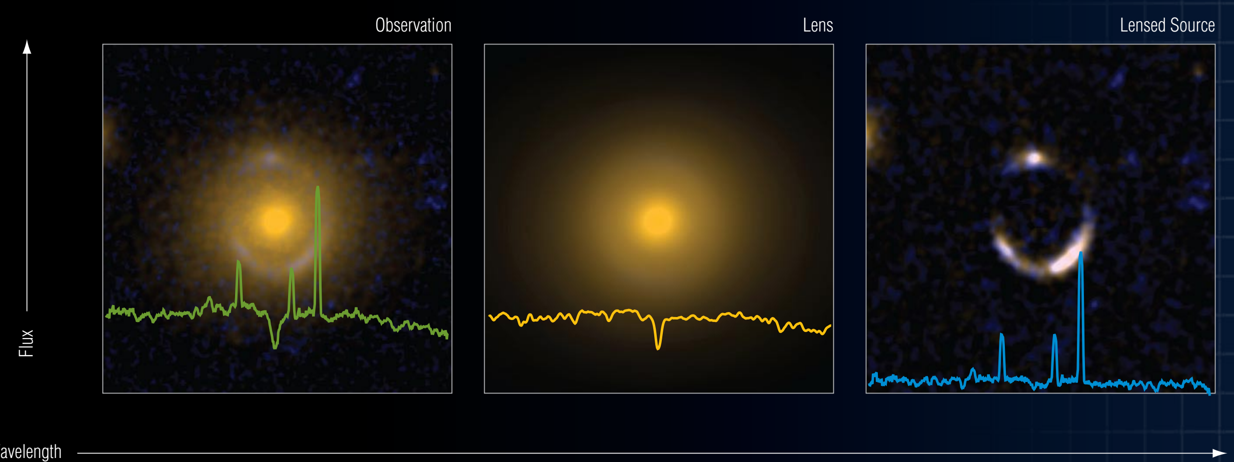
The Optical Illusion of Gravitational Lensing

The more-distant galaxy is the "source," and the intermediate galaxy is the "lens." If the source, lens, and observer are closely aligned, the gravity of the lens will bend some light rays from the source onto new paths towards the observer. To the observer, these bent rays appear as if they originate at points on the sky displaced from the location of lens. Indeed, rays from multiple paths around the lens and at different clock angles may arrive at the observer, creating multiple images of the source. In the case of a near-perfect alignment, it is possible for light rays to be bent towards the observer all around the lens, creating the appearance of a full Einstein ring, as shown!

An Einstein ring does not unambiguously tell how mass is *arranged* within the lensing galaxy. Nevertheless, the arrangement of mass is important for understanding the physical structure of the galaxy and its evolutionary history. We can solve this problem by measuring the distribution, or "spread," of stellar velocities within the lensing galaxy: the faster the stars move, the more the mass must be concentrated towards the center of the galaxy, for gravity to balance centrifugal force.

Until recently, *both* diagnostic tools for studying galactic mass—lensing and velocity spread—were available only for a few objects. Out of the fewer than 100 gravitational lenses known, only a small number were sufficiently near, or luminous enough, to allow accurate measurements of their velocity spreads. To surmount this difficulty, astronomers are now combining two outstanding astronomical resources—the Sloan Digital Sky Survey and the *Hubble Space Telescope*—to find large numbers of new, bright, gravitational lenses, which they can study with great precision from both space- and ground-based observatories.

Begun in 1998, the Sloan survey has imaged roughly one fourth of the sky and measured the brightness and colors of millions of stars, galaxies, and quasars. Using spectroscopy, Sloan has also measured the distances to nearly a million galaxies. (The distances are calculated from the redshifts of the galaxy spectra due to the cosmological expansion of the universe. See the sidebar on quasi-stellar object spectra in Arav's article on active galactic nuclei [AGN] outflow.) Any two objects that are found close together on the sky, but are located at vastly different distances, are prime candidates for gravitational lensing. By sifting through all the Sloan spectra of large, luminous galaxies, astronomers have discovered hundreds of new, bright candidates, which are usually massive elliptical galaxies in front of more distant, faint, star-forming galaxies.



Sloan spectroscopy is key to finding gravitational lenses consisting of two galaxies lined up by coincidence. A difference in distance is indicated by a difference in cosmological redshift, that is, characteristic spectral features appearing at different, redshifted wavelengths. The left panel shows a typical spectrum that the Sloan spectroscopy might observe for a lens candidate (green). This candidate "lensing" galaxy is a giant elliptical galaxy, which exhibits the composite spectrum of myriad typical stars—a spectrum that is well understood and can be easily modeled (middle panel, yellow). When the model spectrum is redshifted to match the absorption lines in the observed spectrum, and then subtracted from the observed spectrum, the spectrum of the distance source or "lensed" galaxy is revealed (blue). It shows "anomalous" emission lines at higher redshift than that of the lensing galaxy.

The Sloan-*Hubble* program has been extremely efficient in finding new Einstein rings. Two of these are shown here (top row). To make the study of the rings themselves easier, astronomers create simple models of the lens galaxies and "subtract" them out of the *Hubble* images. The results for these two lenses are shown in the bottom row.

Finding the true gravitational lenses among the Sloan candidates demands the unrivaled sensitivity and image sharpness of *Hubble*'s Advanced Camera for Surveys (ACS). By the summer of 2006, images have confirmed more than 40 new gravitational lenses. Astronomers are studying the mass distribution in these lenses to better understand how galaxies form and evolve.

Galaxy formation and evolution is a messy business, involving the gravitational force of both normal and dark matter, as well as the myriad processes of normal matter—like star formation, radiation, cooling, turbulence, winds, and chemical enrichment. Adding to the complexity are collisions and mergers between galaxies, and the outflows and jets of supermassive black holes in AGN (which are the subjects of three other articles in this book).

No models or simulations can yet take all these detailed processes into account. Nevertheless, a sufficient theoretical framework is available to make qualitative comparisons with the mass-related results of strong lensing.

From *Hubble* images and Sloan spectra of strong lenses, astronomers gain three types of new information. First, the sizes of the Einstein rings provide the total masses of the lensing galaxies. Second, the images reveal the *shapes* of the lensing galaxies, which are useful for guiding the modeling of mass structure. Third, the Sloan spectra provide initial estimates of the velocity spreads. From this information, astronomers have reached a remarkable conclusion: The mass in the centers of elliptical galaxies has a simple, apparently universal structure, one that has remained the same over most of the age of the universe. Despite the varied, chaotic origins of these galaxies, their luminous and dark matter somehow interact to achieve a single end-state of mass structure. Furthermore, this end-state is very different from the structure predicted for the case of *pure* dark matter, which confirms the dominant role of the processes of normal matter in galaxy evolution.

The Sloan-*Hubble* research program on gravitational lenses will discover more lenses and investigate this growing sample in greater detail. We expect to make a direct determination of how the ratio of total mass to luminosity in elliptical galaxies depends upon galaxy mass. The mass-to-light ratio is connected to the fraction of dark matter in the central region of a galaxy, and holds clues about how and when galaxies formed—clues that we are still deciphering. A dependence of the ratio on galaxy mass has been seen in other types of observations, and it will be determined most accurately by gravitational lensing.

In the future, we expect that spectra from large ground-based telescopes will provide improved measurements of the velocity distributions in individual lensing galaxies, which will improve the accuracy of the measured mass distributions. This will lead to a better understanding of the relationships between the mass distribution and other properties of galaxies, such as the luminosity and the history of star formation.

Sometimes an illusion is much more than it appears, as with Einstein's rings.

Leonidas Moustakas is a Scientist at the Jet Propulsion Laboratory, which is operated by the California Institute of Technology. He has been involved in many searches for gravitational lenses—from the Hubble Deep Field to the *Hubble*-Sloan program—and is currently searching for gravitational lenses in all the *Hubble* data ever taken. He is especially excited about researching the evolution of the structure in the central regions of galaxies, which is only possible with gravitational lenses.

Adam Bolton is currently a Postdoctoral Fellow at the Harvard-Smithsonian Center for Astrophysics in Cambridge, Massachusetts. He devotes most of his time to the study of galaxy structure and evolution using strong gravitational lensing. The *Hubble*-Sloan project originally grew out of the research for his Ph.D. thesis at the Massachusetts Institute of Technology. His work in observational astrophysics combines dual interests in basic physics and amateur astronomy. The *Hubble* images seen here represent a significant improvement over the view through his 8-inch backyard telescope.

The Sloan Lens ACS collaboration also includes Scott Burles, Leon Koopmans, and Tommaso Treu.

Two more examples of new lenses, as in the previous figure. The lens on the right is truly a "cosmic bullseye," where the more-distant source galaxy is just about perfectly aligned with the massive lens galaxy and our view of it from Earth. It is a textbook case of an Einstein ring.