Dark Matter in ms1224 from Distortion of Background Galaxies

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ABSTRACT

We explore the dark matter distribution in ms1224.7+2007 using the gravitational distortion of the images of faint background galaxies. Projected mass image reconstruction reveals a highly significant concentration coincident with the X-ray and optical location. The concentration is seen repeatably in reconstructions from independent subsamples and the azimuthally averaged tangential shear pattern is also clearly seen in the data. The projected mass within a 2.76\arcmin radius aperture is \( \simeq 3.5 \times 10^{14} h^{-1} M_{\odot} \). This is \( \simeq 3 \) times larger than that predicted if mass traces light with \( M/L = 275 h \) as derived from virial analysis. It is very hard to attribute the discrepancy to a statistical fluctuation, and a further indication of a significant difference between the mass and the light comes from a second mass concentration which is again seen in independent subsamples but which is not seen at all in the cluster light. We find a mass per galaxy visible to \( I = 22 \) of \( \simeq 8 \times 10^{12} h^{-1} M_{\odot} \) which, if representative of the universe, implies a density parameter \( \Omega \sim 2 \). We find a null detection of any net shear from large-scale structure with a precision of 0.9\% per component. This is much smaller than the possible detection in a recent comparable study, and the precision here is comparable to to the minimum level of rms shear fluctuations implied by observed large-scale structure.

Subject headings: cosmology: observations – dark matter – gravitational lensing – galaxy clusters – large scale structure of universe

1. Introduction

A puzzle in cosmology is the “\( \Omega \) discrepancy problem”: virial analyses of clusters of galaxies give mass-to-light ratios of typically a few hundred (Davis and Peebles, 1983), implying \( \Omega \simeq 0.1 \sim 0.2 \), while studies of supercluster scale dynamics (see e.g. Dekel, 1994 for a recent review) give larger values and seem compatible with \( \Omega \simeq 1 \). One way to reconcile these results (and the theoretical prediction that \( \Omega = 1 \)) would be to argue that virial analysis underestimates the cluster mass because the galaxies are more concentrated than the dark mass.

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This hypothesis is testable as we can measure the cluster mass directly using the coherent shear of the images of distant background galaxies. The observability of this effect was first demonstrated by Tyson, Valdes and Wenk, (1990) in A1689 and should be measurable, in principle, out to large distances (Miralda-Escude, 1991a; Kaiser and Squires, 1993).

Here we report a measurement of the image shear induced by the cluster ms1224.7+2007. This cluster was selected from the Einstein Medium Sensitivity Survey (see Gioia and Luppino, 1994), has $L_x = 4.61 \times 10^{44}$ erg/sec ($h = 0.5$) and lies at $z = 0.33$. The cluster has recently been extensively mapped in redshift space by Carlberg, Yee and Ellingson (1994; hereafter CYE). While the cluster is very bright in X-rays, it does not appear to be particularly rich, shows no giant arcs and has a rather modest velocity dispersion $\sigma \approx 750$ km/s. Nonetheless, as we will show, we are able to recover a clear signal of weak lensing for this cluster, and we draw some rather interesting conclusions regarding the mass in this cluster and in the universe as a whole. Bonnet et al. (1994) and Mellier et al. (1994) have recently reported a detection of the shear near Q2345+007, and several other groups (Tyson, 1994; Dahle et al., 1994; Smail et al., 1994) are currently pursuing similar studies.

2. Data Analysis

The data were acquired on the night of March 22/23, 1993 at the 3.6m CFHT. The detector was the 2048 × 2048 Lick 2 chip at prime focus with a pixel scale of 0.207′′. We observed a grid of four fields with corners overlapping the centre of the cluster. Each field was observed in the $I$-band three times, with slight positional offsets, for a total integration time of 3600 seconds per field. The seeing for much of the night was excellent (FWHM ≃ 0.5′′). At $z = 0.33$, 1′ = 0.174$h^{-1}$Mpc in physical units ($\Omega = 1$, $\Lambda = 0$) and the observations cover a square approximately 2 Mpc/$h$ on a side and centred on the cluster.

The 12 exposures allowed the construction of an accurate median sky flat. The data were analysed with software which will be described in detail elsewhere (Kaiser and Squires, 1994). The analysis is a three step procedure. First we smooth each exposure with a 2 pixel gaussian and locate all the peaks above a low threshold. Second, noise peaks, cosmic rays etc are eliminated by requiring positional coincidence on overlapping images. Finally, we go back to the unsmoothed images and analyse the pixels around the smoothed peak location to determine shape and luminosity parameters. To determine the luminosity and half light radius we use an aperture of radius min(3$r_p$, 6 pixels) where $r_p$ is the ‘Petrosian radius’ where $l(r)/r$ peaks. We analyse each exposure separately and then average together the catalogue entries for the multiply observed objects. This avoids the problem of psf anisotropy introduced when exposures are registered and added.

Gravitational lensing will distort the surface brightness of background galaxies according to

$$f'(\theta_i) = f(\theta_i + \phi_{ij}\theta_j),$$

where the image shear tensor $\phi_{ij}$ is the second derivative of the surface potential:

$$\phi_{ij} = \pi^{-1} \partial^2 \Phi/\partial \theta_i \partial \theta_j,$$

and $\nabla^2 \Phi = -2\pi \Sigma/\Sigma_{crit}$. For an Einstein – de Sitter universe, the effective critical surface density is $\Sigma_{crit} = (4\pi Ga_l w_l \beta)^{-1}$, where $\beta \equiv \langle \max(0, 1 - w_l/w_g) \rangle$ with subscripts $l, g$ denoting the

fig1.ps

Fig. 1.— Size-magnitude distribution. We find $\approx 5100$ objects in total on about 140 square arcmin, of which $\approx 3200$ were brighter than $I = 23.4$. The box shows our subsample of $\approx 2500$ faint galaxies.
lens and background galaxies. We define comoving distance as $w = 1 - (1 + z)^{-1/2}$ and the scale factor is $a(w) = 6000(1 - w)^2 h^{-1}$Mpc. To determine the shear coefficients $s_\alpha = \{\phi_{11} - \phi_{22}, 2\phi_{12}\}$ we use quadrupole moments (following Tyson, Valdes and Wenk, (1990)). Defining $Q_{ij} = \int d^2\theta \theta_i f(\theta)$, and image polarisation $e_\alpha \equiv \{(Q_{11} - Q_{22})/(Q_{11} + Q_{22}), 2Q_{12}/(Q_{11} + Q_{22})\}$, it is easy to show that a small gravitational shear induces a shift in the mean polarisation $\langle e_\alpha \rangle = s_\alpha$, so we can use $\hat{s}_\alpha = \sum e_\alpha/N$ as an estimate of the shear with statistical uncertainty $\sqrt{\langle e^2 \rangle}/2N$ where $\langle e^2 \rangle$ is the rms intrinsic polarisation and $N$ the number of objects.

The moments as defined above illustrate the idea, but are not practical due to divergent sky noise. To avoid this we define $Q_{ij} = \int d^2\theta W(\theta) \theta_i \theta_j f(\theta)$. The optimal weight function is a compromise between statistical precision and seeing. We have used a gaussian window with scale length of 3 pixels which was found, from experiments with synthetic data (see below), to give good results. With $W(\theta) \neq 1$ we have $\langle e_\alpha \rangle = P^{sh}_{\alpha\beta} s_\beta$ where the linear shear polarisability $P^{sh}_{\alpha\beta}$ measures the response of the polarisation parameters $e_\alpha$ to a gravitational shear (Kaiser and Squires, 1994). We measure $P^{sh}_{\alpha\beta}$ for each object. It is typically quite close to diagonal and we have used as our estimator of the shear $\hat{s}_\alpha = \langle e_\alpha/P^{sh} \rangle$ where $P^{sh}\equiv (P^{sh}_{11} + P^{sh}_{22})/2$.

Seeing will circularise the images. To calibrate this effect and also to test the software we took samples from the actual data, shrunk these by a factor two, applied a known shear and then convolved these images with a gaussian filter to mimic seeing and added noise so that the faintest objects recovered were about as numerous as in the real data. We are effectively modelling the faint galaxies as scaled down replicas of somewhat brighter galaxies which are, in reality, well resolved. Analysing an ensemble of such images made without the seeing smoothing we confirmed that the method does indeed recover the input shear reliably. With realistic seeing included we found that the output was about 65% of the input value. In fact, the galaxies found from the scaled images are slightly smaller than the real galaxies, and artificial simulations indicate that the appropriate value for the real data is $\approx 70\%$ and we correct the observed shear estimates appropriately. To estimate the shear we simply average the shear values for all galaxies with $|\hat{s}| < 1.4$, the cut here removing a small number of typically very noisy images.

The shear we are trying to measure here is expected to be only a few percent. Anisotropies arising from aberration or imperfect guiding are clearly a worry. (Another potential problem, field distortion from the telescope optics, is negligible at CFHT.) We do find a significant psf anisotropy for the foreground stars, but we have corrected for this using the property that a small psf anisotropy induces a shift in polarisation $\delta e_\alpha = P^{sm}_{\alpha\beta} P_\beta$, where $P_\alpha$ is a measure of the psf anisotropy, and where $P^{sm}_{\alpha\beta}$ is the linear smear polarisability (see Kaiser and Squires, 1994 for details).

We used $e_\alpha/P^{sm}$ values from a sample of about 400 moderately bright stellar images to determine $P_\alpha$. We found two significant effects. The first was a pixel position independent $P_\alpha$ which is different in different exposures. The second effect was a gradient across the chip which appears to be constant from exposure to exposure. Both effects were substantial: The gradient term gave stellar anisotropy of about 10% at the edge of the chip relative to the centre in the best seeing, and this would generate a polarization of a few percent in a typical small faint galaxy. The $\chi^2$ statistics for the two stellar polarisation components dropped by a factor $\approx 2.7$ when these terms are removed. Including a quadratic term in the model gave a negligible further improvement so we have used the constant plus gradient model. We have tested the correction method using synthetic images, and we believe that any residual shear from psf anisotropy is well below 1%.

3. Results
From the subset of \( \sim 2500 \) faint, non-stellar images we have removed objects with \( |\hat{s}| > 1.4 \) and also objects which, though real, showed relative positional offsets of more than one pixel in \( x \) or \( y \) (the parent sample shown in figure 1 includes objects with offsets \( \leq 2 \)) as these seemed to be much noisier in polarization, reducing the number to 2147. The shear estimates \( \hat{s}_\alpha = e_\alpha/P^w \) are shown in figure 2, which gives an idea of the kind of precision attainable here. The rms shear (per component) was \( \langle \hat{s}^2_\alpha \rangle^{1/2} \approx 0.43 \).

A reconstruction of the mass surface density is shown in figure 3. This was made using the method of Kaiser and Squires (1993, hereafter KS), though correcting a minor error — the correct result is one half that given in their equation (2.2.1). The reconstruction should not be trusted near the edge of the image, but in the inner regions we see a strong mass concentration whose location coincides very well with the smoothed optical centroid and lies a little to the East of the X-ray location. The rms noise in the estimator is \( \Sigma_{\text{rms}} = \sqrt{\langle \hat{s}^2_\alpha \rangle} / 16 \pi \sigma \Sigma_{\text{crit}}, \) where \( \sigma \) is the gaussian smoothing radius. For the smoothing used here we find \( \Sigma_{\text{rms}} = 0.022 \Sigma_{\text{crit}} \). The peak value is \( \Sigma \approx 0.11 \Sigma_{\text{crit}} \), a 5-sigma upward excursion. In figure 3 we have added a correction for finite data as described below. This raises the peak height to \( \approx 0.13 \Sigma_{\text{crit}} \), but the statistical significance is essentially unaltered. No correction has been made for contamination of our sample by cluster members which will have diluted the signal in the central region.

The mass map in figure 3 is made by convolving the shear estimates with a certain kernel. We can see the signal in the data more directly in figure 4a where we have plotted the mean tangential shear \( s_T = - (s_1 \cos 2\phi + s_2 \sin 2\phi) \) where \( \phi \) is the azimuthal angle of the background galaxy position relative to the cluster centre (which we have taken to be the peak of the mass map shown in figure 3), as a function of radius. The signal is clearly seen at radii \( \approx 1' - 5' \) (any contamination from cluster members is very small at these radii).

We now want to estimate the mass enclosed within a radius of 2.76' (800 pixels) which seems to enclose the significant mass concentration. A fundamental problem of weak lensing analysis is an ambiguity in the base level of the surface density. With finite data the KS estimator underestimates the true surface density. The correction consists of two terms; the first is half the mean tangential shear at the boundary. From figure 4 we can estimate this to be about 2% and we have applied this correction in figure 3. The second term is the mean surface density at the boundary which is not easily measured. A better way to handle this problem is to modify the estimator. The KS estimator is a convolution of the shear estimates with the shear pattern from a point mass. If we truncate the kernel at inner and outer radii \( r_1, r_2 \) and divide by \( (1 - r_1^2/r_2^2) \) the result is a convolution of the surface density with a compensated top-hat; i.e. it measures the mean surface density within a disk of radius \( r_1 \) minus that in a control annulus from \( r_1 \) to \( r_2 \). Since the latter is positive, this gives a lower bound (barring noise) on \( \Sigma(r_1) \), the mean surface density in units of \( \Sigma_{\text{crit}} \) interior to \( r_1 \). A nice feature of this statistic is that is only uses data at \( r > r_1 \), largely avoiding the problem of dilution by cluster members. Evaluating this at the peak of the mass map, we have \( \Sigma(r) > \zeta(\theta) \equiv (1 - \theta^2/\theta_{\text{max}}^2)^{-1} \int_0^{\theta_{\text{max}}} d\ln \theta s_T \), which is plotted in figure 4b. For \( \theta = 2.76' \) this gives \( \Sigma = 6.0\% \pm 1.3\% \).

Fig. 2.— Shear estimates \( s_\alpha \) for the faint galaxy subsample. This shows, to first order, the intrinsic distribution of shear estimates. The effect of the cluster lens would not appear in this plot, but any shear which is coherent over the whole field (as produced by superclusters close to the line of site) would produce an asymmetric shift of the distribution. It is clear that any such shift is very small.
To convert \( \sigma \) to an estimate of the physical mass we need to estimate \( \Sigma_{\text{crit}} \). This depends, through \( \beta \), on the redshift distribution of our galaxies which is still imperfectly known; in fact the uncertainty in \( \beta \) dominates our error budget. For the brighter half of our galaxies we can estimate \( \beta \) directly from the complete redshift samples of Lilly, 1993 and Tresse, et al., 1993 and we find, for \( I = 20 - 22 \), \( \beta \approx 0.27 \), with statistical error \( \delta \beta \approx 0.11 \). To get the appropriate value for the fainter half we need to extrapolate. Splitting the \( I = 20 - 22 \) surveys in two, we find an increase in \( \beta \) of about 30% per magnitude suggesting \( \beta \approx 0.42 \) for our faintest magnitude slice (though the data are consistent with no increase in depth at the 1-sigma level), and we find, for the whole sample, \( \beta = 0.34 \) and therefore \( \Sigma_{\text{crit}} = 1.68h \text{ cm}^{-2} \).

With this \( \beta \)-value, the total projected mass within our 2.76′ aperture is \( \approx 3.5 \times 10^{14}h^{-1}M_\odot \). Let us now compare this with the light. The lower panel in figure 3 shows the surface density predicted by CYE assuming light traces mass with \( M/L = 275h \) as inferred from virial analysis. While the positions of the peaks agree nicely, the shear-derived mass peak is higher and perhaps more extended than the light. According to the virial estimates the mass within our 2.76′ aperture is \( 1.15 \times 10^{14}h^{-1}M_\odot \), which is a factor 3 lower than our estimate.

This is a large discrepancy, so it is worthwhile pausing to consider possible biases and uncertainties in our method. We are aware of a number of biases, but all of these will have tended to cause us to underestimate the mass. First, as mentioned, our estimator tends to underestimate \( \sigma \) if there is mass in the cluster which extends beyond the aperture. A further bias is introduced if, as done in the light-map here, we include material seen in projection in our aperture which is at a different distance without allowing for material in the control annulus at similar distance — this is true whether or not the material is physically associated with the cluster — and removing this increases the discrepancy by about 10%. Finally, there is some reason to suspect that our extrapolation of \( \beta \) for the fainter galaxies is an overestimate as we can infer the relative \( \beta \) values from the strength of the lensing signal and this exercise suggests a further increase of about 10% - 20% in the mass estimate. Thus our estimate of the discrepancy is in many respects a cautious one, and the real discrepancy could well be even larger. The discrepancy is hard to attribute to statistical fluctuation in the shear estimates; it is about 3 times our statistical error. There is also uncertainty in \( \beta \), but to account for the discrepancy with this alone would require \( \beta \approx 0.76 \). This is about 4-sigma removed from our estimate, and corresponds to a typical redshift \( z \approx 4 \) for the sample as a whole, and only slightly smaller values for our brighter galaxies. This is clearly incompatible with the data of Lilly and Tresse et al. If we use the brighter subsample alone, and thus avoid the need to extrapolate, we find \( M \approx 4.5 \pm 1.3 \times 10^{14}h^{-1}M_\odot \) which is somewhat noisier, but still discrepant at the 2.5-sigma level with the virial estimate.

Our large total mass implies an enormous \( M/L \sim 800 \). This, coupled with the well established increase

\[ \text{Fig. 3.— The upper left panel shows a contour plot of the surface density } \sigma(\vec{\theta}) = \Sigma(\vec{\theta})/\Sigma_{\text{crit}} \text{ derived from the background galaxy shear estimates for our full sample. The circles show the aperture and control annulus for our } \sigma \text{ estimate. The panels on the right are derived from independent subsamples. A strong central mass concentration is clearly seen, and the northerly extension or sub-clump is also seen repeatably. The lower left panel shows the surface density predicted from the CYE redshift survey data assuming } M/L = 275h \text{ and with } \Sigma_{\text{crit}} \text{ as appropriate for the full sample. The dotted line shows the extent of their data. All images have been smoothed with a 40'' gaussian filter. The angular coordinates are in arcminutes relative to the giant elliptical galaxy.} \]
in comoving luminosity density of the universe at these redshifts, implies a very large value for the density parameter if this is estimated in the usual manner (i.e. by dividing the cluster $M/L$ by the $M/L$ for a critical density universe). As the luminosity density of the universe is very noisy with the current samples, it is preferable to calculate a mass-per-galaxy and compare this with the mass-per-galaxy for a $\Omega = 1$ universe. Comparing the galaxy counts in our aperture with that in the surrounding annulus — note that this avoids the bias problem — we see an excess of $N_c \simeq 45 \pm 16$ cluster galaxies to $I = 22$ within our aperture. This gives a mass $\simeq 8 \times 10^{12} h^{-1} M_\odot$ per galaxy. Assuming that the number of galaxies per unit mass in the cluster is representative of that of the universe, we obtain an expression for the density parameter:

$$\Omega = \frac{\sigma_d \Omega (1 + z_l)^{1/2} dn/dz}{3 N_c w_l \beta} \simeq 1.9$$

(1)

$\delta \Omega$ is the solid angle of the aperture, and $dn/dz$ is the differential counts per unit redshift per steradian in the appropriate magnitude range, which we estimate from Lilly (1993) and Tresse et al. to be $\simeq 8.2 \times 10^7$ at $z = 0.33$.

These data can also be used to place limits on shear from large-scale structures (Blandford et al., 1991; Miralda-Escude, 1991b; Kaiser, 1992). A similar study to that performed here, though not for a cluster field (Mould et al., 1994), gave an apparent detection of net shear $|s| \simeq 5\%$ when corrected for seeing, though the authors felt unable to reject the possibility that their detection may be a residual artefact. Here we obtain a net shear $\hat{s}_a = \{0.37\% \pm 0.9\%, -0.38\% \pm 0.9\%\}$ which is a null detection of much greater sensitivity.

The Mould et al., 1994 exposures were deeper than ours, and the rms image shear is predicted to increase as $s_{\text{rms}} \propto \langle w^3 \rangle^{1/2}$. They adopt a median redshift $\overline{\pi} \simeq 0.9$ ($\overline{\pi} = 0.27$). From the redshift survey data we obtain $\langle w^3 \rangle^{1/3} \simeq 0.23$ which is a little lower and would suggest a $\sim 25\%$ decrease in cosmological signal. Another way to estimate the relative comoving depths is to compare the number density of galaxies above the respective magnitude limits; theirs was about 2.7 times higher than here. At brighter magnitudes, $\overline{\pi}$ is a rather weak function of number density: $\overline{\pi} \propto n^{0.2}$, so if this trend continues the prediction for their survey should be about 30% larger than for ours for any given model, consistent with the estimate obtained using their estimated median redshift.

The present sensitivity $\langle s^2 \rangle^{1/2} \simeq 1.3\%$ is roughly a factor 4 lower than the Mould et al. result, and so, taking their possible detection as a measure of their sensitivity, our result represents an increase of about a factor 3 in sensitivity to cosmological signal.

The sensitivity we have reached is comparable to the minimum rms shear compatible with the large-scale mass fluctuations implied by bulk flows (Kaiser, 1991). High normalisation CDM models with $\Omega = 1$, $\sigma_8 = 1$ give predictions of a few percent shear, which should be easy to measure or exclude with further observations of this kind. It is difficult to draw strong cosmological conclusions on the basis of the two components of the net shear from a single field — and in any case, one would want to avoid fields such as this one containing a cluster — but the results here show that with more fields of similar precision a direct measurement of large-scale mass fluctuations should be feasible.

Fig. 4.— The upper panel shows the mean tangential shear (corrected for seeing) as a function of radius relative to the peak of the mass distribution seen in figure 3. The lower panel shows $\zeta(r)$, which provides a lower bound on the mean surface density interior to $r$ (see text). The dashed lines are the predictions for isothermal spheres with velocity dispersions 700 and 1000 km/s.
4. Summary

Shape analysis of ∼2000 galaxies behind m1224 clearly reveals the gravitational image shear from the cluster and has allowed us to reconstruct the projected mass, whose main peak coincides to within about one arcminute with the optical and X-ray centroids. Our most surprising result is that the projected mass we infer is much larger than implied assuming mass traces light with the virial mass-to-light estimate $M/L = 275h$. We have argued that it is hard to account for the discrepancy by statistical fluctuation as it would seem to require both that we were the victim of a large positive fluctuation and that the redshifts in current samples at $I \sim 20 - 22$ are unrepresentatively low. This improbable possibility can be eliminated or confirmed with future observations.

The discrepancy is large, and appears at a surprisingly small radius. Our estimator effectively measures the mean projected surface density within our aperture (of about $0.5h^{-1}\text{Mpc}$ radius) relative to an average value at about twice this radius. Adding a halo in a spherical manner at larger radii — which would obviously not conflict with the virial analysis — does not influence our statistic, and adding shells of mass in the control region will actually register as negative mass due to limb brightening.

It is difficult to say whether the light is more concentrated than the mass within our annulus. The shear in the central region is rather weak, and considerably weaker than a singular isothermal sphere model matched to the shear at large radius for instance. This would seem to require a core radius of $\approx 125h^{-1}\text{Mpc}$, but we caution that the shear in the inner region is diluted by cluster members.

A further piece of information which argues in favour of a significant discrepancy between mass and light is the second peak or extension in the mass reconstruction. This feature appears in both bright and faint subsample reconstructions but is not seen at all in the cluster light. With much deeper observations it should be possible, in principle, to reduce the statistical error in the mass-map by potentially a factor 3 or so.

We find a mass-per-galaxy of $\approx 8 \times 10^{12}h^{-1}M_\odot$. If this is representative of the universe at large — which of course it need not be — then $\Omega \approx 2$. The precision of this estimate, like that for the cluster mass, is currently limited by the paucity of faint galaxy redshifts and will improve considerably as more redshift information becomes available.

We have paid particular attention to correcting for the effect of anisotropy of the psf. This, and the generally superior image quality at CFHT, has allowed a sensitivity to shear from large-scale structure which is much greater than previously obtained. While the field here is not ideal for that purpose, we have shown that directly measuring mass fluctuations on scales of order tens of Mpc in this way is indeed feasible.

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