APPLICATIONS OF GRAVITATIONALLY LENSED LONG ARCS IN CLUSTERS OF GALAXIES

Jordi Miralda-Escudé
Institute for Advanced Study, Olden Lane, Princeton NJ 08540
email: jordi@guinness.ias.edu

ABSTRACT

A brief summary of the theory of gravitational lensing needed to analyze the observations in clusters of galaxies is given. We outline some of the main results from present observations of gravitational lensing on the structure of clusters of galaxies, concerning the total mass, mass profiles, substructure, and cD galaxies.

Subject headings: gravitational lenses - galaxies: clustering - X-rays

1. INTRODUCTION

Astronomers are interested in learning about several components that are present in a galaxy cluster, such as the galaxies, the hot gas, and the dark matter. The galaxies and the hot gas can be studied from their optical and X-ray emission. However, in order to achieve a full understanding of their dynamical state, it is also necessary to know about the distribution of the total mass, which determines the gravitational potential.

Up to now, galaxy clusters have been studied by attempting to infer the mass distribution from observations of the galaxies and the hot gas alone. This has generally been based on several assumptions and simplifications: requiring the cluster to be in a stationary equilibrium state, absence of substructure, spherical symmetry, models for the mass radial profile, homogeneity of the hot gas, absence of any motions or pressure on the gas other than thermal, and maxwellian equilibrium.

Gravitational lensing in clusters of galaxies allows us to observe the mass distribution directly for the first time. Most of this mass is dark matter, and therefore it is not observed by other means. Consequently, it should now be of interest to combine any constraints obtained from gravitational lensing on the mass distribution, with the observations of galaxies and the intracluster medium, and see what we can learn on their physical and dynamical state. At the same time, the determination of cluster mass profiles will provide a test for cosmological theories of cluster formation.

2. BASIC THEORY OF GRAVITATIONAL LENSING

Gravitational lensing can be described as a mapping of the surface brightness of any source of radiation from the source plane to the image plane (see Schneider, Ehlers, & Falco 1992 for a detailed description). The source plane, with angular coordinates $\vec{\theta}_s$, contains the source as would be observed in the absence of lensing. The image plane, with angular coordinates $\vec{\theta}_i$, contains the lensed images that are observed. The lens equation gives this mapping:

$$\vec{\theta}_i = \vec{\theta}_s + \vec{\alpha}(\vec{\theta}_i) \; . \tag{1}$$

In the case of the single screen approximation (where it is assumed that most of the lensing mass is at the same distance from the observer, D_l), the angle $\vec{\alpha}$ is equal to the physcial deflection angle of the light rays as they pass by the lens, times the ratio D_{ls}/D_s, of the distance from the lens to the source and the distance from the observer to the source. It is given by:

$$\vec{\alpha} = \nabla\phi \; ; \qquad \nabla^2\phi = 2\,\frac{\Sigma(\vec{\theta}_i)}{\Sigma_{crit}} \equiv 2\kappa \; ; \qquad \Sigma_{crit} = \frac{c^2}{4\pi G}\frac{D_s}{D_l\, D_{ls}} \; . \tag{2}$$

Here, ϕ is the two-dimensional gravitational potential, and Σ is the surface density. As seen from these equations, the action of gravitational lensing depends only on the projected surface density Σ, but not on the distribution of matter along the line-of-sight.

The amplification matrix gives the transformation from the source plane to the image plane of a small element of area: $A^{-1} = (\partial\vec{\theta}_s/\partial\vec{\theta}_i) = 1 - (\partial\vec{\alpha}/\partial\vec{\theta}_i)$. Since $\vec{\alpha} = \nabla\phi$, the matrix A is symmetric and can be diagonalized. From equation (2), the average of the two eigenvalues of A^{-1} is $1 - \kappa \equiv 1 - \Sigma/\Sigma_{crit}$. Thus, the two eigenvalues can be written as $1-\kappa-\gamma$, and $1-\kappa+\gamma$, where γ is called the shear. The magnification in the area (and flux) of a source is $|A| = (1-\kappa-\gamma)^{-1}(1-\kappa+\gamma)^{-1}$, and the axis ratio of the image of a circular source is $q = (1-\kappa-\gamma)(1-\kappa+\gamma)^{-1}$.

When the surface densities are small, so that $\kappa \ll 1$, $\gamma \ll 1$, then we are in the regime of "weak lensing". Each source produces only one image, which experiences only a small distortion of its shape. In this limit, the amplification is $A = 1 + 2\kappa$, while the ellipticity given to a source is 2γ. Weak lensing has been detected in clusters of galaxies, using optical galaxies as sources (Tyson, Valdes & Wenk 1990; see also the contributions by Kaiser, Smail and Soucail in these proceedings). Since the original shape of the background galaxies is unknown, one can only measure the average shear over a certain area by averaging the ellipticities of several galaxies, and assuming that the orientations of the major axes of the sources are random and uncorrelated. Once the shear is obtained at several points, the surface density of the cluster can be recovered with an accuracy and resolution that is ultimately limited by the number of background sources and their intrinsic ellipticities (Tyson et al. 1990; Kochanek 1990; Miralda 1991; Kaiser & Squires 1993).

When one of the two eigenvalues of the matrix A^{-1} is equal to zero (i.e., $\kappa + \gamma = 1$ or $\kappa - \gamma = 1$), two new images appear around a "critical line". Since the magnification is very large along the principal axis of the vanishing eigenvalue, the images appear very elongated. Such strongly distorted images were discovered by Soucail et al. (1987, 1988) and Lynds & Petrosian (1989), and by now they have been seen in ~ 30 clusters (Fort 1992). They were originally called "arcs" because they are often curved, owing to the change of the orientation of the principal axis of the shear along the image (it has later been shown, however, that this curvature can be very small in many cases). When κ, $\gamma \sim 1$, "arclets" are generally produced (Fort et al. 1988).

3. WHAT HAVE WE LEARNED FROM GRAVITATIONAL LENSING IN CLUSTERS?

3.1 Dark matter and core radii

First of all, gravitational lensing has given us the best evidence we have for the presence of dark matter. The first observations of the long arcs showed that the mass within $\sim 100h^{-1}$ kpc is indeed much larger than what can be accounted for from visible stars and gas, by a factor of about 10. In a spherical cluster, the condition $\kappa + \gamma = 1$ to form a long arc is equivalent to $\bar{\Sigma} = \Sigma_{crit}$, where $\bar{\Sigma}$ is the average surface density within the radius of the arc. This condition remains approximately correct for more complicated potentials.

This large amount of dark matter in the center implies that any flat core of the mass distribution should be smaller than the radius of the observed arcs (see Grossman & Narayan 1988). The basic reasons are that, if the surface density varied only slowly with radius near the arcs, then a very small decrease of the critical surface density (corresponding to a small increase in the redshift of the source) would allow for arcs to appear at much larger radii; moreover, the large masses that would be implied at large radius would be inconsistent with other dynamical measurements. At the same time, a lens with a very shallow profile would tend to produce arcs with very low curvature (Miralda 1993).

The narrow widths of the arcs have also been used as an argument against large cores; in particular, Hammer (1991) has claimed that the observed widths also imply a very steep profile. Here, we notice that such conclusions are very sensitive to the assumed properties of the background galaxies being lensed, and the way that the arc widths are measured. For example, a barred spiral galaxy will typically produce very thin arcs, because the arc width will be determined mostly by the minor axis of the source. The sources will typically be clumpy (they probably are star-forming galaxies and are seen in their rest-frame ultraviolet); if only the bright, small clumps are observed, this will also cause the arcs to appear thinner.

Elliptical galaxies with bright cusps in the center may also produce apparently thin arcs if their outer envelopes are below the limiting observable surface brightness.

3.2 Do all the clusters have similarly concentrated mass profiles?

A question which has proved particularly hard to answer is the following: do all clusters of galaxies have similar density profiles, and is the small core radius of the lensing clusters a general feature, or are the lensing clusters only a special class, having a much more centrally concentrated mass than the majority of clusters? This can be addressed by analyzing the frequency of highly distorted arcs in well-defined samples of clusters. Two such samples have been published so far, an optically selected one by Smail et al. (1991), and an X-ray selected one by Le Fèvre et al. (1994), and they seem to indicate that the fraction of clusters which are able to lens with large critical radii, typical of the observed arcs, is not very small. There are, however, several difficulties of interpretation: the probability that a cluster with a fixed mass distribution will lens a background source and produce an observable arc is rather uncertain, because it depends on the number counts of faint galaxies, their angular sizes, and their redshift distribution. Thus, if long arcs are not observed in some massive clusters, this may only be due to the absence of any background source sufficiently close to the caustics of the cluster and sufficiently extended to produce a long arc.

From a theoretical point of view, if clusters were formed via hierarchical gravitational collapse, and baryon dissipation has not increased the mass significantly within the radius of the observed arcs, one would expect that all relaxed clusters should have similar density profiles (Efstathiou et al. 1988; Navarro, Frenk & White 1994). However, there should be different degrees of relaxation, so that relaxed clusters may have most of their mass concentrated in one central clump, and would therefore be better able to lens, while clusters with several merging units will have several massive clumps, each one of them having a smaller critical radius, and a lower probability of producing long arcs. Occasionally, however, various clumps may appear superposed in projection, and this should enhance the lensing effects.

In fact, substructure on small scales is indicated by the morphology of the arcs in several clusters (e.g., Pelló et al. 1991, 1992; Kassiola, Kovner, & Blandford 1992; Miralda 1993).

3.3 Correlation of the Mass and Light Distribution

Gravitational lensing also allows us to test the correlation between mass and light substructure. One would generally expect that any merging clump of mass in a cluster would be associated with either a large elliptical at the center of the clump, or a group of galaxies which had collapsed before merging into the cluster. This suggests a general approach to be taken in modeling arcs lensed by clusters of galaxies: to assume that the cluster is made of mass clumps associated with the brightest cluster galaxies. Moreover, such galaxies are often cD galaxies, with stellar envelopes extending to radii similar to the observed arcs, and in these cases the ellipticity of the stellar envelope gives us the ellipticity of the gravitational potential. This method was suggested by Mellier et al. (1993) and Kneib et al. (1993), and applied to the cases of A370 and MS2137 very successfully. There may be, however, some exceptions: the arcs in A2390 require the presence of two mass clumps, but only one of them can be associated with a bright cluster galaxy, while there is no obvious concentration of galaxies that could be identified with the second clump (Pelló et al. 1991). Clearly, the long arcs, as well as weak lensing (see Soucail, these proceedings) can be a good tool to find out if there are any dark clumps of mass in clusters of galaxies.

3.4 cD Galaxies

Since the long arcs are often seen embedded in the stellar halos of cD galaxies at the center of the lensing potentials, this implies that the velocity dispersion of the stellar halos must rise to a high value consistent with the observed splitting angles. The velocity dispersions required are typically $\sim 1000\,\mathrm{km\,s^{-1}}$, much higher than the observed dispersions in the center of cD galaxies. Therefore, one can predict that velocity dispersions of cD galaxies (at least in the lensing clusters) will be observed to rise very fast at radii of $\sim 50h^{-1}kpc$, contrary to what is observed in other galaxies, where velocity curves are generally flat. This also implies that the inner profiles of clusters ***must*** be flatter than isothermal, otherwise even the central velocity dispersions of cD galaxies would need to be similar to that of the whole cluster. This flattening of the density profile towards the center has been confirmed from the observation of a "radial arc" in MS2137 (Fort et al. 1992; Mellier et al. 1993), which is a gravitationally lensed image very close to the center of the potential, and radially elongated. The position of this radial arc gives a powerful constraint on the form of the density profile in the inner $50h^{-1}$ kpc (Miralda 1994). This allows one to predict the velocity dispersion profile of the cD galaxy, and is consistent with a velocity dispersion in the range $300 - 400\,\mathrm{km\,s^{-1}}$ at the center, but which should rise to $700\,\mathrm{km\,s^{-1}}$ at a radius of only $30h^{-1}$ kpc (Fig. 9 in Miralda 1994).

This fast rise of the velocity dispersion of a cD galaxy may lead to a problem for their formation through mergers: how is it possible to maintain a population of cold stars within such a small region of the cluster center? Simulations of the formation of cD galaxies are usually done assuming that galaxies merge by dynamical friction within a cluster profile with a large core (e.g., Richstone 1990). New N-body simulations are needed to see if a cold cD galaxy can be formed within a small cluster core, or if one would always produce cluster stellar halos with much lower surface brightness and much higher central velocity dispersions.

3.5 Lensing masses and X-ray masses

Gravitational lensing measurements of the masses of clusters of galaxies can be compared with the values obtained from other methods. The long arcs give us the projected mass within the radius where the arcs are observed, usually $\sim 50h^{-1}$ kpc. Miralda & Babul (1994a,b) have compared these masses with the ones obtained from X-ray observations, assuming the gas is in hydrostatic equilibrium at the observed X-ray temperature, in the clusters A2218, A1689 and A2163. The mass obtained from lensing is at least a factor of ~ 2 larger than that obtained from the X-ray analysis in A2218 and A1689, while in A2163 the lensing mass is the same as the maximum mass consistent with the X-ray analysis (there is some uncertainty in the comparison since the detailed mass profile is not known). The disagreement arises from the fact that the gas distribution has a core radius of $\sim 100h^{-1}$ kpc, while the mass is more concentrated. This could be understood if the gas was hotter than the dark matter in the center, but the observed X-ray temperatures suggest it is not. There are two classes of explanations for this difference: the first is to assume that the lensing clusters are all highly elongated along the line of sight, either due to a prolate shape of the central clump or to the superposition of several clumps. In this case, the masses derived from X-ray observations could be basically correct, and most X-ray selected clusters should not show this difference, since only a small fraction of clusters can be pointing towards us. One should notice, however, that strong lensing will always be seen more easily in clusters where the surface density is enhanced by projection.

The second class of explanations is to say that the masses from the X-ray analysis are underestimated. This could be due to several things, all of which invalidate the assumption of hydrostatic equilibrium at the observed X-ray temperature: hydrodynamic motions of the gas (with the corresponding substructure in the gas distribution), a multiphase medium with an effective temperature higher than the observed one in the X-ray spectrum (a hot phase, with lower density, would emit less X-rays than cooler phases), rotation of the gas, magnetic pressure,... At some level, both types of effects must be present. The question is, which one is more important? In retrospect, it should not be too surprising that the lensing and X-ray masses are different by a factor of 2. In fact, it is reassuring that all the effects one can think of tend to make the lensing mass larger than the X-ray mass.

Many of the reasons why the X-ray masses could be underestimated might be even more important at large radius. If that was true, it would have profound implications for cosmology: clusters would be more massive than what we thought, and the ratio of gas mass to total mass in clusters could come to much better agreement with nucleosynthesis and a dark matter density corresponding to a flat universe (see White et al. 1993). Observations of weak lensing in X-ray selected samples of clusters are needed to measure lensing masses at large radius. The very preliminary present detections of weak lensing (see Kaiser, Smail, Soucail, these proceedings) seem to be reminiscent of the conclusions from the discovery of the long arcs: masses are large.

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