

# Gravitational Lensing of Distant Field Galaxies by Rich Clusters: II. Cluster Mass Distributions.

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## ABSTRACT

We construct a photometric catalogue of very faint galaxies ( $I \lesssim 25.5$ ) using deep CCD images taken with the 4.2m William Herschel telescope taken of fields centred on two distant X-ray luminous clusters: 1455+22 ( $z_{cl} = 0.26$ ) and 0016+16 ( $z_{cl} = 0.55$ ). Using a non-parametric procedure developed by Kaiser & Squires (1993), we analyse the statistical image distortions in our samples to derive two dimensional projected mass distributions for the clusters. The mass maps of 1455+22 and 0016+16 are presented at effective resolutions of 135 kpc and 200 kpc respectively (for  $H_o=50$  kms  $\text{sec}^{-1}$   $\text{Mpc}^{-1}$ ,  $q_o = 0.5$ ) with a mean signal to noise per resolution element of 17 and 14. Although the *absolute* normalisation of these mass maps depends on the assumed redshift distribution of the  $I \lesssim 25.5$  field galaxies used as probes, the maps should be reliable on a *relative* scale and will trace the cluster mass regardless of whether it is baryonic or non-baryonic. We compare our 2-D mass distributions on scales up to  $\sim 1$  Mpc with those defined by the spatial distribution of colour-selected cluster members and from deep high resolution X-ray images of the hot intracluster gas. Despite the different cluster morphologies, one being cD-dominated and the other not, in both cases the form of the mass distribution derived from the lensing signal is strikingly similar to that traced by both the cluster galaxies and the hot X-ray gas. We find some evidence for a greater central concentration of dark matter with respect to the galaxies. The overall similarity between the distribution of total mass and that defined by the baryonic components presents a significant new observational constraint on the nature of dark matter and the evolutionary history of rich clusters.

**Key words:** cosmology: observations – clusters: clusters – gravitational lensing, dark matter.

## 1 INTRODUCTION

The nature of the dark matter in clusters of galaxies has been a central theme in cosmological research since its existence was inferred over sixty years ago (Zwicky 1933). Although the early evidence was based on the virial analysis of the relative velocities of cluster member galaxies, the discovery of X-ray emission from a hot intracluster medium

provided independent verification of the so-called ‘missing mass problem’ (Jones & Forman 1984).

Until recently, most of the interest in clusters of galaxies has focussed on determining the *amount* of dark matter contained. As clusters are the largest bound structures known, their mass/light ratios and baryonic fractions should approach that for the cosmos as a whole. In fact, careful studies of selected nearby clusters (Fabian 1991, White *et al.* 1993, Mushotzky 1993) have revealed a much higher baryonic fraction than expected in the inflationary  $\Omega_{tot}=1$  Universe whose baryonic component is constrained by primordial nucleosynthesis arguments (White *et al.* 1993). This dilemma might be resolved if it could be demonstrated that the dark matter in clusters was less concentrated than the baryonic component. Such arguments indicate that the observations

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constraining the relative *distribution* of dark matter are as important as those which estimate its total amount.

Both the classical spectroscopic and X-ray techniques are ill-suited to tackling this problem. In the case of the radial velocities of cluster galaxies, the one-dimensional nature of the dynamical data necessitates assumptions about the distribution of orbits which even extensive data (Kent & Gunn 1982, Sharples, Ellis & Grey 1988) has been unable to resolve definitively. Simulations have shown (Fitchett 1988) the difficulty of recognising substructure even with several hundred radial velocities unless it is of a particular form (e.g. bimodal) and conveniently well-separated on the sky or in velocity. Beyond a few core radii (i.e.  $r > 500$  kpc), contamination from non-members increases to such an extent that useful samples of cluster galaxies must be taken from well down the galaxy luminosity function making such surveys highly inefficient probes of the mass distribution on large scales.

Analyses of the X-ray gas distribution is less complicated by projection effects and provides a better sampling of any spatial structure on scales less than a few hundred kiloparsecs. The fundamental limitation of X-ray studies to date has been the lack of spatially resolved temperatures profiles. Detailed studies of nearby clusters have shown no evidence for strong temperature gradients in clusters (Hughes 1989, Eyles *et al.* 1991) and within the central 1 Mpc the assumption of isothermality is apparently consistent with all published data (excluding the central cooling core of 100–200 kpc radius). The ASCA X-ray satellite is currently generating spatially-resolved temperature profiles for many clusters and thus considerable progress will be made in this area in the next few years. However, as with the cluster galaxies, the surface brightness of the X-ray emission falls precipitously with radius from the cluster centre and to determine mass distributions on the large scales required to resolve the ‘baryon catastrophe’ discussed by White *et al.* (1993), very long exposures are needed to obtain the necessary temperature data.

Thus far, mass distributions derived from the modelling of the X-ray emission have been published for a few nearby clusters and are claimed to indicate a dark matter component more centrally concentrated than both the galaxies and the X-ray gas (Eyles *et al.* 1991, Gerbal *et al.* 1992). One recent study (Buote & Canizares 1992) has compared the morphologies of the 2-D distributions of mass and galaxies in a sample of local clusters using X-ray imaging data. Although the orientations of the two distributions (X-ray gas and galaxy number density) are in good agreement, they conclude that the potential traced by the X-ray gas in the central  $\sim 1$  Mpc of their clusters is too round to be generated by the observed galaxy distribution if the galaxies exactly trace the mass. The difference might be reconciled if the galaxies and mass have a different radial scale lengths. This would mean that the X-ray analysis of Buote & Canizares would include regions outside the cores of the mass distribution resulting in an inferred ellipticity for the mass in better agreement with that traced by the galaxies.

A related issue in the quest for the nature and distribution of dark matter in clusters is the evolutionary history of the gravitational potential of clusters. Conventional theories that postulate a significant non-baryonic component predict remarkably recent growth (Frenk *et al.* 1990). X-ray imaging

(Henry *et al.* 1992) and all-sky scanning (Edge *et al.* 1990) surveys have revealed evidence for evolution at surprisingly low redshifts ( $z \leq 0.2$ ), in the sense that there are fewer of the highest X-ray luminosity ( $L_x > 8 \times 10^{44}$  erg s<sup>-1</sup>) clusters in the past. In contrast, optical surveys find a nearly constant co-moving space density of rich clusters to  $z_{cl} \sim 0.5$  (Gunn *et al.* 1986, Couch *et al.* 1991). To reconcile this discrepancy, Kaiser (1991) has proposed that the X-ray emitting gas was heated prior to the formation of clusters and became bound to the potential wells only when the latter had grown sufficiently deep to contain the gas. In any case the mechanism of hierarchical merging that underlies the observed X-ray evolution may introduce significant differences in the optical and X-ray properties of clusters in the period leading up to and immediately after a cluster-cluster merger. Thus we might expect morphological differences between the distributions of the X-ray gas and the gravitating mass in moderate redshift clusters. In a search for such signatures of merger activity we have made a detailed comparison of optical, X-ray and gravitating mass distributions for two high X-ray luminosity clusters.

The analysis of the gravitational lensing signals, derived from the distortion of background galaxies viewed through clusters, offers an independent probe of the mass distribution in clusters (for recent reviews see Soucail 1992, Blandford & Narayan 1993). Geometrical considerations indicate the phenomenon will be most effective in constraining mass distributions in clusters with redshifts  $z_{cl} \gtrsim 0.2$ . The classical techniques for recovering mass distributions rely on *in situ* probes of the gravitational potential about which various assumptions are made concerning their thermodynamic state. For the lensing methods, however, the results depend on the characteristics of sources totally unrelated to the cluster. In many cases these can be directly measured or they can be statistically understood from large samples.

## 2 GRAVITATIONAL LENSING AS A PROBE OF CLUSTER MASS DISTRIBUTIONS

The lensing of distant galaxies by rich clusters produces two observable phenomena: ‘giant arcs’ and ‘arclets’.

As highly elongated images of serendipitously positioned background galaxies, the giant arcs are easily recognisable manifestations of strong lensing by cluster cores (Grossman & Narayan 1989). Several have spectroscopic redshifts which when combined with detailed modelling of their image characteristics have provided important constraints on the total mass in the centres of rich clusters. Employing a variety of gravitationally lensed features in Abell 370, Kneib *et al.* (1993) claim a bimodal mass distribution which is morphologically similar to that delineated by the X-ray emission and cluster red light. However, for Abell 2390, Kassiola, Kovner & Blandford (1992) require a mass distribution which differs from that seen in the cluster galaxies.

Unfortunately, with at most a single giant arc per cluster, such models are not uniquely constrained by the available data. Using a sample of cluster with arcs Wu & Hammer (1993) claimed a marked concentration of dark compared to visible mass from the mean cluster radius where the arcs are found compared to the canonical X-ray core radius. However, they conclude that further information on the sources

(e.g. their sizes) is required to derive robust conclusions. The apparent concentration of dark compared to visible mass would only remain a valid conclusion if the distant sources are comparable in intrinsic size to present-day galaxies. The recent discovery of multiply-imaged pairs in the cores of rich clusters (Kneib *et al.* 1993, Smail *et al.* 1994) suggests that at least some  $B \simeq 26$ -28 galaxies are very compact, as these images would otherwise appear as elongated connected arcs (Miralda-Escudé & Fort 1993).

In a detailed study of three clusters with both arcs and X-ray data available from the literature, Babul & Miralda-Escudé (1994) conclude that the mass estimates from the arc modelling can be nearly a factor of  $\simeq 2$ -3 larger than those from the X-ray observations of the inner-most regions of the cluster core. As they discuss, this discrepancy may arise from a number of sources, including the simplified geometry adopted for the lensing clusters or other invalid assumptions used in the X-ray modelling.

The rarity of the giant arcs together with uncertainties about the intrinsic source properties (including sizes and even redshifts in many cases) precludes reliable constraints. In very rare cases such as AC114 (Smail *et al.* 1994), the combination of giant arcs and a multiply-imaged pair *resolved* with the aid of Hubble Space Telescope can yield tight constraints on the mass distribution but only for the inner 1-200 kpc of a single cluster. The frequency of occurrence of multiply-imaged pairs remains unclear, although there is good cause for being optimistic if the sources are  $B \simeq 26$ -28 galaxies as detailed modelling suggests.

Arclets are a much more promising probe of the mass distribution. These images are generally too faint for direct spectroscopy and are insufficiently elongated to be convincingly due to gravitational lensing on an individual basis. However, the tiny distortions induced by the lensing cluster form a coherent pattern superimposed upon the intrinsic ellipticities and orientations of the faint background population. The coherence thus overcomes the low signal to noise of the individual arclets.

The most basic lensing statistic is the proportion of field galaxies aligned tangentially to a suitably-defined lens centre. In a pioneering study Tyson *et al.* (1990) analysed images of the central regions of Abell 1689 ( $z = 0.18$ ) and Cl1409+52 (3C295,  $z = 0.46$ ). Using the alignment of blue galaxies, they derived radial ‘mass’ profiles for the clusters which were found to resemble the profiles of cluster light. As Kaiser & Squires (1992) show, Tyson *et al.*’s statistic measures the surface potential rather than the mass.

With deep CCD images reaching  $I \simeq 25$ ,  $B \simeq 27$ , a very high surface density of background sources can be attained. Techniques can then be developed to determine the mass distribution with a resolution that matches the best available from the X-ray and optical tracers in the cluster. The unique advantage of this method over those discussed above is that, providing the cluster mass distribution has a non-zero gradient, the technique works equally well in the cluster peripheries as in the core, since the basic signal is provided by an isotropic population of faint field galaxies.

Of course, the lensing signal depends on the redshift distribution,  $N(z)$ , of the source population, as well as on the desired mass distribution,  $M(r)$ , within the cluster. At the limiting magnitudes essential for generating a high surface density of background sources, even with 10-m telescopes

it seems unlikely that spectroscopy can usefully constrain  $N(z)$ . Another possible route to achieve arbitrarily high surface density of spectroscopically attainable background sources is to combine shallow images of many clusters to study the profile of an ‘average’ cluster.

More complex analysis combining the results from individual clusters can be used to separate the dependency on  $N(z)$ . We therefore began a deep imaging programme for 3 X-ray luminous clusters, carefully selected to cover a range of cluster redshifts,  $z_{cl}$ . By imaging each cluster to the *same limiting magnitude*, the lensing signals can be analysed to test both  $N(z)$  to the chosen limiting magnitude and  $M(r)$  for each of the clusters. Paper I of this series (Smail, Ellis & Fitchett 1994) describes the overall approach, the observational datasets and tests in some detail. *The reader is strongly advised to consult that article first.*

In Paper I, we derive maximum-likelihood constraints on the redshift distribution,  $N(z)$ , of the faint field population imaged to  $I \leq 25$ . The most probable distribution is close to that expected in the absence of pure luminosity evolution, although a tail of high redshift sources cannot be excluded. Our analysis technique also quantified the amount and concentration of the mass in the two lower redshift ( $z=0.26, 0.55$ ) clusters for which a strong lensing signal is seen. The mass distributions were, however, only derived in a form parametrised by the depth of the potential and its scale in the isothermal case (i.e. in terms of the line of sight velocity dispersion,  $\sigma_{cl}$ , and core radius,  $r_c$ ). No true morphological information on  $M(r)$  was discussed.

In Paper I the joint dependence of the lensing signal on  $N(z)$  and  $M(r)$  was only partially separated. Whilst the parameters satisfying the cluster mass distributions are consistent with those inferred from dynamical and X-ray data, the uncertainties are too great to examine any possible differences. Nevertheless, for the redshift distributions (which formed the basic motivation of Paper I), significant constraints are possible by combining the results from the three clusters.

This second paper extends the analysis begun in Paper I and examines the *relative mass distributions* in the two lowest redshift clusters in a non-parametric form. This is made possible by the non-parametric lens inversion technique developed by Kaiser & Squires (1993). The projected maps of the total cluster mass are presented with a relative normalisation and are thus *independent of any uncertainties in the source  $N(z)$* . The unique feature of our study is the comparison of these maps with the distribution of *both* cluster members and the X-ray gas. We can therefore compare the large scale distribution of dark matter with that for the baryonic component in two clusters. Our study is thus a logical extension of Tyson *et al.*’s original method. By creating a deeper sample of background galaxies and applying a new analytic technique, we can achieve a sufficiently high galaxy surface density in good seeing to allow us to resolve structure in the lensing clusters.

A plan of the paper follows. In Section 3 we begin by briefly recapping the target selection, optical data acquisition and reduction methods before discussing the reduction and analysis of the ROSAT X-ray images of the two selected clusters. In Section 4 we discuss our implementation of the Kaiser & Squires procedure. The mass maps are presented in Section 5 and compared with the distributions of galax-

ies and hot X-ray gas in the clusters. Section 6 gives our discussion of the comparison between the mass distribution and that of the baryonic tracers. Our conclusions are summarised in Section 7.

### 3 OBSERVATIONAL DATA AND METHODS

The philosophy behind our observational programme is thoroughly discussed in Paper I where the criteria by which the clusters were selected are given. All of the optical CCD observations and their reduction procedures are reviewed in considerable detail. Here we briefly summarise the optical characteristics and respective datasets for the two clusters for which mass distributions are presented before discussing the X-ray images and their treatment. The latter data was not presented in Paper I.

The 3 clusters chosen for our survey span the redshift range  $0.26 < z_{cl} < 0.89$  and X-ray luminosities are available for each. 1455+22 ( $z_{cl} = 0.26$ ) was originally identified by the EINSTEIN X-ray satellite (Henry *et al.* 1992) whereas 0016+16 ( $z_{cl} = 0.55$ ) was first found on deep optical photographic plates (Koo 1981). Both clusters are amongst the most X-ray luminous examples known and can, effectively, be regarded as X-ray selected. The highest redshift cluster, 1603+43 ( $z_{cl} = 0.89$ ) was optically discovered and is a much weaker X-ray emitter. No significant lensing signal was detected with this cluster, which provides important constraints on the redshift distribution of the field galaxies (Paper I) but clearly eliminates it from further consideration in any determination of cluster mass distributions.

The optical observations were made in July 1990 and May 1991 using the TAURUSII f/4 focal reducer on the 4.2m William Herschel Telescope (WHT) (see Table 2 of Paper I) with the largest format EEV CCD then available. This arrangement provides  $0.27 \text{ arcsec pixel}^{-1}$  sampling over a  $5 \times 5$  arcmin field (corresponding to 1.5 Mpc and 2.2 Mpc for the clusters concerned). Multiple exposures of duration  $\lesssim 1000$  sec were taken in *V* and *I* offsetting in-between each so that the data frames can be combined to create a sky flatfield for the entire night. The *I* band data was used to determine image shapes for the lensing analysis. For 1455+22 the final *I* frame has an effective seeing of 0.90 arcsec FWHM, for 0016+16 it is 0.95 arcsec FWHM. The final on-source integrations for the two clusters are: 1455+22 -  $t_{exp}(V)=12.0$  ksec and  $t_{exp}(I)=20.8$  ksec; 0016+16 -  $t_{exp}(V)=11.0$  ksec and  $t_{exp}(I)=25.5$  ksec.

The dataset was reduced to matched *V, I* object catalogues using the FOCAS image processing algorithm (Jarvis & Tyson 1981) with some minor modifications as described in detail in Paper I. The final catalogues have  $1 \sigma$  isophotal limits of: 1455+22 -  $\mu_V = 28.9 \text{ mag arcsec}^{-2}$  and  $\mu_I = 27.8 \text{ mag arcsec}^{-2}$ ; 0016+16 -  $\mu_V = 28.8 \text{ mag arcsec}^{-2}$  and  $\mu_I = 28.2 \text{ mag arcsec}^{-2}$ . These limits are sufficiently faint to obtain reliable ellipticities and colours to at least  $I=25$ . At this limit, the signal to noise of a single galaxy image is typically  $\simeq 15\text{-}20\sigma$  in the seeing disk. The 80% completeness limits for the catalogues are  $I=25.3$  and  $V=26.5$  for 1455+22 and for 0016+16,  $I=25.7$  and  $V=26.4$ . The high source densities available ( $\sim 40 \text{ arcmin}^{-2}$  at  $I=25$ ) enables us to resolve mass structures on scales comparable to those available from our X-ray images. Note that although a lens-

ing signal could be *detected* using a brighter magnitude limit with fewer field galaxies per unit area, very deep images are required to derive mass maps of the required spatial resolution *and* signal to noise.

We now describe the properties of the individual clusters, paying particular attention to the X-ray images and their reduction.

#### 3.1 1455+22

This cluster was discovered as a serendipitous source in the EINSTEIN Medium Sensitivity Survey (EMSS, Henry *et al.* 1992). The cluster is the most X-ray luminous cluster within a redshift of 0.5 in the EMSS:  $1.6 \times 10^{45} \text{ ergs sec}^{-1}$  in the 0.3–3.5 keV band. Unfortunately, redshifts are available for only 4 cluster members (Mason *et al.* 1981), including the dominant central galaxy ( $z = 0.258$ ). The velocity dispersion determined from so few galaxies is of course highly uncertain,  $\sim 700_{-100}^{+2000} \text{ kms sec}^{-1}$ , where the uncertainties are 90% confidence limits assuming a gaussian velocity dispersion. The central galaxy also exhibits the strongest optical line emission of any of the EMSS clusters (Donahue *et al.* 1992) and therefore probably contains a cooling flow. While the X-ray luminosity is very high the optical richness derived from counts of colour-selected cluster members (see below) is low, being about half that expected from lower redshift clusters (Edge & Stewart 1991) and a third of the value for Coma.

As a part of a larger programme to obtain detailed X-ray images of a sample of moderate redshift clusters ( $z = 0.2\text{--}0.3$ ) for X-ray/optical gravitational lensing study, a ROSAT HRI observation was taken of 1455+22. A total exposure of 8.3 ksec was obtained in two parts on 11<sup>th</sup> January 1992 and the 20<sup>th</sup> January 1993. Although this exposure is half that originally requested it provides sufficient signal-to-noise to detect the cluster out to 1 Mpc and resolve the central 50 kpc of the cluster. Figure 1(a) shows this image overlaid on the composite *V+I* WHT image. The emission is highly peaked on the central galaxy but shows no evidence for a significant point source (less than 5% of the total X-ray flux). Deprojection of the surface brightness profile (Arnaud 1987, White 1992) indicates that the cluster does indeed contain a cooling flow of  $630_{-178}^{+257} M_{\odot} \text{ yr}^{-1}$ . The deprojection analysis uses an assumed form for the cluster potential and combines this with the observed X-ray surface brightness distribution to determine a temperature profile for the cluster. Ideally this is then matched to the observed temperature profile. In the absence of such information this procedure unfortunately prevents the determination of an exact mass profile. However, taking an isothermal temperature of  $8 \pm 3 \text{ keV}$  for the cluster (consistent with the luminosity-temperature relation) and a core radius where the ratio of gas mass to total mass is constant, the best fit King potential has a velocity dispersion of  $1000 \pm 200 \text{ kms sec}^{-1}$  and a core radius of  $150_{-50}^{+100} \text{ kpc}$ . A more detailed description of the analysis and how the results relate to other clusters will be presented elsewhere (Edge *et al.* in prep.).

In summary, the high inferred mass and its compact distribution strongly suggest that this cluster is a very good candidate for deep lensing studies proposed in Section 1.

### 3.2 0016+16

This cluster is the second most luminous EMSS cluster (Henry *et al.* 1992) at  $1.43 \times 10^{45}$  ergs  $\text{sec}^{-1}$ . However, in contrast to 1455+22, it has been well studied both optically and in the near-infrared (Koo 1981, Ellis *et al.* 1985, Aragón-Salamanca *et al.* 1993). The cluster's redshift is  $z = 0.545$  with a rest-frame velocity dispersion of  $\sigma = 1324$  kms  $\text{sec}^{-1}$  from 30 members (Dressler & Gunn 1992, and priv. comm.).

Morphologically, the cluster is very different to 1455+22 containing no dominant central galaxy. The peak in the galaxy surface density lies slightly to the south-west of a linear structure defined by 3 bright members (Figure 1(b)). The optical counts indicate a richness of  $\simeq 2 \times \text{Coma}$ , but possible contamination by foreground systems may reduce this estimate (c.f. Ellis *et al.* 1985). The absence of a prominent population of blue members suggests the cluster is unusual advanced in evolutionary terms for its redshift. This conclusion is supported by the analysis of the rest frame  $U - V$  colours of the red early-type cluster members. These exhibit a remarkably small scatter showing that the population is extremely homogeneous and implying that it is very old even at  $z = 0.55$ .

A deep EINSTEIN HRI image of 0016+16 (White *et al.* 1981) determined an X-ray core radius of 220 kpc which is comparable to the intrinsic resolution of the image. Unfortunately the high internal background of the EINSTEIN HRI prevented any study of more extended, low surface brightness emission. Recently a ROSAT PSPC image with an exposure of 43.2 ksec was obtained by Hughes and collaborators, this is now publicly available from the ROSAT archive. The hard (0.4–2.4 keV) image is overlain on the composite V+I frame in Figure 1(b). The X-ray map reveals an elliptical or bimodal distribution centred on the optical cluster center. A detailed comparison of the X-ray and optical morphologies is given below. A deprojection analysis of the X-ray surface brightness profile with a King model potential gives a velocity dispersion of  $1300 \pm 200$  kms  $\text{sec}^{-1}$  and a core radius of  $400_{-150}^{+200}$  kpc.

0016+16 is a very rich and concentrated cluster and ideally suited for lensing studies. In addition its morphology contrasts usefully with that of 1455+22.

### 3.3 Field and Cluster Galaxy Catalogues

Paper I describes in more detail how photometric catalogues of galaxies to  $I \lesssim 25$  can be used to define 'field' and 'cluster' samples on a statistical basis. From the aperture  $V - I$  colours, well-defined colour-magnitude relations are observed for the early-type members of both clusters. The tightness of these relations ( $\Delta(V - I) = 0.04$  mag for 1455+22 and  $\Delta(V - I) = 0.06$  mag for the bright end of the 0016+16 sequence), enables us to selectively label galaxies in the sequence as 'cluster members' and those outside this narrow colour relation are assumed to be 'field galaxies'. The number-magnitude counts for this field population agree closely with published data in random fields at high Galactic latitude (Lilly *et al.* 1991). The same procedure can be used to show there is no statistically significant excess from cluster members fainter than  $I=22.0$  (for 1455+22) and  $I=23.5$  (for 0016+16). These limits are equivalent to

absolute magnitudes of  $M_V \sim -17$  and  $M_V \sim -18.5$  respectively.

For 0016+16, an excess of *bright* galaxies is apparent, most likely associated with foreground groups identified by Ellis *et al.* (1985). For this cluster, additional colour information is available from an  $R$  band Service exposure taken with a large format EEV CCD at the 2.5m INT prime focus. This frame has a total exposure time of 6 ksec and is adequate to provide colours to  $I=24$  accurate to better than 0.2 mag. Additional colour criteria were thus used on the  $(V - R) - (R - I)$  plane to isolate galaxies with colours similar to E/S0's at  $z = 0.55$ .

In the case of 1455+22, our cluster samples contains  $\simeq 180$  galaxies brighter than  $I=22$  over the  $5.4 \times 5.0$  arcmin field. For 0016+16, we have 174 cluster galaxies to  $I=23.5$  in a  $3.3 \times 5.1$  arcmin region. The corresponding field samples contain 1583 and 831 galaxies respectively above their 80% completeness limits.

We note that neither of the clusters presented here show giant arcs ( $a/b \geq 10$ ) down to surface brightness limits of  $\sim 0.05\%$  of the night sky. The absence of giant arcs in these two clusters is not a particular concern as their creation is very sensitive to the detailed structure of the mass distribution on small scales in the cluster centres (e.g. Smail *et al.* 1991). As we show below, both our clusters *are* massive lenses and therefore the absence of giant arcs even to very deep limits has little or no bearing on this. This conclusion compromises the use of shallow surveys for giant arcs to study the properties of the lensing clusters, although such surveys are still useful to study the high redshift galaxies seen as arcs.

The lensing techniques described below rely upon our ability to accurately estimate the ellipticities of faint objects. This issue is discussed at length in Paper I where we argue for the introduction of a new weighting scheme for ellipticity measurements compared to that originally implemented in the FOCAS package. Our approach, originally proposed by Bernstein (priv. comm.), is to use a *radial* weighting function within *circular* apertures when calculating second moments instead of using the detection isophote to define pixel membership at each surface brightness. In this scheme, the optimal weighting function has the same profile as that for the image itself. Bernstein has shown that using profile shapes individually tailored to each object does not significantly improve the weighting scheme considering the large computational burden introduced (Bernstein priv. comm.). The weighting function adopted therefore is a circular gaussian whose variable width is determined from the intensity-weighted radius of the image after seeing convolution. We refer to these moments as 'optimally-weighted'.

Using tests discussed in Paper I, we demonstrated a considerable improvement in the robustness of the optimally-weighted ellipticity measurements for very faint objects compared to the traditional measurement. For a typical  $I \simeq 25$  galaxy we obtain roughly a four-fold reduction in the scatter: ( $\langle \Delta \epsilon_{opt} \rangle = 0.04$  versus  $\langle \Delta \epsilon \rangle = 0.16$  from analysis of independent frames of the same field). However, tests of simulated frames populated with objects of known ellipticity indicate this improvement in reliability is at the expense of a small systematic bias (rounder by  $\simeq 0.1$ ) in the returned ellipticity (where the FOCAS moments provide an unbiased measure). As we are primarily interested in the

relative strength of the lensing signal across our field, the disadvantage of a small systematic bias is outweighed by the improved signal/noise of the optimally-weighted moments. In particular we can adopt a lower effective ellipticity cut-off than when using FOCAS moments as the orientations of rounder objects can be successfully measured due to the lower scatter. Owing to the intrinsic distribution of image shapes this provides a much larger sample of objects for analysis.

#### 4 DETERMINING THE DISTRIBUTION OF DARK MASS

Various statistical tools have been developed to analyse the weak lensing of faint galaxies by rich clusters. The methods fall into two main classes: parametric likelihood tests which assume some form for the distribution of mass in the lens and then attempt to determine the most likely values of the model parameters (Kochanek 1990, Miralda-Escudé 1991a, 1991b, Paper I), and non-parametric tests which directly derive the mass distribution from the variation of the lensing signal across the cluster image (Kaiser & Squires 1993).

The parametric methods are particularly well-suited for constraining the faint galaxy redshift distribution provided there are some constraints on the depth and scale of the cluster potential well, e.g. from dynamical or X-ray data. In Paper I we used likelihood versions of these methods to obtain the most probable redshift distribution for the  $I=25$  field population from the lensing signal observed in the 3 clusters at  $z_{cl}=0.26, 0.55$  and  $0.89$ .

Alternatively, the non-parametric technique developed by Kaiser & Squires (1993, see also Fahlman *et al.* 1994) is better suited for investigating the relative distribution of mass in the lensing cluster. Not only can the method provide a genuine ‘map’ of the projected mass distribution in moderate and high redshift rich clusters with a resolution appropriate for comparison with the baryonic tracers, but importantly, the results are totally independent of the *in situ* estimators allowing us to test the basic assumptions those methods adopt.

The mathematical derivation of the projected mass density estimator in the Kaiser & Squires (KS) method is not repeated here; the interested reader is referred to their original article. The basic principle is that the distortion signal produced by a foreground point mass is of a fixed pattern. This pattern can be compared to the observed alignment of faint galaxies (positions  $\vec{r}_g$ ) around a selected point ( $\vec{r}$ ) in the cluster image plane. The degree of similarity between the two patterns is a direct estimate of the surface density of lensing mass at that point,  $\Sigma(\vec{r})$ . The statistic is evaluated repeatedly over a grid of centres ( $40 \times 40$ ) across the cluster yielding a ‘map’ of the projected mass. We define  $e_1$  and  $e_2$  such that  $e_1$  measures the stretching of a galaxy image along the X and Y axes while  $e_2$  measures the stretching in the direction  $Y=X$  in terms of the intensity weighted second moments of the image shape,  $I$ .

$$e_1 = \left( \frac{I_{xx} - I_{yy}}{I_{xx} + I_{yy}} \right) \quad e_2 = \left( \frac{2I_{xy}}{I_{xx} + I_{yy}} \right)$$

Kaiser & Squires show that the surface mass density,  $\Sigma(\vec{r})$ , is related to the local induced distortion by the sum

over the components  $e_1$  and  $e_2$  for all galaxies around that position weighted by the function,  $W(\vec{r}_g - \vec{r})$ .

$$\Sigma(\vec{r}) = \frac{1}{\bar{n}} \sum_{\text{galaxies}} W(\vec{r}_g - \vec{r}) \chi_i(\vec{r}_g - \vec{r}) e_i(\vec{r}_g)$$

$$\chi_1(\vec{r}) = \frac{(x^2 - y^2)}{r^2} \quad \chi_2(\vec{r}) = 2 \frac{xy}{r^2}$$

$W(\vec{r}_g - \vec{r})$  is the pattern of the induced distortion from a point mass as a function of radius. The average surface density of background sources in the field is given by  $\bar{n}$ .

The reconstruction is unstable to the noise caused by the intrinsic orientations and ellipticities of the background sources. To overcome this the derived mass distribution is filtered. The filter function,  $T(r)$ , can be directly combined into the pattern function,  $W(r)$ , for the point mass template.

$$W(r) = \frac{1}{2} \int_0^\infty \kappa T(\kappa) (2J_1(\kappa r)/\kappa r - J_0(\kappa r)) d\kappa$$

In the following analysis we use a gaussian for  $T(r)$ , with a separate  $\sigma$  adopted for each cluster. An estimator for the uncertainty in the mass reconstruction is also given by Kaiser & Squires:

$$\langle \Sigma(\vec{r}) \rangle = \frac{1}{8\pi^2 \bar{n}} \langle e^2 \rangle \int_0^\infty T^2(\kappa) d^2\kappa$$

where  $\langle e^2 \rangle$  is the intrinsic dispersion in the ellipticities of the background galaxy population. For a given filter function the errors depend strongly on the surface density of sources (hence the importance of obtaining very deep images) and weakly on their redshift distribution  $N(z)$  assuming the cluster is foreground to the bulk of the population. The systematic effects of our weighting scheme used in the ellipticity measurement are compensated for by the factor  $\langle e^2 \rangle$ . The form of the error estimator given above is only valid for a dataset of infinite extent. In reality the error depends upon the number of objects contributing, through the filter function, to the reconstruction at each grid point. Close to the frame border the average weighted sum over the contributing images will be less than in the frame centre by a factor dependent upon the form of the filter function. The resulting variable signal to noise across the reconstruction makes simple mass maps hard to interpret. In the following discussion, the mass maps produced from the standard KS prescription are further divided by a map of the noise estimated using a local source surface density. The resulting maps have constant noise properties and can be more easily visualised. Apart from the morphological comparison our other analysis uses the standard KS mass map. The local noise estimator is:

$$\langle \Sigma(\vec{r}) \rangle = \frac{1}{8\pi^2 \bar{n}} \langle e^2 \rangle \sum_{\text{galaxies}} T^2(\theta)$$

Where  $\vec{\theta} = \vec{r}_g - \vec{r}$ .

We can make a simple test of the KS noise estimator and the systematics in our data by analysing the deep images of our third cluster 1603+43,  $z = 0.89$ , discussed in Paper I but not included in this work because significant lensing is not detected even with low order statistics such as the orientation histogram (Figure 9(c) of Paper I). We therefore adopt the cluster as a ‘blank field’. Using the global error

estimator the highest significance peak in the reconstruction is  $3.4 \sigma$  on the edge of the frame. Using the local error estimator this spuriously high significance is reduced to  $2.5 \sigma$ . This value is broadly consistent with expectations from random noise given the number of grid centres used. The quoted errors were estimated using the no-evolution  $N(z)$  for the sample magnitude limits ( $I \in [23, 25.5]$ ) as discussed in Paper I.

When estimating the total mass in our clusters we have to correct the values taken from our mass maps as the surface density estimator as given assumes that the surface density is zero at the frame boundaries (Fahlman *et al.* 1994). At the cluster radii available in our field of view this is not true and we should therefore correct the central mass estimates for the mean mass surface density at the frame border. This is unfortunately ill-defined, although using a King profile for the cluster mass we would anticipate that the correction ought to be small, only  $\sim 20\%$  of the central mass. Given the additional uncertainties due to the background redshift distribution we prefer to include this systematic error in the overall error budget for our mass estimates.

## 5 RESULTS

In this section we present the mass maps for 1455+22 and 0016+16 using the Kaiser & Squires technique modified as discussed in §4. Ellipticities and orientations of the field samples used the optimal weighting scheme discussed in §3 and Paper I. The sample magnitude limits are:  $I \in [23, 25.3]$  for 1455+22 and  $I \in [23, 25.5]$  for 0016+16. These limits provide the highest surface density of sources with reliable shape measurements whilst minimising the foreground contamination (for our adopted redshift distribution). All objects whose isophotes touch the frame boundaries have been removed from the cluster catalogues.

### 5.1 1455+22

In Figure 2 the mass map derived from the Kaiser & Squires analysis of the field catalogue is compared with the smoothed number density distribution of colour-selected cluster members defined according to the prescription discussed in §3. Adopting a straight number weighted scheme is equivalent to the assumption that the galaxy's luminosity does not appreciably effect its dynamical properties. For both maps the smoothing scale is 135 kpc (0.45 arcmin) and is shown by a scale bar. The mass contours intervals are based on errors calculated using the local weighting scheme discussed in §4 thereby reducing spurious features on the frame boundary. These errors also depend on the adopted redshift distribution,  $N(z)$ , for the faint galaxies. Following Paper I, we adopted the 'no evolution'  $N(z)$  for both cluster analyses, but our results are not sensitive to this assumption. Indeed, the *relative* mass maps are independent of  $N(z)$ .

The morphological similarities between the distributions of cluster members and lensing mass are striking. If we fit elliptical contours to the two distributions out to a scale of 360 kpc (1.25 arcmin), the position angles ( $\theta$ ) agree within the errors:  $\theta_{gal} = 145 \pm 2$  degrees compared to  $\theta_{mass} = 146 \pm 2$  degrees. This is illustrated in Figure 3

for all four distributions available for 1455+22. More interestingly the ellipticities ( $\epsilon$ ) of the two distributions are also in surprisingly close agreement  $\epsilon_{gal} = 0.52 \pm 0.03$  and  $\epsilon_{mass} = 0.47 \pm 0.03$ . This is as expected if the galaxies act as virialised mass-less tracers of the cluster potential.

To determine if the elliptical mass distribution is produced by unresolved substructure reconstructions were performed using smaller smoothing scales. While noisier the mass peak does not show any internal structure on scales greater than 60 kpc. In support of this on yet smaller scales ( $< 40$  kpc), the orientation of the cD ( $\theta = 148 \pm 2$  degrees) is also a close match to the mass distribution as would be expected from dynamical arguments that account for its growth. The ellipticity of the cD halo on these scales is  $\epsilon_{cD} = 0.23 \pm 0.01$ , considerably rounder than the mass or cluster galaxy distributions. These parameters are summarised in Table 1.

The agreement between the positions of the peaks of the distributions is less good, although the discrepancies while formally significant are all less than the respective smoothing scales. The offset between the peaks in the galaxy number density and mass distributions is  $120 \pm 20$  kpc, with the cD offset  $90 \pm 15$  kpc from the peak of the galaxy number density. Both the mass and galaxy number density distributions peak to the north-west of the cD. These offsets are a concern but we note that there is growing evidence that cD's do not always lie at the dynamical centres of their cluster (e.g. Bird 1994). The positional offset determined here is negligible compared to that inferred in other systems from the observed velocity offsets. Also, for a cluster with asymmetry along the line-of-sight it is not necessary for the position of the projected peak surface density to exactly match the projected position of the peak in the local density distribution.

Figure 2 also shows an equivalent comparison between the mass map and the X-ray surface brightness distribution smoothed to the same resolution, the X-ray surface brightness is plotted with a logarithmic intensity scale. The X-ray surface brightness peaks within 40 kpc of the cD. Again the contours are similarly oriented with  $\theta_X = 136 \pm 8$  degrees and  $\epsilon_X = 0.16 \pm 0.06$  out to 360 kpc. On the assumption that the X-ray surface brightness reflects the shape of the the potential then, for a logarithmic potential at radii  $r \gg r_c$ , we can convert the ellipticity of the X-ray contours into that of the surface density (Binney & Tremaine 1987, Eq. 2-55). This gives  $\epsilon_{mass}^X \simeq 0.46 \pm 0.18$ , in very good agreement with the value determined from fitting to the mass surface density.

Whilst there is obviously excellent agreement between the projected morphologies of the three distributions, in terms of shapes and orientations, it is critical to know whether the lensing matter has the same characteristic scale length as that of the visible baryonic component. Figure 4 shows the radial profiles derived from the mass and red cluster galaxy distributions. Both profiles have been centred on their respective maximum, corrected for the ellipticity of their distributions and normalised to the inner-most bin. The error-bars show the spread in values at a given radius. For clarity the galaxy profile has been offset slightly.

Within 400 kpc (1.3 arcmin) both profiles obey a similar functional form, with the distribution of galaxies being marginally more extended. To quantify this we fit a modi-

fied Hubble profile ( $\Sigma(r) \propto 1/(1+(r/r_c)^2)$ ) to the projected distributions. The adopted functional form is an adequate description of the shapes of our distribution profiles given the limited range. For comparison the parametric likelihood analysis undertaken for 1455+22 in Paper I gave a best fitting core radius of  $r_c^{mass} = 210 \pm 100$  kpc. Here we obtain maximum likelihood values of: ( $r_c$ ):  $r_c^{mass} = 200^{+70}_{-40}$  kpc and  $r_c^{gal} = 210^{+80}_{-40}$  kpc respectively. These values are azimuthally averaged and retain the effects of the smoothing used to generate the distributions. These are very similar to the core radii estimates obtained from X-ray imaging:  $\sim 200$  kpc (c.f. Jones & Forman 1992). The X-ray core radius from analysis of our HRI image is  $r_c^X = 150^{+100}_{-50}$  kpc. We can obtain the true core radius by correcting the profiles for the effects of the smoothing function and the ellipticity of the observed distributions. Comparison of the observed distributions with model profiles convolved with the same smoothing function gives maximum likelihood fits of  $r_c^{mass} = 100^{+80}_{-50}$  kpc and  $r_c^{gal} = 180^{+70}_{-50}$  kpc corrected to the semi-major axis. Within the errors from our model fitting we cannot formally discard the hypothesis that the two distributions have the same core radius. However, the more extended scale of the galaxy distribution is clearly apparent in Figure 4 at radii  $r \gtrsim 200$  kpc.

While a useful exercise, comparing parameters derived from functional fits to the 1-D profiles is a relatively insensitive tool for determining if the distributions have different scale-lengths. A more informative approach to understanding the relative distribution of mass and light is to take the 2-D maps and calculate the effective ‘mass/light’ ratio as a function of position. Figure 5 shows the median ratio of the mass surface density ( $\Sigma_{mass}(r)$ ) to the galaxy surface density ( $\Sigma_{gal}(r)$ ) as a function of radius in the cluster taken from this comparison:  $M/N_{gal} = \Sigma_{mass}(r)/\Sigma_{gal}(r)$ . The error bars denote the 1 sigma scatter at a given radius and the points are normalised to the central bin. This ratio shows a constant decline out to 500 kpc, amounting to a factor of 3 drop. Figure 5 thus confirms the earlier suggestion, based on the profile fitting, that the mass distribution is more centrally concentrated than the galaxies, the observed trend is significant at the  $3.3 \sigma$  level. Adopting a luminosity-weighting scheme for the galaxy distributions rather than our number-weighted one gives a marginally flatter, but statistically indistinguishable, slope for  $M/N_{gal}$ . This luminosity-weighted scheme has a larger scatter but indicates a drop of a factor of 2 in the mass/light ratio out to 500 kpc, although the slope is also consistent with zero within the large errors.

Returning to Figure 2 we note a significant secondary maximum ( $\simeq 10\sigma$ ) in the mass map  $\simeq 500$  kpc due east of the cluster centre. As this is well clear of the frame boundary, it is important to determine if this peak correlates with any other physical feature. Interestingly the peak does not lie close to any feature in either the distributions of X-ray emission, cluster members or field galaxies. The bow-wave like structure seen in the mass map persists when we use a smoothing scale of 60 kpc in the reconstruction, showing that the structure does not consist of individual mass peaks on scales larger than about 60 kpc.

Turning to the X-ray analysis, we have shown that the potential adopted is reasonably representative of that delin-

eated by the lensing mass. We can then combine the total cluster mass within a radius of 450 kpc, derived from the X-ray analysis on an *absolute* scale with the lensing signal to estimate the mean redshift of the  $I \leq 25$  background sources. This can be viewed either as a check of the conclusions of Paper I, or, adopting  $N(z)$  from Paper I, it provides a self-consistent check on the X-ray mass estimates.

Figure 6 shows the variation in the cluster mass derived from the lensing analysis parametrised as a function of the median source redshift. This is a lower limit to the mass as the KS technique assumes the mass surface density goes to zero at the boundary of our  $5 \times 5$  arcmin field (c.f. Fahlman *et al.* 1994). Also shown is the the projected mass determined from the X-ray analysis. Due to extrapolation to large radii necessary to determine the *projected* mass from the X-ray analysis it would be better to deproject the lensing mass distribution to give the mass of the central regions of the cluster and directly compare this with the X-ray determination. Unfortunately this deprojection requires the cluster mass profile at large radii which currently is poorly-constrained observationally. The flatness of the curve combined with the probable errors in the X-ray mass estimate make this a relatively insensitive tool with which to derive an upper limit to the background source redshift. A spatially resolved temperature profile for 1455+22 would significantly reduce the systematic errors in the X-ray mass determination. Nevertheless, Figure 6 does provide a rigorous lower limit of  $M \gtrsim 2.2 \times 10^{14} M_\odot$  for the projected cluster mass in the central 0.9 Mpc or so – comparable to  $M_X \lesssim 2 \times 10^{14} M_\odot$  in the similar region of Coma from Hughes (1989) most concentrated X-ray models. Moreover, if we adopt the preferred redshift distribution from Paper I we obtain good agreement between the X-ray and lensing derived total masses in the cluster centre. The resulting mass in the cluster centre is  $M \sim 3.1 \times 10^{14} M_\odot$ , roughly 50% higher than the maximum equivalent value for Coma. We note that this mass estimate is independent of the dynamical state of the cluster.

Studying Figure 6 it is readily apparent that a difference between the X-ray and lensing determined masses of the magnitude claimed by Babul & Miralda-Escudé (1994) if typical of the whole cluster would be difficult to achieve unless the field redshift distribution was peaked close behind 1455+22. As we will see below this can be ruled out by a similar analysis of 0016+16 which also shows good agreement between the central cluster masses derived from the lensing and X-ray data.

Having determined that there is relatively good agreement between the mass estimates from the lensing and X-ray analyses we convert these into rough estimates of the mass to light ratio for the cluster. The integrated luminosity of all the red cluster galaxies within 450 kpc of the cluster centre is  $L_V = 6.8 \times 10^{11} L_\odot$ . This is a lower limit to the total cluster luminosity owing to possible contributions from foreground structures and cluster members with colours bluer than the E/S0 sequence. Integrating the light of all the galaxies in the field seen within 450 kpc of the cluster centre assuming they are cluster members gives  $L_V \sim 1.0 \times 10^{12} L_\odot$ . Using the lower bound to the cluster mass determined above we can thus derive a minimum mass to light ratio for the cluster of  $M/L_V \gtrsim 220$  in solar units. This is similar to values derived from virial analysis of rich clusters,  $M/L_V \gtrsim 250$ . However, adopting the total central mass indicated by *both*

the X-ray and lensing methods and the red cluster galaxy luminosity requires  $M/L_V \sim 460$ . For comparison the mass to light ratio required for closure density is  $M/L_V \sim 700$ .

## 5.2 0016+16

This cluster is morphologically quite different to 1455+22 having no central cD and a considerably higher optical richness although with a similar X-ray luminosity. Nevertheless, most of the conclusions derived in §5.1 apply equally well to 0016+16. The analysis of this cluster is complicated primarily by the small field available, the source density beyond  $z = 0.55$  is still sufficiently high at  $I \sim 25$  to allow us to robustly map the cluster morphology.

Figure 7 compares the lensing mass map derived from the Kaiser & Squires technique with the distribution of red cluster members. The effective spatial resolution in the mass reconstruction is 200 kpc (0.45 arcmin). Although the salient features reproduce between the two maps, there are many more apparently spurious features in the lensing maps away from the cluster centre than observed in 1455+22. Nevertheless, the central region free of these features still comprises an area equivalent to that probed in our intermediate redshift cluster, 1455+22. The most striking feature common to both maps is a elliptical-like peak with bimodal substructure straddling the optically-defined centre. The mass map indicates the two clumps have a projected separation of 600 kpc with the more concentrated sub-clump in the south-west. The galaxy distribution reveals at least 3 sub-clumps orientated similarly to the mass distribution. A fourth sub-clump to the south-east is not detected in the mass map. The orientations of the mass and galaxy distributions between 300–600 kpc agree closely:  $\theta_{mass} = 131 \pm 6$  degrees and  $\theta_{gal} = 124 \pm 8$  degrees. As in 1455+22 the orientation of the central galaxies (in this case a linear chain rather than the cD envelope) follows that of the mass on larger scales ( $\theta = 125 \pm 10$  degrees). The best fit ellipticities, shown in Figure 8, are  $\epsilon_{mass} = 0.59 \pm 0.01$  and  $\epsilon_{gal} = 0.21 \pm 0.02$ .

In Figure 7 we also compare the mass map with the ROSAT PSPC image of similar spatial resolution, the latter displayed with a logarithmic scaling. Again the distributions are well aligned with  $\theta_X = 127 \pm 4$  degrees over the range 300–600 kpc. The ellipticity on these scales is  $\epsilon_X = 0.21 \pm 0.02$ . As for 1455+22 we convert this to that appropriate for the surface density yielding  $\epsilon_{mass}^X \simeq 0.61 \pm 0.06$  for  $r \gg r_c$  and  $\epsilon_{mass}^X \simeq 0.28 \pm 0.03$  for  $r \ll r_c$ . Adopting the core radii determined below we are closer to the  $r \gg r_c$  regime on the scales where the ellipticity is measured.

Summarising, there is reasonable agreement between the ellipticity of the mass distribution and that for the X-ray gas. Although the complex structure in the galaxy distribution precludes a detailed comparison, both the galaxy and mass distributions have similar bimodal forms. To determine if the two peaks of the mass distribution are dynamically distinct, we divided Dressler & Gunn's (1992) spectroscopic sample along a line perpendicular to the axis of the two sub-clumps. The rest-frame velocity difference is  $\sim 400$  kms  $\text{sec}^{-1}$  and not statistically significant. In view of the apparently different surface densities for the two mass peaks we would predict a temperature difference between the X-ray gas in the two structures. Therefore a spatially resolved X-

ray temperature map of the cluster from ASCA is of great interest.

Figure 9 shows the projected profiles for the mass and galaxy distributions centred on their respective maxima and normalised to their innermost bin. The galaxy distribution reveals an intrinsic deconvolved core of  $\sim 330$  kpc (semi-major axis) after correction for the ellipticity of the galaxy distribution. This is larger than the value obtained from the mass distribution of  $\simeq 210$  kpc although both values are systematically uncertain due to both the complex structures in the two distributions and the problems of background subtraction associated with the small field. Nevertheless, the mass core radius from our lensing reconstruction compares well with that determined from the parametric analysis in Paper I,  $r_c^{mass} = 210 \pm 250$  kpc. Equally the lensing core radius is smaller than that derived from the PSPC image of  $400_{-150}^{+200}$  kpc.

Figure 10 shows the estimate of the total mass within a radius of 600 kpc of the centre of 0016+16 as a function of the median redshift of the background population. The derived mass surface density is a lower limit as it assumes that the project surface density in the cluster is zero at our frame boundaries. From the lensing analysis we determine a robust lower limit to the projected mass of  $M \gtrsim 3.4 \times 10^{14} M_\odot$ . This can be compared to the X-ray determined value for the central 600 kpc of  $M_X \sim 7.3 \times 10^{14} M_\odot$ . Adopting the preferred median redshift for the background population, for the magnitude range used in the lensing analysis, predicts a mass of  $M \sim 9.9 \times 10^{14} M_\odot$  close to the X-ray determined value. As in 1455+22 we have good agreement between not only the morphology of the mass determined from the lensing and X-ray analysis but also the total masses inferred for the cluster. For completeness we also calculate the apparent mass to light ratio as for 1455+22 inside a radius of 600 kpc. Summing the luminosities of the red cluster members in this aperture gives  $L_V \sim 2.3 \times 10^{12} L_\odot$ , while summing all the galaxies in the field within this projected radius yields  $L_V \sim 4.9 \times 10^{12} L_\odot$  retaining the central galaxies as the brightest cluster members. Combining the lower limit on the cluster mass from the lensing with the upper limit on the luminosity we then obtain a mass to light ratio of  $M/L_V \gtrsim 70$  in solar units, such a low value is not surprising given the large amount of foreground contamination known to exist in this field. Adopting the luminosity of the red cluster members and the lensing derived mass we calculate  $M/L_V \sim 430$  in the central 1.2 Mpc of 0016+16. The uncertainties on this value are of course large.

## 6 DISCUSSION

When comparing the results from our two clusters we are struck by the many common features observed, despite their different morphologies and redshifts.

Firstly, in each cluster we have four independent estimates of the orientation of the major axis of the cluster projected upon the plane of the sky (c.f. Table 1). These four estimates span a range in scales between the central galaxies ( $\sim 20$ kpc) out to  $\sim 0.5$ Mpc (the lensing mass, the X-ray gas and the cluster galaxy distribution). In both clusters *all* four estimates are in good agreement. This implies that at least to first order the systems are relaxed in their

central regions. This is the first time that such a comparison has been made and it is encouraging to find such good agreement.

Secondly, we find from the lensing analysis that both clusters have moderately elliptical  $\epsilon \sim 0.5$ – $0.6$  mass distributions. These values are close to the average ellipticity ( $\epsilon \sim 0.5$ ) predicted for clusters from the effects of tidal distortion on proto-clusters by Binney & Silk (1979). Moreover, in both clusters the ellipticities of the X-ray surface brightness distributions when converted to the surface density agree with those derived from the lensing signal. This agreement does not extend to the galaxy distributions, where in 1455+22 the galaxies act as tracers of the underlying mass distribution, while in 0016+16 their general distribution is possibly rounder and more clumpy. Thus it appears that in the more relaxed system the galaxies are good tracers of the mass. A similar conclusion was reached for Abell 370 by Kneib *et al.* (1993). Using detailed modelling of several gravitationally lensed features they determine a mass distribution in the cluster which closely matches the light. We believe our result is more robust as it is derived from the full two dimensional mass and galaxy distributions rather than parametric fits to these distributions.

From profile fitting in both clusters we find that the mass is marginally more centrally concentrated than the two baryonic tracers, although because of the large errors in profile fitting, this effect is not formally significant. A direct comparison of the mass and galaxy surface density distributions in 1455+22 gives a more significant gradient in the ratio of mass to galaxy surface density. Specifically, in Figure 5 we detect a factor of 3 drop in this ratio within  $r < 500$  kpc. A similarly steep drop is claimed for the mass to light ratio in the centre of the Perseus cluster (Eyles *et al.* 1991).

The apparent concentration of mass compared to the baryonic tracers in 1455+22 is contrary to some theoretical predictions for hierarchical growth of clusters (e.g. West & Richstone 1988). These show the galaxies more centrally concentrated than the mass due to dynamical friction. One way to concentrate the mass relative to the galaxies is for dissipation to occur preferentially in the mass component, this appears unlikely if the mass is principally weakly interacting dark matter, which is by definition incapable of dissipation. Other ways include removing galaxies from the central regions of the cluster (for instance by merging them into a central galaxy) leading to an apparent flattening of the galaxy surface density at smaller radii and luminosity segregation, with fewer, but brighter, galaxies nearer the centres of rich clusters. Using luminosity-weighting for 1455+22 we do indeed obtain a shallower slope for the variation of mass to light. Unfortunately, due to the errors the slope is consistent with both zero and that derived previously with number-weighting. A further possibility is to invoke incomplete virialisation to explain the relative distributions of galaxies, gas and mass. However, the close morphological similarities between the distributions on large scales would require us to have caught both clusters between the point where they have relaxed sufficiently to allow the distributions to have aligned but not quite enough for them to have reached equipartition.

With adequate data for only two clusters, it is clear that above option cannot be ruled out. A larger sample is needed to fully explore the dynamical states of the centres of rich

moderate redshift clusters. Enlarging the angular coverage available for the lensing analysis will also allow us to determine the asymptotic form of the radial mass profile and compare this to that shown by the baryonic components of the cluster. This will provide a simple and direct test of the existence of dark halos around clusters (Smail, Edge & Ellis 1994, in prep).

The estimates of the total projected mass in the central 1-1.5 Mpc of our two clusters from the X-ray analyses and the lower limits available from our lensing technique are in reasonable agreement. If we adopt the redshift distribution derived independently of the X-ray analysis in Paper I this agreement becomes good: within 16% in 1455+22 and 26% for 0016+16. Without detailed temperature information about the X-ray gas in our clusters it is impossible to make a more detailed comparison of the mass profile inferred from the X-ray imaging and that provided by the lensing analysis. Nevertheless, adopting reasonable values for the global cluster temperatures our result is inconsistent with an extrapolation to larger scales of Babul & Miralda-Escudé (1994) result from their analysis of arcs in cluster cores.

Probably the easiest way to reconcile these two results is to recognise that optical identification of clusters preferentially selects systems with high projected central galaxy densities. With a population of reasonably high ellipticity clusters, as seems to be indicated both from this work and optical studies (Plionis, Barrow & Frenk 1991), this bias will result in a large fraction of the more distant systems having their major axis parallel to the line of sight. Such a bias will cause the projected mass surface density (i.e. along the major axis) to be higher than the inferred mass from the X-ray analysis which adopts a spherical symmetry. Such an effect was discussed by Babul & Miralda-Escudé but discarded because they did not consider the possible selection bias present in the original cluster identification. Two of Babul & Miralda-Escudé's clusters are very concentrated optically and may fall into the aligned class, the third cluster, their most X-ray luminous, is not optically concentrated and as they show has a lensing derived mass which is consistent with the X-ray determination in accord with our findings. Owing to their geometry and the selection criteria adopted neither of our clusters should be affected by this bias. Hence, it appears that a more detailed study of the biases inherent in studying optically-selected clusters with giant arcs may hold the explanation to our disagreement with the apparent results for cluster centres derived by Babul & Miralda-Escudé.

Combining our estimated masses with the luminosities of the red cluster members gives mass to light ratios for the central regions of the clusters of  $M/L_V \sim 460$  for 1455+22 and  $M/L_V \sim 430$  for 0016+16. Correcting these for the surface densities at the frame border assuming a King profile gives  $M/L_V \sim 550$ . If these regions are representative of the Universe as a whole we obtain  $\Omega \sim 0.8$ . We reiterate that these results are independent of the dynamical state of the clusters.

Finally, studying both clusters it is apparent that they contain significant substructure in their mass distributions. We detect an apparently significant sub-clump in 1455+22, while 0016+16 is strongly bimodal. This observation, if supported by a larger sample, has interesting consequences for

the growth of clusters and the evolution of the galaxies within them. Comparing the lensing maps with the X-ray surface brightness (which follows the potential) highlights the sensitivity of the lensing technique for studying the occurrence of substructure in clusters.

## 7 CONCLUSIONS

Deep statistical lensing studies such as those presented here are both difficult and time consuming. However, they present one of the cleanest methods of studying the distribution of mass in rich clusters. The mass mapping technique of Kaiser & Squires (1993) is a very powerful and model-independent method for probing the morphology of the cluster mass.

- We have reconstructed projected mass distributions for two luminous X-ray selected clusters, one at intermediate (1455+22;  $z = 0.26$ ) and one at moderate redshift (0016+16;  $z = 0.55$ ). These are accurate on a relative scale independent of any assumed redshift distribution for the background field galaxies. Despite the different cluster morphologies, both mass maps show a remarkable similarity to the X-ray and galaxy surface density maps of the clusters on large scales. This agreement extends to include the orientations and ellipticities of the distributions.

- A comparison of the relative distribution of the mass and the galaxies shows that whilst galaxies are good tracers of the mass *morphology* they appear to be less concentrated. However, the X-ray gas and mass are more closely distributed. In our intermediate redshift cluster we find a continuous decrease of  $\times 2-3$  in the ratio of mass to galaxy surface density out to the limits of our data,  $r \sim 500$  kpc. We obtain corrected maximum likelihood core radii for the 3 distributions of  $r_c^{mass} = 100_{-50}^{+80}$  kpc,  $r_c^{gal} = 180_{-50}^{+70}$  kpc,  $r_c^X = 150_{-50}^{+100}$  kpc.

- The moderate redshift cluster (0016+16) shows a large amount of structure in the mass, X-ray gas and galaxy distributions. All three maps show bimodal distributions spanning the optically determined cluster centre, although this bimodality is not seen in redshift space using the limited spectroscopic dataset. The presence of substructure 0016+16 and also 1455+22 implies significant growth in the cluster mass at relatively recent epochs. This substructure is more readily apparent in the lensing mass maps than in our X-ray images due to the dependence of the X-ray emissivity on the smoother cluster potential rather than directly on the mass distribution. This graphically illustrates the bias inherent in determining the prevalence of substructure in clusters on the basis of X-ray imaging alone. For the intermediate scale substructure crucial to understanding the inner regions of rich clusters this currently makes lensing a more sensitive technique.

- Adopting from Paper I the most likely redshift distribution for the faint galaxy population used as probes in the lensing analysis we determine the projected mass in the central 1-1.5 Mpc of our two clusters. These estimates are in extremely good agreement with those from deprojection of our X-ray images, a result which is at variance with the conclusions of Babul & Miralda-Escudé (1994). The mass to light ratios obtained in the inner regions of our clusters, from both

the lensing and X-ray analyses, if indicative of the universal value imply  $\Omega \sim 0.8$ .

- High X-ray luminosity clusters lie on the extreme tail of the cluster mass distribution in hierarchical models of structure formation. The exponential nature of this tail makes the abundances of such clusters an extremely sensitive test of these models. As we demonstrate lensing observations are a direct route to the underlying mass distribution of these clusters at moderate redshift, allowing high resolution ‘imaging’ of the cluster mass on scales comparable to the best available from X-ray imaging.

- We have demonstrated the use of weak gravitational lensing to map the mass distribution in distant clusters. Enlarging both the optical and X-ray datasets and the optical area coverage in individual clusters will allow us to study the prevalence of mass substructure as a function of epoch in the largest bound structures known and the role of this substructure in the X-ray evolution of clusters. Wider field observations will also allow us to follow the mass of the clusters out to scales of 2-3 Mpc to determine the asymptotic form of the mass profile and the run of mass to light in the outskirts of the cluster (e.g. Bonnet, Mellier & Fort 1994).

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## REFERENCES

- Arnaud, K. 1987, PhD. thesis, University of Cambridge.  
 Babul, A. & Miralda-Escudé, J. 1994, preprint.  
 Binney, J. & Tremaine, S. 1987, Galactic Dynamics, Princeton Univ. Press.  
 Bird, C. 1994, ApJ, **422**, 480.  
 Blandford, R.D. & Narayan, R. 1993, ARAA, **30**, 311.  
 Bonnet, H., Mellier, Y. & Fort, B. 1994, ApJ, submitted.  
 Buote, D.A. & Canizares, C.R. 1992, ApJ, **400**, 385.  
 Couch, W.J., Ellis, R.S., Malin, D.F. & MacLaren, I. 1991, MNRAS, **249**, 606.  
 Dressler, A. & Gunn, J.E. 1992, ApJ Supp., **75**, 1.  
 Donahue, M., Stocke, J.T. & Gioia, I.M. 1992, ApJ, **385**, 49.  
 Edge, A.C., Stewart, S., Fabian, A. & Arnaud K.A. 1990, MNRAS, **245**, 559.  
 Edge, A.C. & Stewart, S. 1991, MNRAS, **254**, 51.  
 Ellis, R.S., Couch, W.J., MacLaren, I. & Koo, D.C. 1985, MNRAS, **217**, 239.  
 Evrard, A.E. 1990, ApJ, **363**, 349.  
 Eyles, C.J., Watt, M.P., Bertram, D., Church, M.J., Ponman, T.J., Skinner, G.K. & Willmore, A.P. 1991, ApJ, **376** 23.  
 Fabian, A.C. 1991, MNRAS, **253**, 29.  
 Fahlman, G., Kaiser, N., Squires, G. & Woods, D. 1994, preprint.  
 Fitchett, M.J. 1988, MNRAS, **230**, 161.  
 Frenk, C.S., White, S.D.M., Efstathiou, G. & Davis, M. 1990, ApJ, **351**, 10.  
 Gerbal, D., Durrte, F., Lima-Neta, G. & Lachièze-Rey, M. 1992, A&A, **253** 77.

- Gioia, I.M., Henry, J.P., Maccacaro, T., Morris, S.L., Stocke, J.T. & Wolter A. 1990, ApJ, **356**, L35.
- Grossman, S.A. & Narayan, R. 1989, ApJ, **344**, 637.
- Gunn, J.E., Hoessel, J.G. & Oke, J.B. 1986, ApJ, **306**, 30.
- Henry, J.P., Gioia, I.M., Maccacaro, T., Morris, S.L. & Stocke, J.T. 1992, ApJ, **386**, 408.
- Hughes, J.P. 1989, ApJ, **241**, 924.
- Jarvis, J.F. & Tyson, J.A. 1981, AJ, **86**, 476..
- Jones, C. & Forman, W. 1984, ApJ, **276**, 38.
- Jones, C. & Forman, W. 1992, in *Clusters and Superclusters of Galaxies*, ed. Fabian, A.C., Kluwer.
- Kassiola, A., Kovner, I. & Blandford, R.D. 1992, ApJ, **396**, 10.
- Kaiser, N. 1991, ApJ, **383**, 104
- Kaiser, N. & Squires, G. 1993, ApJ, **404**, 441.
- Kent, S.M. & Gunn, J.E. 1982, AJ, **87**, 692.
- Kochanek, C.S. 1990, MNRAS, **247**, 135.
- Koo, D.C. 1981, ApJ, **251**, 75.
- Kneib, J-P., Mellier, Y., Fort, B. & Mathez, G. 1993, A&A, **273**, 367.
- Lilly, S.J., Cowie, L.L. & Gardner, J.P. 1991, ApJ, **369**, 79.
- Miralda-Escudé, J. 1991a, ApJ, **370**, 1.
- Miralda-Escudé, J. 1991b, ApJ, **380**, 1.
- Miralda-Escudé, J. & Fort, B. 1993, ApJ, **417**, L5.
- Mushotzky, R. 1993, Ann. Ny. Acad., **688**, 184.
- Plionis, M., Barrow, J.D. & Frenk, C.S. 1991, MNRAS, **249**, 662.
- Sharples, R.M., Ellis, R.S. & Gray, P.M. 1988, MNRAS, **231**, 479.
- Soucail, G. 1992, in *Clusters and Superclusters of Galaxies*, ed. Fabian, A.C., Kluwer.
- Smail, I., Ellis, R.S., Fitchett, M.J., Nørgaard-Nielsen, H.U., Hansen, L. & Jørgensen, H.E. 1991, MNRAS, **252**, 19.
- Smail, I., Ellis, R.S. & Fitchett, M.J. 1994, MNRAS, submitted (Paper I).
- Smail, I., Ellis, R.S., Couch, W.J. & Sharples, R.M. 1994, in prep.
- Tyson, A.J., Valdes, F. & Wenk, R. 1990, ApJ, **349**, 381.
- West, M.J. & Richstone, D.O. 1988, ApJ, **335**, 532.
- White, D.A. 1992, PhD. thesis, University of Cambridge.
- White, S.D.M., Silk, J. & Henry, J.P. 1981, ApJ, **251**, L65.
- White, S.D.M., Navarro, J.F., Evrard, A.E. & Frenk, C.S. 1993, Nature, **366**, 429.
- Wu, X. & Hammer, F. 1993, MNRAS, **262**, 187.
- Zwicky, F. 1933, Helv. Phys. Acta. **6**, 489.

## FIGURES

**Figure 1:** a) The ROSAT HRI exposure of 1455+22 overlaid on a grey-scale of our deep combined V+I exposures. b) A similar comparison between the ROSAT PSPC image of 0016+16 and our V+I exposure.

**Figure 2:** The upper panel shows the mass distribution in 1455+22 from the lensing analysis contoured over the smoothed galaxy number density distribution for the red cluster members. The contours start at zero surface density and are spaced every 2 sigma. The smoothing scale (135 kpc) used to construct both distributions is marked and the position of the cluster cD is indicated (+). This map has been normalised by the local error estimate. The high degree of similarity between the two distributions should be noted. The lower panel is the surface brightness distribution of X-ray gas from the ROSAT HRI image of 1455+22 compared to the derived mass map. The X-ray distribution's morphology is also very similar to the mass. The marked symbols correspond to those in the previous figure. The orientation corresponds to that of Figure 1(a).

**Figure 3:** The four separate tracers available in 1455+22 to map the mass distribution. Overlaid on these are the best-fit ellipses to high-light the strong similarities between the orientations of the distributions over a range of scales.

The ellipse shown for the X-ray surface brightness map has not been converted into the value for the mass (c.f. Table 1). Upper-left panel, the lensing derived mass map. Upper-right panel, the X-ray surface brightness distribution. Lower-left, the number density of the red cluster members. The panel at lower-right shows the central galaxy. The orientation and symbols correspond to those of Figure 2.

**Figure 4:** A comparison between the azimuthally averaged profiles for the mass (●) and galaxy surface density (○) in 1455+22. The profiles have been corrected for the ellipticity of their respective distributions. The more compact nature of the mass distribution is evident on scales  $\gtrsim 200$  kpc.

**Figure 5:** This figure shows a more sensitive test of the relative distribution of galaxies and mass in 1455+22. By combining the mass and galaxy surface density maps directly and then azimuthally averaging we obtain a more direct measure of the relative concentration of the two distributions. It is readily apparent that the mass is more centrally concentrated than the galaxies.

**Figure 6:** The total mass, in solar units, interior to 450 kpc from the lensing analysis of 1455+22 as a function of the median redshift of the background galaxy distribution (●). This is compared to the mass derived from the analysis of the X-ray image within the same radius (solid line). The predicted value from our preferred redshift distribution (a no-evolution  $N(z)$  to  $I = 25$ , Paper I) is also marked (○) – in close agreement to the X-ray measurement. The redshift of the cluster is shown by the vertical dashed line. The total mass is not corrected for the background surface density at the frame edge.

**Figure 7:** The left-hand panel shows the mass distribution in 0016+16 from the lensing analysis contoured over the smoothed galaxy number density distribution for the red cluster members. The contours start at zero surface density and are spaced every 1 sigma. The smoothing scale (200 kpc) used to construct both distributions is marked and the position of the optical cluster centre is indicated (+). This map has been normalised by the local error estimate. The right-hand panel shows the surface brightness distribution of X-ray gas from the ROSAT PSPC image of 0016+16 compared to the derived mass map. The X-ray distribution's morphology is a close match to the mass. The marked symbols correspond to those in the previous figure. The orientation corresponds to that of Figure 1(b).

**Figure 8:** Maps for 0016+16 of the four possible tracers of the cluster mass distribution. Contoured over these are the best-fit ellipses showing the strong similarities between their orientations on scales from 200 kpc to 1.5 Mpc. The ellipse shown for the X-ray surface brightness map has not been converted into the value for the underlying mass. The lensing derived cluster mass distribution is shown in the upper-left panel. The upper-right panel is the X-ray surface brightness map. Lower-left, the distribution of colour-selected red cluster members. The central galaxy distribution is the lower-right panel. The orientation and symbols correspond to those of Figure 7.

**Figure 9:** The azimuthally averaged profiles for the mass (●) and galaxy surface density (○) in 0016+16. The profiles have been corrected for the ellipticity of their respective distributions.

**Figure 10:** The total projected mass derived from the lensing analysis for the central 1.2 Mpc of 0016+16. This is

shown in solar units parametrised in terms of the median redshift of the background galaxy distribution ( $\bullet$ ). This is compared to the mass determined from the analysis of the X-ray image within the same radius (solid line). The predicted value from our preferred redshift distribution (the no-evolution  $N(z)$  model, Paper I) is also marked ( $\odot$ ) – in good agreement with the X-ray measurement. The redshift of the cluster is shown by the vertical dashed line. The projected mass is uncorrected for the background surface density at the frame edge.