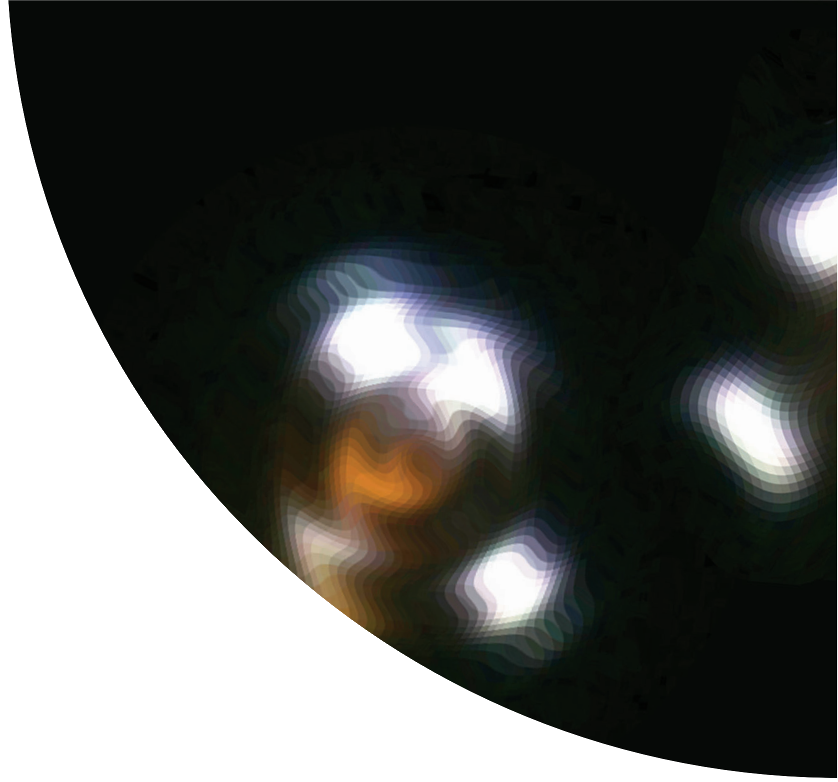
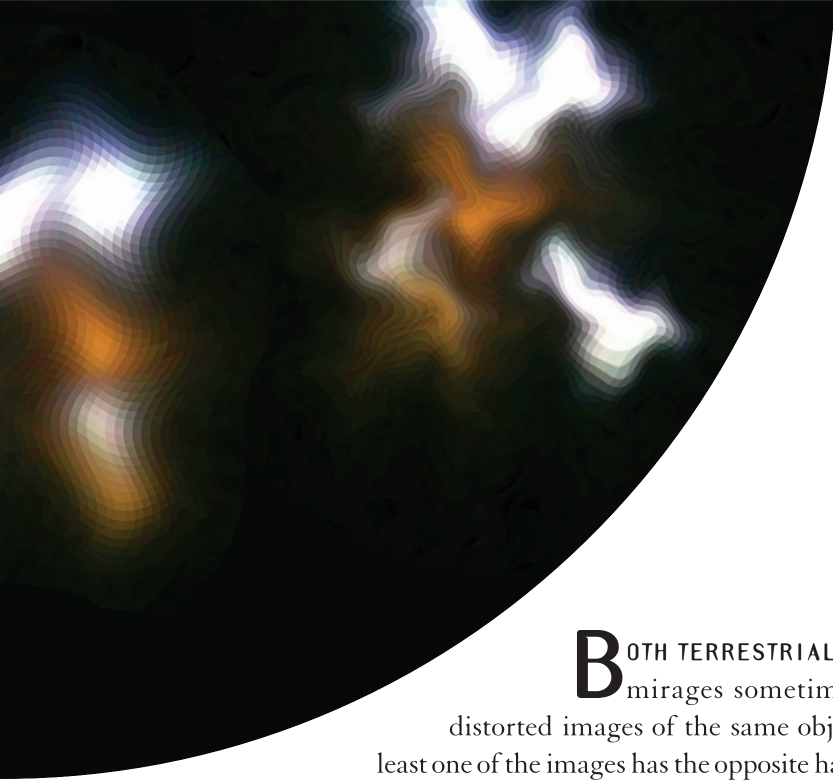


Paul L. Schechter

Einstein's Mirage

The first prediction of Einstein's general theory of relativity to be verified experimentally was the deflection of light by a massive body—the Sun. In weak gravitational fields (and for such purposes the Sun's field is considered weak), light behaves as if there were an index of refraction proportional to the gravitational potential. The stronger the gravitational field, the larger the angular deflection of the light.

The Sun is not unique in this regard, and it was quickly appreciated that stars in our own galaxy (the Milky Way) and the combined mass of stars in other galaxies would also, on very rare occasions, produce observable deflections. Variations in the "gravitational" index of refraction would also distort images, stretching them in some directions and shrinking them in others. In the analogous case of terrestrial mirages, the deflections and distortions are due to thermal variations in the index of refraction of air.



BOTH TERRESTRIAL AND GRAVITATIONAL mirages sometimes produce multiple distorted images of the same object. When they do, at least one of the images has the opposite handedness of the object being imaged—it is a mirror image, but distorted. At least one of the other images must have the correct handedness, but it will also be distorted. The French call such distorted images GRAVITATIONAL MIRAGES.

In the half century following the confirmation of general relativity, the idea that cosmic mirages might actually be observed was taken seriously by only a small number of astrophysicists. Most of the papers written on the subject treated them as academic curiosities, far too unlikely to actually be observed. But in 1979 what appeared to be a close pair of virtually identical quasars was observed. Quasars are very bright distant sources, so light from them sometimes passes near galaxies on its way to us. The suspicion that they were the multiple images of a single quasar expected for a gravitational mirage was confirmed when a galaxy, the source of the needed gravitational potential, was observed between the two images.

In the ensuing quarter century nearly a hundred cases of galaxy potentials producing multiple images of quasars have been discovered. In another hundred cases, clusters of galaxies (with masses 100 to 1,000 times that of a single galaxy) produce multiple images of background galaxies. The galaxy or cluster of galaxies responsible for the mirage is usually referred to as a GRAVITATIONAL LENS (although, as we shall see, of rather inferior optical quality).

“Perhaps the most important outstanding question about galaxies is the amount and distribution of dark matter within them.”

Figure 1 shows four images of a single quasar (HE0230-2130) as lensed by a pair of galaxies. The quasar images appear bluish white while the galaxies appear reddish brown. This particular lensed system was discovered in 1998 by then MIT graduate student Nicholas Morgan. The color image shown here is a composite of images taken at three different wavelengths by Professor Scott Burles with the Baade 6.5 meter telescope of the Magellan Observatory.[1]

Gravitational mirages provide a wealth of information about the gravitational potentials that produce them. Perhaps the most important outstanding question about galaxies is the amount and distribution of dark matter within them. A great many lines of evidence lead us to believe that only 4% of the mass-energy content in the universe is in the form of ordinary matter: protons, neutrons, and electrons. Most ordinary matter is in the form of protons and neutrons, *i.e.* baryons. We call it BARYONIC MATTER. Roughly 30% of the mass-energy content is in something we call DARK MATTER, for lack of a better name or any physical understanding of what it might be.

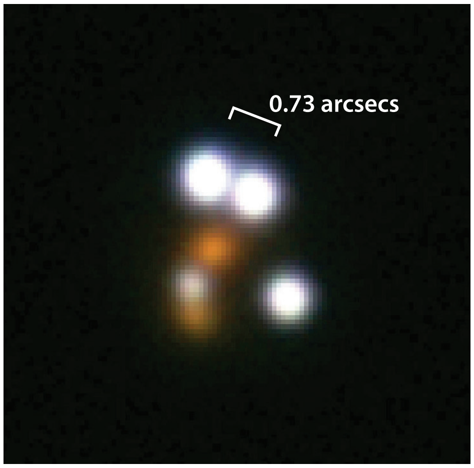


FIGURE 1

A gravitational mirage: *the distant quasar, HE0230-2130, split into four images by a pair of lensing galaxies, as seen with the Baade 6.5 meter telescope. The galaxies appear reddish brown and the quasar appears bluish white. The close pair of bright images obeys the theorem that demands they be of nearly equal brightness.*

Dark matter is the gravitational anchor and trigger for the formation of the observable structures in the universe—galaxies and clusters of galaxies. But the stars and gas that we see are only a small fraction of the total mass. Dark matter and ordinary baryonic matter are fundamentally different in that dark matter cannot cool (or be heated) by radiation. In the course of the formation of galaxies and clusters of galaxies quite a bit of baryonic cooling and heating take place, producing partial segregation of the dark matter and the baryons. Galaxies are almost certainly regions with higher-than-average baryonic content (and lower-than-average dark matter content), but just how much depends upon details of the galaxy formation that are extremely difficult to model. Gravitational lenses give us a handle on the dark matter content.

Typically, one uses a model of the lensing galaxy to predict the positions and brightness of the images of a lensed quasar. Since the quasar is small in angular extent compared to the resolution of optical telescopes, one cannot observe the details of the distortion of an image but only the overall magnification or demagnification of the quasar resulting from that distortion. One adjusts the parameters of the model to get the best possible agreement with the observed positions and fluxes, *i.e.* brightness.

"The most dramatic failure mode is associated with close pairs of images in quadruple images."

Even simple models do a superb job of fitting the position of each image, sometimes to a few parts per thousand. But they often fail abysmally in predicting the brightness, sometimes erring by a factor of two and in one case by a factor of ten.

The most dramatic failure mode is associated with close pairs of images in quadruple images. There is a theorem that says for smooth gravitational potentials, close pairs of images in quadruple systems will be highly magnified and will have very nearly the same brightness. One of these images has the original handedness of the source, while the other has its handedness flipped. The quasar HE0230-2130 in *Figure 1* adheres to the theorem; you see two bright images close together. But a number of recently discovered systems appear to violate it.

The most extreme case was discovered in late 2001 by Naohisa Inada, a graduate student at the University of Tokyo, who found what appeared to be a triple-image quasar. Triple quasar mirages are possible and at least one is known among the multiple-imaged systems. But the triple images are expected to be nearly in a line, and for this system they were not.

We looked at Inada's system in December 2001 with the Baade 6.5 meter telescope and clearly saw a lensing galaxy nestled among the three images. With the galaxy position measured we made a model, but it predicts a fourth image (one with flipped handedness) close to the brightest image and roughly comparable in brightness. Careful examination of Magellan images *(Figs. 2a and 2b)* shows something close to the predicted position, but at roughly a factor of ten fainter than predicted.

Several similar cases have been discovered recently, including two at Magellan with factor of two discrepancies. With the benefit of hindsight, the earliest example of such a system is one discovered by Professor Jackie Hewitt 12 years ago. An interesting pattern has emerged: in almost every case, of the two images to which the theorem applies, it is the image with flipped handedness that is too faint.

Lensed systems with a close pair of images constitute a minority of the known quadruple systems, but other quads also fail to reproduce the brightness ratios predicted by smooth models. And again, it tends to be the images with flipped handedness that are too faint. The failure of simple models to produce the observed brightness ratios is now called the ANOMALOUS FLUX RATIO PROBLEM.

> **"The failure of simple models to produce the observed brightness ratios is now called the ANOMALOUS FLUX RATIO PROBLEM."**

Flux ratio anomalies were actually predicted within months of the discovery of the first lensed quasar. It was argued that the gravitational potential of the lensing galaxy had small scale structure (graininess) because the galaxy is composed of hundreds of billions of individual stars. In the same way that a galaxy deflects and distorts the images of a quasar, sometimes making multiple images, a star can deflect and distort one of *those* images, sometimes further splitting it. The deflections produced by individual stars are a million times smaller than those produced by a galaxy, undetectable with today's telescopes. The changes in brightness that accompany the distortions and splittings are nevertheless detectable. The lensing effects of such stars go by the rubric MICRO-LENSING.

Could micro-lensing produce flux ratio anomalies as large as those seen, preferentially reducing the flux of images with flipped handedness? Yes, but only under special circumstances. In 1995, two colleagues and I tried to explain the flux anomaly in Jackie Hewitt's system. While galaxies are thought to contain a substantial amount of smoothly distributed dark matter, we reasoned that we would maximize the amount of micro-lensing by assuming that the mass in the galaxy was entirely in the form of micro-lensing stars. We were just barely able to explain the observed factor of two discrepancy—it was not outside the realm of reasonable possibility. However, the factor of ten observed in *Figure 2* would have been impossible.

As it turns out, our reasoning was faulty. Counterintuitively, for cases like Inada's and Hewitt's systems, the effects of micro-lensing are maximized by taking roughly three-quarters of the mass in the galaxy to be in a smooth (and presumably dark) component and the rest in stars.

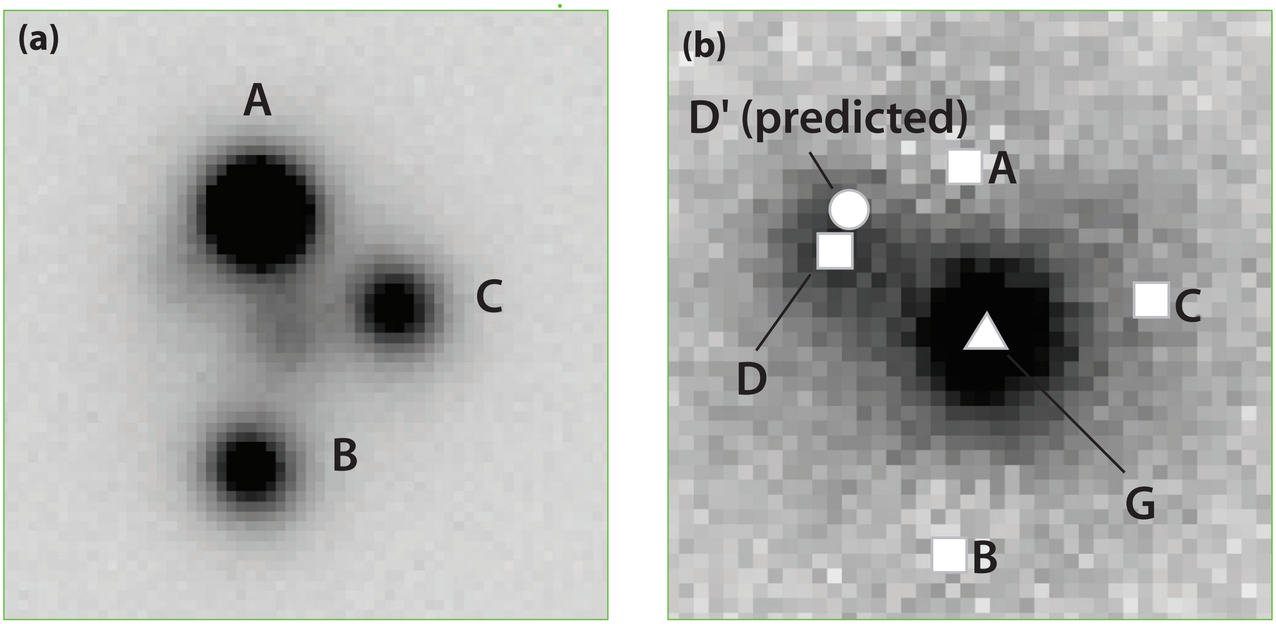
Quasar SDSS0924+0219 (FIGURE 2)

Figure 2a. Three images, labeled A, B, and C, of the quasar SDSS0924+0219, as seen by the Baade 6.5 meter telescope. The faint smudge in between the three images is the lensing galaxy. There is a hint of something protruding at eight o'clock from the bright *A* image.

Figure 2b. The same data shown in *Fig. 2a*, but with the light from images *A, B*, and *C* subtracted. The contrast has been enhanced to show the lensing galaxy, *G*, and a faint something else—a fourth image of the quasar—labeled *D*. The position of the lensing galaxy and those of images *A, B*, and *C* can be used to generate a model for this system that predicts a fourth image at position *D*.

Our embarrassment at having missed this point is more than compensated for by our delight in having found a way to measure the smooth dark matter content of galaxies. The idea would be to compute the fluctuations expected for a sample of quadruple lenses assuming varying proportions of smooth (dark) and grainy (stellar) matter, and to compare these with observations for a sample of quadruple systems. With twenty systems we can begin to set interesting limits on the dark matter content.

There is, however, more to the story. Our interpretation for the observed flux anomalies requires substructure in the gravitational potentials of the lensing galaxies that is small compared



to the image separations. Stars certainly qualify as substructure, but there is another possibility.

Most of the dark matter in galaxies is expected to be smoothly distributed. But roughly 10% is expected to be in clumps (fossils of early generations of cosmic structure), with masses roughly one millionth the mass of a galaxy but still a million times more massive than a star. Such clumps would produce deflections one thousandth the size of the deflections produced by galaxies. The clumps act as millilenses. There is as yet no observational evidence for this prediction, but they would also produce flux ratio anomalies. As is often the case in astrophysics, there is a surfeit of explanations.

Fortunately we have a method for distinguishing between the two possibilities. Both micro- and milli-lensing depend crucially upon the source being small in angular extent compared to the deflections caused by the micro- or milli-lenses. Quasars are complex objects. They have broad emission lines, due to atomic species such as hydrogen, carbon, and nitrogen, that arise in a region that is large compared to the deflections produced by micro-lenses. And they have thermal continuum emission between the lines that arises in a region smaller than the micro-lensing deflections. If the observed anomalies are due to micro-lensing and not milli-lensing, they should manifest themselves in the continuum but not in the emission lines.

Conversely, if the emission lines exhibit the same flux ratio anomalies as the optical continuum, dark matter clumps must be responsible. In the coming year, Scott Burles and I will be measuring emission line flux ratios using the Hubble Space Telescope and the new IMACS spectrometer on the Magellan I (Baade) telescope. One way or the other, we will be getting a handle on the dark matter content of galaxies, smooth or clumpy.

"Our embarrassment at having missed this point is more than compensated for by our delight in having found a way to measure the smooth dark matter content of galaxies."

ENDNOTE

1. The Magellan Project was a collaboration between the Observatories of the Carnegie Institution of Washington (OCIW), the University of Arizona, Harvard University, the University of Michigan, and MIT, to construct two 6.5 meter optical telescopes in the southern hemisphere. The telescopes are located at Las Campanas Observatory, at an altitude of 8000 feet in the Chilean Andes, and operated by OCIW. MIT's participation in the consortium was made possible by the generosity of Neil (EE '64) and Jane Pappalardo and Cecil (EE '23) and Ida Green.

PAUL L. SCHECHTER *is the William A.M. Burden Professor of Astrophysics at the Massachusetts Institute of Technology. He is an observational astronomer who studies galaxies and clusters of galaxies and the distribution of dark matter therein. Schechter earned his A.B. from Cornell in 1968 and the Ph.D. from Caltech in 1974. He served on the faculty at Harvard and the staffs of the Kitt Peak National Observatory and the Mt. Wilson and Las Campanas Observatories before coming to MIT in 1988. For the last several years, he has been carrying out ground-based optical and Hubble Space Telescope observations of the mirages produced by extragalactic gravitational potentials.*

Schechter was the Chair of the Science Advisory Committee for the Magellan Telescopes project, and was recently elected to the National Academy of Sciences for "distinguished and continuing achievement in original research."