MAPPING DARK MATTER WITH GRAVITATIONAL LENSES

Most of the matter in the cosmos can't be seen directly at any wavelength. But we can map and weigh great clumps of this dark matter as they bend the light shining through them from distant background galaxies.

Anthony Tyson

Through the long-range force of gravity, mass controls the evolution of the universe. Studies of the internal motion of large, gravitationally bound systems such as galaxies and clusters of galaxies have already shown us, rather convincingly, that the mass in these systems is dominated by some form of matter that is not luminous at any wavelength from radio to x ray. (See the article by Scott Tremaine in PHYSICS TODAY, February, page 28.)

The total mass of this "dark matter" exceeds that attributable to luminous matter—stars, gas and dust—by at least a factor of ten. Even without surveying the vast space between clusters of galaxies, astronomers have already concluded that there is enough dark matter within the clusters to add up to 20% of the critical "closure" density ρ_c, given by $3H_0{}^2/8\pi G$, where G is the gravitational constant and H_0 is the present Hubble constant. Unless the present mean mass density of the universe exceeds ρ_c, the Hubble expansion will continue forever. The current fashion in cosmology is to suppose that inflation in the first moments after the Big Bang has brought us almost precisely to the closure density.

Until recently, all the evidence that dark matter dominates the mass of large stellar systems has come from dynamical observations: redshift measurements of the line-of-sight velocities of galaxies moving within clusters and of stars and gas clouds orbiting within galaxies. Applying energy conservation and the virial theorem (which assumes that statistical equilibrium has been reached) to such a gravitationally bound system, one always finds that the total mass within any distance from its center is much larger than the stars and gas clouds can account for. In galaxies and clusters, the observed dispersion of velocities about the mean is so large compared with what one would expect from assigning one solar mass per solar luminosity that one might think these systems are not gravitationally bound. Thus unseen matter has to be invoked just to provide gravitational binding against the rapid internal motion we do see.

Gravitational lensing

The redshift measurements have provided strong dynamical evidence for dark matter on scales from galaxies to superclusters of galaxies. But it is worthwhile to explore independent techniques that do not rest on assumptions about stellar and galactic orbits. My colleagues and I have chosen to look for the gravitational deflection of light from very distant sources by dark matter in the foreground. By this means we have sought to map and weigh the dark matter in several large clusters of galaxies. Our collaboration includes astronomers from Bell Labs, Princeton University, the University of Arizona, the University of Cambridge, the Institute for Advanced Study, the National Optical Astronomy Observatories and the Toulouse Observatory.

Arthur Eddington's famous solar eclipse expedition of 1919 was the first to measure gravitational lensing by a celestial body, thereby verifying the prediction of general relativity and making Einstein a household name. When a photon passes close by the Sun or any other sufficiently massive foreground system, visible or invisible, the gravitational bending of its path makes the source appear to be at an altered position. The bending angle is just

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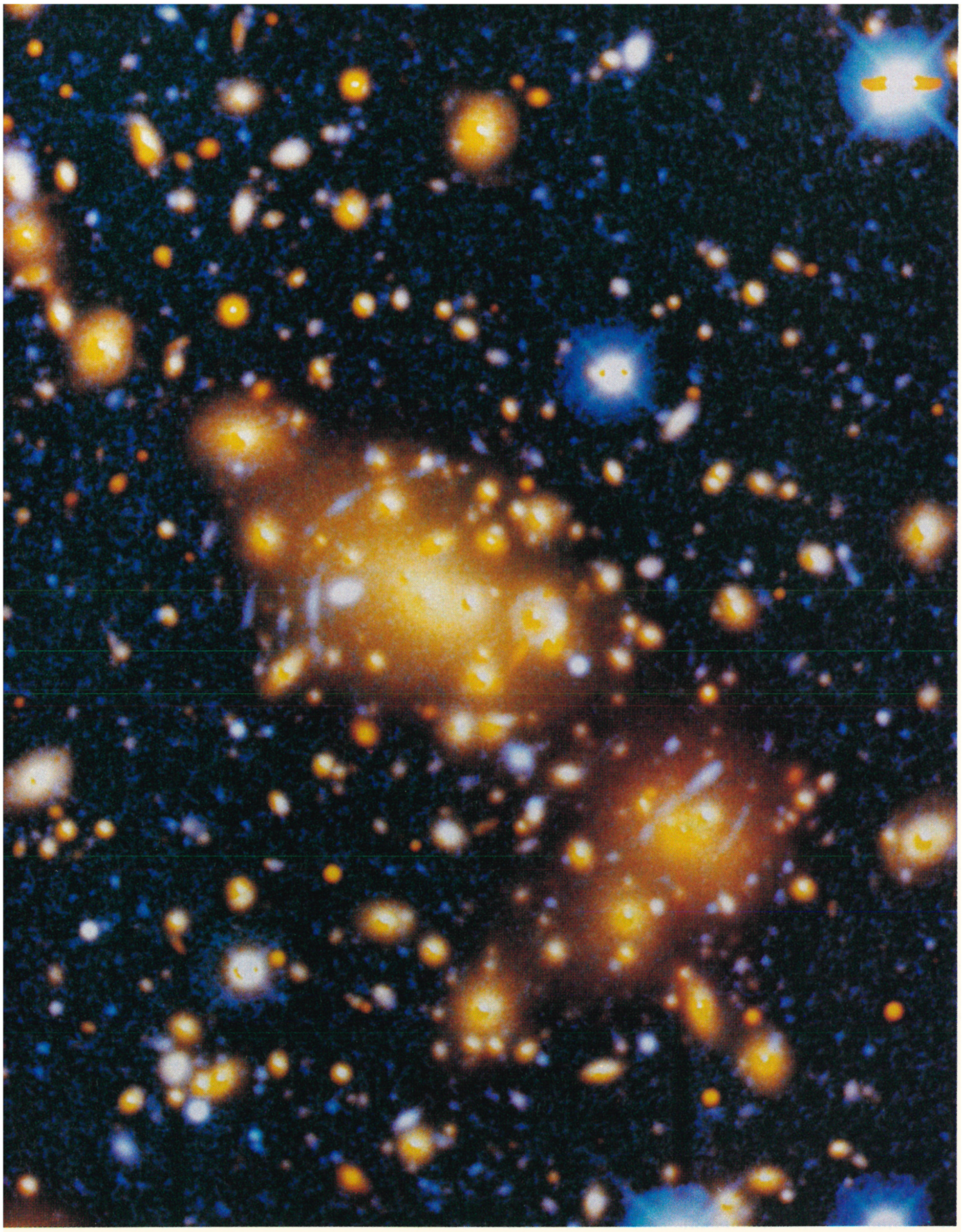


Faint blue arcs circling a massive cluster of reddish-yellow galaxies are actually much more distant blue galaxies elongated by gravitational lensing as their light passes through the cluster Abell 2218, whose redshift is only 0.17. These distorted background images can provide a map of the mass of the foreground cluster, most of which is otherwise invisible dark matter. This CCD image, 4 arcminutes wide, was taken by Gary Bernstein and the author at the 4-meter telescope on Kitt Peak. **Figure 1**

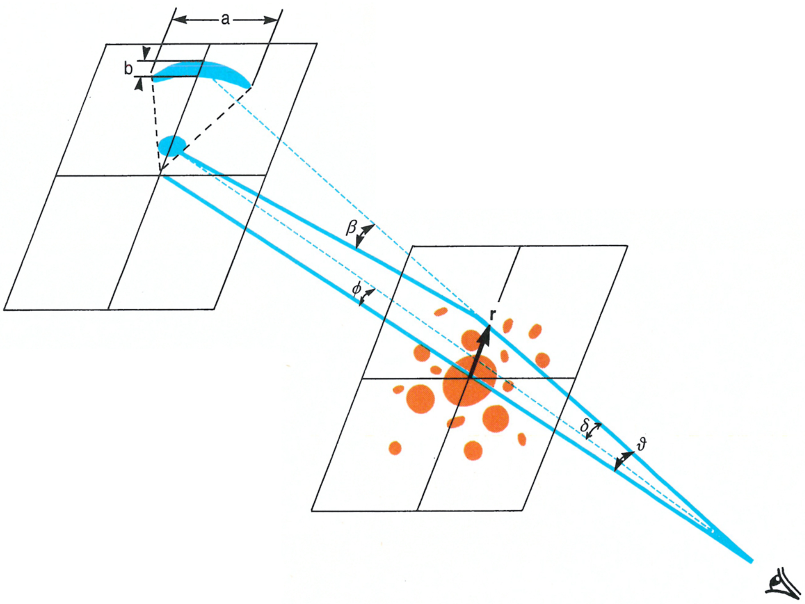
twice the Schwarzschild radius of the massive body divided by the impact parameter. In this way, a clump of dark matter in the foreground will act as a gravitational lens, systematically distorting the images of more distant background galaxies. (See figure 1.)

As shown in figure 2, light from a distant galaxy passing through a foreground mass concentration at a closest distance r from its center will be gravitationally bent through an angle $\beta = 4GM(r)/rc^2$, where $M(r)$ is the total mass *interior* to the projected radius r. In addition to being displaced, the image of a sufficiently wide backgroung galaxy can also be severely distorted. A galaxy of angular size 1 arcsecond seen through a foreground cluster may be elongated into a circular arc many arcseconds long.

Suppose the lensing foreground mass is a cluster of galaxies whose dark mass component we seek to map out by measuring the distorted images of the background galaxies. Because a photon traverses the foreground cluster in a time much shorter than the typical orbital periods of the cluster galaxies, one is in effect taking a snapshot. It is not necessary to assume, as one must in the dynamical dark matter searches, that the cluster is an equilibrated bound state. Other mass estimates, based on x-ray flux maps, rest on assumptions about the state of the hot gas. Our technique does not even require the observation of any radiation from the system being weighed. Gravitational lensing could be used to discover mass concentrations that are entirely dark.

Dark matter and evolution

One of the central questions of cosmology and the evolution of galaxies is the role played by dark matter. As the universe expands, regions with a sufficient overdensity of dark matter will tend to collapse gravitationally, generating structures that survive today in the clustered and filamented distribution of galaxies and its underlying dark matter. If we knew the distribution of dark matter at



Gravitational displacement and distortion of the image of a distant background galaxy (blue) by a compact foreground cluster of galaxies (orange). A light ray passing the cluster plane at an impact parameter vector **r** is gravitationally bent through an angle β. Thus we see it displaced (through an angle δ) from ϕ, its true angular distance from the cluster centroid, to the larger angle ϑ. Because of its finite width, the image also is distorted into a circular arc (of length a and width b) concentric with the cluster. **Figure 2**

any epoch in the evolution of the universe, we could calculate it at some other epoch and examine its physical implications. Was the dark matter that now resides in galactic clusters assembled along with the galaxies, or did pre-existing dense clumps of dark matter help to seed the formation of galaxies and clusters of galaxies?

Some dark matter candidates would have performed this seeding task more efficiently than others. Models in which the thermal motion of dark matter particles is too relativistic, for example, don't produce enough structure on the 10-kiloparsec scale typical of galaxies. (A parsec, abbreviated pc, is about 3 light-years.) On the other hand, models in which dark matter particles are too cold produce too much structure on the megaparsec scale of clusters of galaxies. For example, if relativistic neutrinos weighing no more than a few electron volts dominated the mass density, mass could not clump gravitationally on the galactic length scale. The free-streaming light neutrinos would prevent the growth of galaxies.

The line-of-sight component of a galaxy's velocity is measured by its Doppler shift z, the fractional wavelength displacement of its spectral features. In the universal Hubble expansion all distant galaxies are redshifted. The more distant the galaxy, the greater is its redshift. Light from a galaxy at a redshift of $z \equiv \Delta\lambda/\lambda = 1$, for example, has been on its way to us for half the age of the universe. In cosmology it is often convenient to use z as *the* indicator of distance.

Of course cosmological redshifts are modified by internal motion within galaxies and clusters. Within a cluster of galaxies there is a dispersion about the mean redshift related to the local gravitational potential. Dynamically determining the mass of a cluster from its internal motion requires that one measure the redshifts of many of its galaxies. Gravitational lensing gives us a second, independent determination of the mass of such a cluster, thus providing a valuable check on the virial and orbit assumptions underlying dynamical mass estimates. Furthermore, because clusters of galaxies are dominated by dark matter, the detailed distribution of mass in a cluster may provide a useful constraint on our conjectures about the nature of dark matter. One wants to know on what distance and time scales it clumps and how its spatial distribution relates to that of the cluster's luminous matter.

Our preliminary lens studies appear to confirm the large dark masses in rich galaxy clusters suggested by the virial theorem calculations using velocity dispersion data. We find that the dark matter distribution in a cluster looks like a smoothed distribution of the galaxies in the cluster. In the rich clusters we have studied thus far, there is evidence that the dark matter distribution has a soft core of up to 70 kpc radius. Because we don't yet know well enough how fast the density falls off outside this core, it is difficult to estimate the *total* dark mass associated with a rich cluster. If, for example, the density fell off like r^{-2} with no outer cutoff, the mass integral would diverge!

These gravitational lensing investigations promise to do more than just complement the dynamical studies of galactic clusters. Looking for lensing distortions of background galaxies in the "empty" regions between foreground clusters, we may well find concentrations of dark matter where there is no luminous matter to be seen.

The background galaxies

Optical images of the extra-Galactic sky show a variety of galaxies of diverse luminosities, shapes and distances. At the limit of what can be seen with photographic surveys, one finds as many as 18 000 faint galaxies per square degree.[1] With modern charge-coupled devices one can look farther out. During the past decade, ultradeep CCD imaging[2] over the wavelength range 0.3–1 micron has revealed a surprisingly dense and ubiquitous population of faint blue galaxies. Exposing CCD detectors sensitive to as little as one photon per pixel per minute at the 4-meter Interamerican Observatory telescope on Cerro Tololo in the Chilean Andes, we have found more than 300 000 of these faint blue background galaxies per square degree of sky.[3] This is the backdrop we exploit to study foreground concentrations of dark matter. Of course this previously unknown background of faint blue galaxies also deserves study for its own sake.

Figure 3 is a CCD color image of a randomly chosen 4.5×5.7 arcminutes of sky. These faint blue galaxies are, in general, too dim for spectroscopic measurement of their redshifts at existing telescopes. But several indirect indicators put their redshifts z between 0.5 and 3. We are probably seeing these galaxies early in their lives, when star formation was rampant. The resulting abundance of hot massive stars would shine brightly in the ultraviolet. Severely redshifted by a journey of billions of years, the ultraviolet from these young stars would now look like the blue spectra we see. The unusual blue color and low surface brightness of these background galaxies is particularly convenient for the use we make of them: They are easy to distinguish from the red galaxies of the foreground cluster whose dark matter we seek to map. We are seeing the latter at much more advanced ages, when most of their stars are old and red. Their star-forming gas has long since been swept away.

How do we know that most of these faint galaxies have redshifts of less than 3? Ultraviolet light traversing hydrogen gas exhibits a sharp spectral cutoff at 912 Å, the hydrogen ionization threshold. At wavelengths below this "Lyman break," stellar photons are heavily absorbed by the interstellar gas of their galaxy of origin. With a terrestrial telescope one can't see the Lyman break for most galaxies, because ultraviolet wavelengths shorter than about 3200 Å don't get through our own atmosphere. But if the z of a galaxy in question is high enough, the Lyman break can be redshifted all the way up to accessible wavelengths. The fact that our observations of the faint blue galaxies do not show any clear sign of a short-wavelength cutoff[4] tells us that few if any of these background galaxies exceed a redshift of 3.

We can't, in general, measure the redshifts of individual faint blue galaxies. But we do have rough statistical limits. The faintest galaxies for which spectroscopic surveys are available show a redshift peak at about $z = 0.4$. But the bulk of the faint blue population is over 16 times fainter than these faintest spectroscopically surveyed galaxies. The strongly lensing foreground clusters have redshifts up to about 0.4. So we can conclude that most of the background galaxies lie beyond $z = 1$. Some are certainly as far away as $z = 2$. That is, their light began its journey to us when the universe was only a third of its present size.

The first lenses

The idea that a massive foreground object would significantly distort the image of a background object is an old one. In 1937 Fritz Zwicky argued that galaxies would act as gravitational lenses, distorting and amplifying background objects.[5] The light deflection is proportional to the mass in the lens. For a typical galaxy it's about 2 arcseconds.[6]

In figure 2 the true angular distance between the distant galaxy and the centroid of the foreground cluster is ϕ. As a result of the bending of the traversing light by the cluster, the background source appears to us to be at the larger angular distance ϑ. The lensing displacement $\delta \equiv \vartheta - \phi$ is related to the gravitational bending angle β by

$$\delta = (D_{\rm LS} / D_{\rm S})\beta$$

where and $D_{\rm LS}$ and $D_{\rm S}$ are the lens–source and observer–source distances.[6] In the thin-lens approximation, we treat the cluster as a two-dimensional system, labeling the projected impact parameter of a ray by the two-dimensional vector $\mathbf{r}$. Then the bending angle β is given in terms of the projected two-dimensional mass density distribution σ by

$$\beta(\mathbf{r}) = \frac{4G}{c^2} \int \frac{(\mathbf{r} - \mathbf{r}')\, d^2\mathbf{r}'\, \sigma(\mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^2}$$

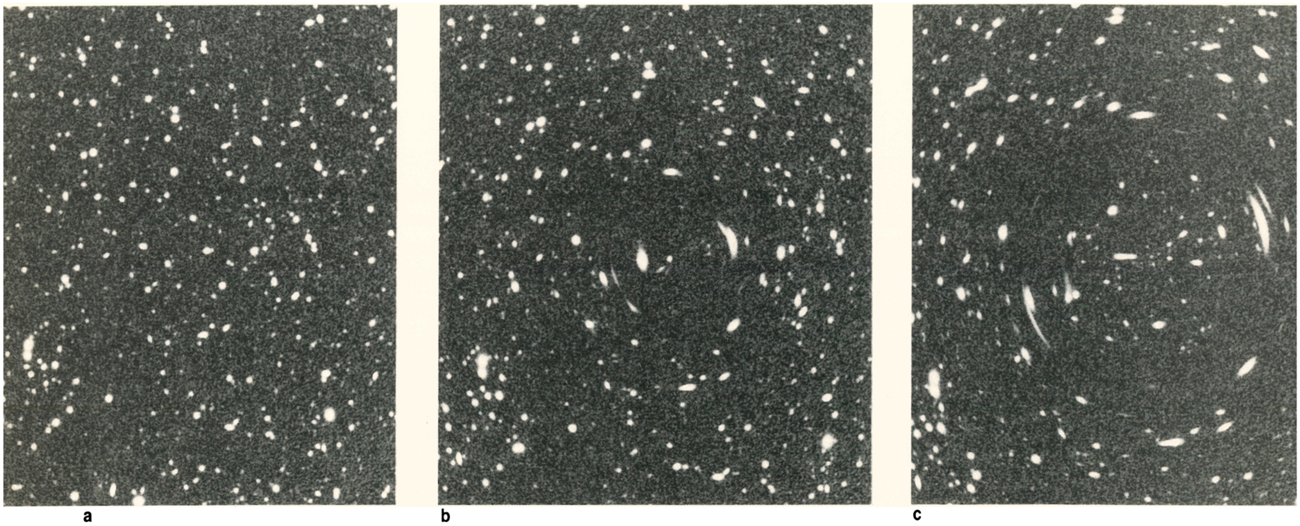
Because we don't know the true, unlensed position of the background source galaxy on the sky, we can't measure β. But its shear—that is to say, the gradient of the gravitational bending—is observable. For most foreground mass distributions we can simplify the integral equation above. If the projected density distribution $\sigma(\mathbf{r})$ of the foreground cluster can be expressed as a sum of circularly symmetric components, the vector arguments reduce to scalar angles. In the simple case of a foreground point mass, $\beta = 4GM/rc^2$, where $2GM/c^2$ is the Schwarzschild radius of the mass M.

A source galaxy exactly behind this point mass would appear as an "Einstein ring" image of radius

$$\vartheta_{\rm E} = \sqrt{(M/10^{11}\ M_\odot)\,(D_{\rm LS} \times 10^9\ {\rm pc}/D_{\rm L} D_{\rm S})}\ {\rm arcsec}$$

where $M_\odot$ is the mass of the Sun. If the lensing mass is elliptical or otherwise not circularly symmetric, this ring symmetry is broken. Therefore complete, circular Einstein rings are rare in the heavens. If the source angle ϕ is

Ubiquitous background of distant faint blue galaxies shows up on this deep CCD survey image of a random 4.5×5.7-arcminute field of sky. Three different filters were used to produce the color image. The digital output reveals more than 300 000 such faint background galaxies per square degree of sky. Most of them have redshifts between 0.5 and 3. **Figure 3**



Computer simulations of a background field of faint blue galaxies seen through a gravitational lensing foreground cluster (not shown) whose mass, as measured by its velocity dispersion, is a variable parameter. In **a** the cluster mass is set at zero, so there is no gravitational lensing. In **b** the velocity dispersion of the cluster's galaxies is 1200 km/sec. In **c** a greater cluster mass produces more distortion. Here the velocity dispersion is 1800 km/sec. **Figure 4**

less than ϑ_E, one sees two images of the source, separated by about $2\vartheta_E$.

How big are these effects? Single galaxies acting as lenses of about 10^{12} solar masses will produce multiple images with separations on the order of 3 arcseconds. Cluster lenses with masses of about $10^{14}\ M_\odot$ can produce image separations as large as an arcminute. For a gravitationally bound collection of luminous objects, the virial theorem lets one deduce the total mass, visible and invisible, from the observable velocities. The theorem states that the binding energy of the system equals its internal kinetic energy. It follows that $\langle \Delta v^2 \rangle$, the square of the velocity dispersion of observable components within a distance r of the center, equals $GM(r)/r$. For an equilibrated, isothermal distribution of gravitationally bound masses, the gravitational bending angle β will just be $4\pi\langle \Delta v^2 \rangle / c^2$. (Isothermality implies that mass density falls like r^{-2}.) The velocity dispersion also gives the Einstein-ring size:

$$\vartheta_E = \frac{29(D_{LS}/D_S)\langle \Delta v^2 \rangle}{(10^3\ \text{km sec}^{-1})^2}\ \text{arcsec}$$

Many clusters of galaxies have measured velocity dispersions on the order of 10^3 km/sec. One can calculate the gravitational bending for fairly realistic mass distributions,[7] for example a soft-core isothermal sphere, by substituting the appropriate projected density $\sigma(\mathbf{r})$ into the integral that gives $\beta(\mathbf{r})$. Generally the image distortion or, in the case of split images, the separation between images depends only on the mass distribution interior to the impact parameter r.

In 1973 William Press and James Gunn at Caltech pointed out that a cosmologically significant density of massive foreground objects would produce distorted and split images of background galaxies.[8] The first gravitational lens was discovered six years later: a distant quasar split into at least two images by the gravity of a foreground galaxy.[9]

In the 13 years since that first discovery, only eight more unambiguous split quasar images have been found, in searches that looked at a total of more than 4000 quasars. In several of these cosmic mirages the gravitational lensing clearly seems to be done by an isolated foreground galaxy dominated by its dark matter. The rarity of these lensed quasar images is consistent with the known abundance of quasars and foreground galaxies. The effective mass M and radius R of the foreground lensing galaxy can be deduced from the distortion of the quasar image. One finds M to be on the order of $10^{12}\ M_\odot$ and M/R around $3\times10^{10}\ M_\odot$/kpc. This is in accord with typical virial theorem results for heavy galaxies.[10] Dark matter appears to account for about 90% of M.

With so few gravitationally lensed quasar images in hand, we can't learn very much about the mass distributions in the lenses. These background quasars typically have redshifts on the order of 2. At these redshifts we can see a lot more galaxies than quasars. So if we want to find out as much as possible about dark matter in the foreground we must avail ourselves of the great abundance of background galaxies rather than the occasional quasar.

Galaxy clusters as lenses

When we first got into this business we used the distortion of background galaxies to set limits on the putative dark matter halos of individual foreground galaxies.[11] But with individual galaxies doing the lensing, the image distortions were painfully small whenever the source and lens were separated by more than a few arcseconds.

In 1981 Arthur Hoag of Lowell Observatory pointed out a peculiar blue arc near a bright galaxy in the cluster Abell 370, captured on a photographic plate.[12] Definitive evidence of more such bright blue arcs was reported five years later.[13] The idea that foreground clusters might lens *quasars* had been around for some time, but theoretical work on the lensing of background galaxies began in earnest in 1986.[14] A large arc implies that a distant galaxy is located on the sky very close to a point of infinite magnification on a foreground lens. In optics this is called a caustic projection. Soon observers began to find more than one arc associated with a single foreground cluster of galaxies.[15]

In effect, this lensing distortion magnifies the background galaxies. A few of them even become bright enough to be studied spectroscopically. Redshift measurements of nine such bright blue arcs, from background galaxies that would be quite faint (25th magnitude) in the absence of gravitational magnification, yielded values of z ranging from 0.5 to 2.2. Unfortunately these caustic projections of background galaxies are rare. The required alignment of source and lens is very restrictive.

If the angle ϕ between the center of the lens and the true source position is larger than ϑ_E, one doesn't get multiple images. But any source of resolvable width will be distorted as well as displaced, because each point of its image is displaced radially outward from the center of the lens. Because the faint blue background galaxies appear nice and fat, despite their great distances, a foreground lens will elongate them into concentric arcs, as shown in figure 2. The great masses associated with rich clusters of galaxies affect background galaxy images over large patches of sky behind them. They distort all the faint background galaxies within several arcminutes of the cluster. Foreground galaxy clusters with redshifts from 0.2 to 0.5 and line-of-sight velocity dispersions exceeding 700 km/sec have mass densities high enough to significantly distort background galaxies that are at least twice as far away. (Note that lensing dispacement is proportional to the lever arm D_{LS}.) Lensing preserves the surface brightness (per unit apparent area) and spectrum of the source, so that most arcs have the very faint surface brightness and characteristic blue color of the unlensed background galaxies.

We searched for distorted background images in several rich clusters, employing very sensitive CCD detectors to do deep, multiband imaging at the 4-meter telescope on Cerro Tololo and at the 3.6-meter Canada–France–Hawaii telescope on the island of Hawaii. Centered on several of the more massive galaxy clusters we found dozens of distorted background galaxy images. Their systematic, concentric alignment around the lensing foreground cluster was unambiguous.[16]

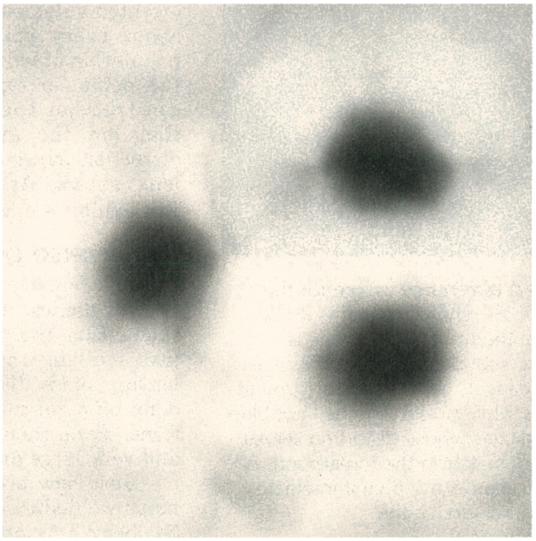
We select the background galaxy population by its extreme blue color relative to the red cluster galaxies of the foreground. In our deep, three-hour-long CCD exposures at large telescopes we find 30 to 100 background galaxies per square arcminute wherever we look. That's an adequate background population for the task of mapping the dark matter in a foreground cluster anywhere in the sky.

The high-redshift background galaxies falling within the central square arcminute of a foreground compact cluster of galaxies are strongly lensed. Typically they are distorted into faint circular arcs up to 30 arcseconds long. These are not the relatively rare caustic alignments we occasionally find when single galaxies are doing the lensing. Around large foreground clusters every background galaxy appears stretched along a circle centered on the lens. It is the ubiquitous high density of faint background galaxies revealed by our sensitive imaging detectors that provides us with enough statistics to construct an approximate map of the dark matter distributions in the foreground lensing systems.

Simulations

It is instructive to simulate the gravitational distortions of background galaxies by tracing rays through different realistic models of foreground clusters. We then compare our real observations with what the simulations give for different cluster distributions of luminous and dark matter. For these simulations we synthesize background galaxy fields to have the same statistical distributions of

a

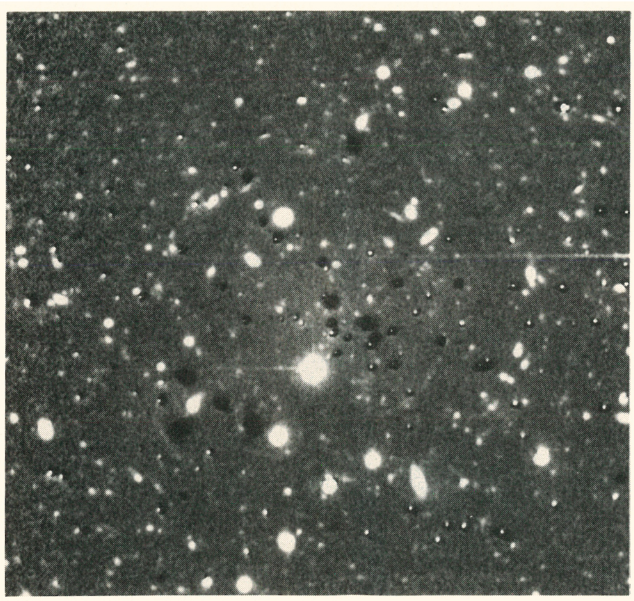


b

The inverse problem, solved for a complex lensing mass configuration. Given the simulated background field distortion in **a**, a computer program tries to determine the simulated foreground mass distribution that did the gravitational lensing. Its solution **b** is a good approximation to the triangle of three isothermal mass spheres for which the lensing had actually been calculated. **Figure 5**

shape and intensity we have seen in the deep surveys. We place these background galaxies at redshifts ranging from 0.5 to 2.0. We place the dark matter that dominates the simulated lensing cluster in various soft-core mass distributions with various velocity dispersions. After we have calculated the gravitational distortion of the background by a simulated cluster, we fold in atmospheric blurring, add Poisson noise and present the results in bins appropriate to the resolution of the CCD detectors.

Figure 4 shows the results of such a simulation with various masses of dark and luminous matter in the foreground cluster. The foreground galaxies of the cluster are not shown. (In real observations they are removed by subtracting images taken with different color filters.) In figure 4a we see the simulated field of faint blue background galaxies distorted only by atmospheric blurring. The mass of the foreground cluster has been set to zero. In figures 4b and 4c we've turned on the foreground cluster mass. By the virial theorem, a cluster's total mass is proportional to $\langle \Delta v^2 \rangle$ of its visible component. So we can use the rms velocity dispersion to label mass. In both 4b and 4c the dark matter component of the foreground cluster is given a core radius of 60 kpc. That's about ten times the radius of a typical galaxy.



Blue-minus-red difference image for the cluster Abell 1689, whose redshift is 0.18. The intensity of the red-filtered image is adjusted so that subtracting it from the blue-filtered image cancels out the red foreground cluster galaxies while preserving the faint blue background galaxies whose distortion serves to measure dark matter in the foreground. A few bright blue stars in our own immediate neighborhood also survive the subtraction. **Figure 6**

In figure 4b the velocity dispersion of the foreground cluster is set at 1200 km/sec. The lensing mass is higher in figure 4c, where the velocity dispersion has been raised to 1800 km/sec. The dark matter is not distributed with strict spherical symmetry; mass has been added to each individual cluster galaxy. Both these figures exhibit evident distortion of the background field. The gravitational lensing effect of the massive foreground cluster is to stretch the image of the background galaxy along a circular arc centered on the cluster. And indeed that's the kind of thing we see when we look at the field of faint blue background galaxies in parts of the sky near foreground clusters with high velocity dispersion. By comparing the Monte Carlo simulations with the CCD observations we are able to narrow down the parameter space that describes the elusive dark matter.

The systematic alignment of the ellipticities of the background images provides a strong gravitational signal. We characterize this image-stretching by a dimensionless combination of two measured length parameters in two orthogonal directions: the intensity-weighted second moments of the distorted image along the radius from the center of the lens and in the orthogonal direction on the sky. These moments are labeled b and a, respectively, in figure 2. To detect the coherent stretching by the lens in the presence of noise and the intrinsic shape variations of galaxies, we average these scale lengths over all the background galaxies for a given putative lensing center. From the two mean scale lengths we form a dimensionless quantity, similar to an ellipticity, called the net tangential alignment or lens distortion and denoted by T. The lens distortion is related to the projected mass density clumping. It is defined[11] in terms of the moments $a(x,y)$ and $b(x,y)$ about any reference point (x,y) in the image plane by

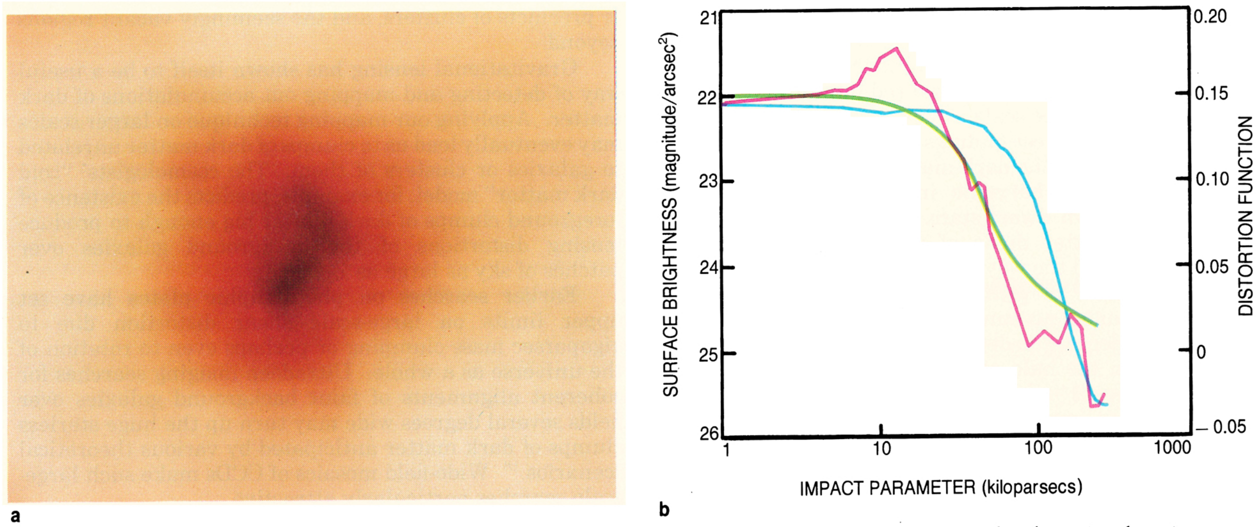
$$T(x,y) = \frac{a^2 - b^2}{a^2 + b^2}$$

An unlensed population of randomly placed and oriented galaxies will give a net distortion $T(x,y)$ of zero about every point (x,y) in the image plane, while a population of lensed galaxies will yield a positive value at the point corresponding to the actual lens center. To construct an approximate map of the mass distribution that did the gravitational lensing, we compute the distortion parameter $T(x,y)$ for a grid array of candidate lens centers. At the effective center of a real lens, $T(x,y)$ will exhibit a maximum.

The inverse problem

Given a lensing mass distribution and a background of faint galaxies, there is a straightforward recipe for calculating the distortion of the background. But our task—solving the inverse problem to approximate the lensing mass distribution—is more difficult. It can be done only for certain simple foreground mass distributions. Even then, the solution isn't so good at very small and very large distances from the lensing center.

Just how accurate are the foreground dark matter maps we deduce from the distorted background? Figure 5a shows a Monte Carlo simulation of a background field



For the background of faint blue galaxies in figure 6, the false-color map **a** shows the distortion function $T(x,y)$ for every point in the field. The darker the color, the greater is the lensing distortion. The mass revealed here is centered on the luminosity centroid of the cluster. In **b** the averaged radial dependence of this distortion function is plotted (blue curve) against distance from the center of Abell 1689. For comparison we show the averaged radial dependences of the normalized lensing mass distribution (green curve) deduced from T and of the red-light surface brightness (red curve) from the foreground cluster galaxies. **Figure 7**

distorted by a fairly complex foreground lensing configuration: an equilateral triangle made of three spherically symmetrical, isothermal balls of mass. Figure 5b shows the foreground mass distribution our inverse algorithm deduced from figure 5a. It shows that we can reliably recover such complex mass distributions. But the technique fails for foreground mass components with velocity dispersions less than about 500 km/sec. For such meager lensing masses the coherent distortion signal is swamped by the random ellipticities of the background galaxies.

Once we have found the lensing center, we can avail ourselves of a more direct method of solving for the mass M and core radius R_c of the dark matter. Assuming a circularly symmetric lens with a neatly parametrizable radial mass distribution, one can determine both M and R_c by a maximum-likelihood calculation. The tangential distortion function $T(x,y)$ locates the lensing mass and determines its morphological shape on the sky.

Assuming that the faint blue arclets we see are gravitationally lensed background galaxies in the redshift range 0.5–1.5, we have obtained maximum-likelihood solutions for a class of plausible lens models. These solutions yield total cluster masses in good agreement with what one deduces from the observed velocity dispersion, and they provide at least an upper bound on the core radius of the dark matter distribution.

We want to study the distribution of dark matter at various stages in the evolution of clusters of galaxies. We therefore seek to obtain deep imaging exposures through a wide variety of rich foreground clusters with various optical and x-ray properties at various redshifts. Our survey of rich clusters will eventually employ CCD mosaics as large as 13 cm on a side, so that we will be able to construct dark matter maps extending more than a megaparsec from the center of the cluster under scrutiny.

Because most cluster galaxies are much redder than the faint background population, we can just about cancel out the foreground by subtracting an appropriately scaled red image from a blue image of the same field. Figure 6 is such a scaled blue-minus-red difference image of the rich cluster Abell 1689 and its surroundings. The faint blue galaxies of the background survive, as do a number of blue foreground stars. But the cluster galaxies have disappeared. We then reduce these difference images to a catalog of background galaxy images by means of automated procedures for detection, image splitting and photometry.[2–4] The positions, intensities and second moments of the faint blue galaxies are then passed on to software that calculates the net tangential alignment $T(x,y)$ around any point (x,y) on the image.

Abell 1689 exposed

Figure 7a is the "distortion map" that shows the calculated value of $T(x,y)$ for every point on figure 6, the difference image of the Abell 1689 neighborhood. With this map our software attacks the inverse problem of finding the lensing mass distribution. Figure 7b displays the mass density distribution of our best fit for Abell 1689 as a function of distance from the centroid. For comparison we also plot the averaged radial dependences of $T(x,y)$ and the red-light intensity of the cluster image itself. The radial extent of the mass core thus deduced turns out to be significantly smaller than what one gets from x-ray intensity maps of nearby clusters. Perhaps the x-ray-emitting gas in galactic clusters is less dynamically relaxed than the dark matter.

We see in figure 7b that the gravitational image distortion extends at least as far out from the center of the cluster as do the visible galaxies. Also, the centers of the two distributions coincide fairly well. This implies that the dark matter distribution is essentially a smoothed version of the distribution of galaxies. Much of the cluster's mass, invisible as well as visible, sits within 100 kpc of a common center.

In much the same way, we looked for evidence of coherent lensing distortion in a dozen patches of sky that had no foreground clusters of galaxies. These searches have thus far revealed nothing.

Our first cluster lens studies would seem to confirm the existence of the large, invisible masses in rich galaxy clusters that had been deduced from the measured velocity dispersions and the assumptions implicit in the use of the virial theorem. But gravitational lensing gives us something extra: a map of the mass. We find the distribution of dark matter in the inner reaches of these clusters to be similar to the distribution of total red luminosity, though smoother on a 100-kpc scale.

By themselves these findings would be consistent with the supposition that the dark matter concentrated within galactic clusters is baryonic in origin; it could be a multitude of brown dwarf stars. But baryonic matter—the ordinary matter made of protons and neutrons—cannot bring us all the way up to the critical density. The standard scenario of primordial nucleosynthesis assets that baryons cannot account for more than about 7% of ρ_c. Efforts are under way to detect brown dwarf stars, or even black holes, in the halo of our Galaxy by searching for their gravitational "microlensing."

Our cluster results are also consistent with nonbaryonic dark matter composed of remnant neutrinos with rest masses on the order of 10 eV. It is, however, unlikely that such neutrinos dominate the dark matter that is presumed to exist in halos around individual galaxies.[17]

Many of the less compact clusters we have looked at show no strong lens distortion effects. Presumably this means that their masses are too small (corresponding to velocity dispersions of less than 700 km/sec) or that their dark matter core radii exceed 200 kpc. The cluster velocity dispersion, being in effect an integral over the distortion function, is the best-determined parameter. Our cluster sample is still too small for us to reach firm conclusions regarding the maximum radial extent of the dark matter.

Our best-fit lens solutions for the rich clusters imply a total velocity dispersion (for dark plus luminous matter) equal to or somewhat smaller than the measured velocity dispersion of the cluster galaxies. For the optically compact clusters, we find peak dark matter densities of about 10^5 times the critical closure density, and dark matter core radii as large as 60 kpc. We have no data as yet on dark matter beyond 300 kpc from the cluster center.

It is also of interest to inquire on what scale the dark matter clumps together within a cluster. This subclumping has to be on scales significantly larger than individual galaxies; otherwise the long arcs seen in several dynamically relaxed cluster lenses would be broken up into fragments several arcseconds long. As we increase our sample of galaxy-cluster fields, we hope to get a clearer picture of how dark matter distributes itself within clusters. And we may even get some important clues about what it's made of.

These gravitational shear-distortion studies measure the radial mass function $M(r)$, the mass within a distance r of the cluster's center. With only one exception, we find that our results are in good agreement with dynamical measurements of $M(r)$ for those few clusters for which both kinds of data exist. Therefore the gravitational lensing results thus far have strengthened our confidence that the assumptions behind the application of the virial theorem are generally valid for compact clusters of galaxies. Our results also suggest that individual galaxies belonging to clusters are no more massive than lone galaxies, and that the dark matter in a cluster resides primarily in its diffuse component.

What should we expect to find if the universe is just closed by dark matter? If the mean mass density of the universe is very close to ρ_c, dark matter must fill the cosmos; very likely it is to be found in places where there has been no star formation. After all, the amount of dark matter we believe to be associated with galaxies and the inner regions of clusters would still only account for 10% or 20% of ρ_c. Therefore we urgently need to study the outer precincts of clusters, and the seemingly vacant regions beyond.

Gravitational lensing has shown itself to be a useful way of detecting and mapping out accumulations of dark matter. Applying our mapping technique on larger scales may eventually lead us to clumps of dark matter unrelated to galaxies or clusters of them. The cosmologists' "cold dark matter" model, for example, predicts the existence of foreground clumps of dark matter big enough to produce lensing distortions of the background galaxies over patches of sky as large as 1°.

Earlier searches on photographic plates have set upper limits on large-scale shear distortion due to gigaparsec mass clumping or perhaps even to rotation of the universe as a whole. Ultradeep imaging searches for coherent alignments of faint background galaxies over fields several degrees wide may turn up the huge starless clumps of dark matter anticipated by various theoretical scenarios.[18] Wide-field mosaics of CCDs make such large-scale searches particularly attractive.

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