CROSS-CORRELATION WEAK LENSING OF SDSS GALAXY CLUSTERS. III.
MASS-TO-LIGHT RATIOS

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ABSTRACT

We present measurements of the excess mass-to-light ratio (M/L) measured around MaxBCG galaxy clusters observed in the Sloan Digital Sky Survey. This red-sequence cluster sample includes objects from small groups with $M_{200} \sim 5 \times 10^{12} h^{-1} M_{\odot}$ to clusters with $M_{200} \sim 10^{15} h^{-1} M_{\odot}$. Using cross-correlation weak lensing, we measure the excess mass density profile above the universal mean $\Delta \rho(r) = \rho(r) - \bar{\rho}$ for clusters in bins of richness and optical luminosity. We also measure the excess luminosity density $\Delta \ell(r) = \ell(r) - \bar{\ell}$ measured in the $z=0.25$ i band. For both mass and light, we de-project the profiles to produce three-dimensional mass and light profiles over scales from 25 $h^{-1}$ kpc to 2 $h^{-1}$ Mpc. From these profiles we calculate the cumulative excess mass $\Delta M(r)$ and excess light $\Delta \ell(r)$ as a function of separation from the BCG. On small scales, where $\rho(r) \gg \bar{\rho}$, the integrated mass-to-light profile $(\Delta M/\Delta \ell)(r)$ may be interpreted as the cluster $M/L$. We find the $(\Delta M/\Delta \ell)_{200}$, the $M/L$ within $r_{200}$, scales with cluster mass as a power law with index $0.33 \pm 0.02$. On large scales, where $\rho(r) \sim \bar{\rho}$, the $\Delta M/\Delta \ell$ approaches an asymptotic value independent of cluster richness. For small groups, the mean $(\Delta M/\Delta \ell)_{200}$ is much smaller than the asymptotic value, while for large clusters $(\Delta M/\Delta \ell)_{200}$ is consistent with the asymptotic value. This asymptotic value should be proportional to the mean M/L of the universe $(M/L)$. We find $(M/L) b^2_{M/L} = 362 \pm 54h$ (statistical). There is additional uncertainty in the overall calibration at the $\sim 10\%$ level. The parameter $b^2_{M/L}$ is primarily a function of the bias of the $L \lesssim L_*$ galaxies used as light tracers, and should be of order unity. Multiplying by the luminosity density in the same bandpass we find $\Omega_m b^2_{M/L} = 0.20 \pm 0.03$, independent of the Hubble parameter.

Key words: dark matter – galaxies: clusters: general – gravitational lensing – large-scale structure of universe

Online-only material: color figures, machine-readable table

1. INTRODUCTION

Comparison of luminous to total mass through the mass-to-light ratio $(M/L)$ dates back at least to Kapteyn (1922), who found values of $M/L \sim 2 M_\odot/L_\odot$ in the solar neighborhood. Similar values were found by Hubble for the disk of Andromeda in 1929 (Hubble 1929). Extension of this approach to larger scales was first attempted by Zwicky in 1933 for the Coma cluster (Zwicky 1933, 1937). Under reasonable assumptions about the cluster’s dynamical state, Zwicky estimated the mass of the cluster. The inferred average $M/L$ for cluster galaxies was around 500 $M_\odot/L_\odot$, implying a surprising dominance of dark over luminous matter.

Decades of observation confirm Zwicky’s conclusion that dark matter dominates on large scales. The simplest model capable of accommodating current observations is the cold dark matter (CDM) model. It is assumed that approximately 80% of the cosmic mass density is in the form of some dynamically cold, collisionless species of the subatomic particle. Monte Carlo predictions for the evolution of structure in such a CDM universe have reached a high level of sophistication. Given a set of cosmological parameters and initial conditions, modern simulations are accurate and predictive within well understood limitations imposed by resolution and simulation volume (see, e.g., the comparison paper of Heitmann et al. 2008, and references therein). However, accurate simulations of the baryonic components of clusters remain beyond both current theoretical understanding and simulation technology. In the absence of direct theoretical prediction, observations of the connection between observable light and computable dark matter remain important. The simplest connection, still relevant 90 years after Kapteyn, is the $M/L$.

Observations of both mass and light have advanced considerably since Zwicky’s time. Dynamics of cluster galaxies still provide important constraints on cluster masses. These have confirmed Zwicky’s essential conclusions with improved accuracy over a broader range of environments (e.g., Carlberg et al. 1997). There are also new analysis techniques such as the
“caustics” method (Rines et al. 2004) and velocity stacking methods (e.g., Becker et al. 2007) which confirm and extend the standard analyses.

The X-ray emission from the hot intra-cluster plasma has become a favored proxy for cluster mass. Under the assumption of hydrostatic equilibrium, masses and \( M/L \) can be calculated from X-ray temperatures and, less directly, luminosities. These X-ray analyses confirm the dynamical measurements of high \( M/L \) (e.g., Lin et al. 2004).

Weak gravitational lensing, an effect which Zwicky thought promising (Zwicky 1937), is now an established technique for studying the mass distributions in clusters of galaxies. The effect, deflection of light from background objects as it passes foreground clusters, is generally less precise on a cluster-by-cluster basis than X-ray or velocity measurements. But it is complementary in that it is independent of the dynamical state of the system, is linear in the density, and can be measured at a large range of separations from the cluster center.

Weak lensing studies have traditionally focused on measuring the mass of individual clusters. However, averaging the lensing signal over many clusters is more robust and easier to interpret (see the discussions in Johnston et al. 2007a; Sheldon et al. 2009; Johnston et al. 2007b). With this method, the full \( M/L \) profile can be measured from small scales to well beyond the bound regions of the clusters. Early stacked \( M/L \) results for group-sized objects (e.g., Hoekstra et al. 2001; Parker et al. 2005) showed the promise of this approach. The pilot study of Sheldon et al. (2001) demonstrated the great potential of the Sloan Digital Sky Survey (SDSS; York et al. 2000) for measuring cluster masses.

In this work we measure the mean \( M/L \)'s for SDSS groups and clusters drawn from the MaxBCG cluster sample (Koester et al. 2007b, 2007a). We compare the ensemble mass estimates from the first two papers in this series (Sheldon et al. 2009; Johnston et al. 2007b) with ensemble measurements of the total light. We measure the mean mass using lensing, and the mean luminosity by correlating the clusters with the surrounding galaxies. Each measurement spans a range of separations from 25 \( h^{-1} \) kpc to 22 \( h^{-1} \) Mpc, extending the volume over which the \( M/L \) is measured well beyond the virial radii of the clusters.

Because lensing is not sensitive to uniform mass distributions, aka “mass sheets,” we measure the mean mass density of a lens sample above the mean density of the universe \( \Delta \rho = \rho(r) - \bar{\rho} \) (actually we measure a two-dimensional projection of the three-dimensional \( \Delta \rho \) which we will de-project). In other words, we measure the cluster-mass cross correlation function times the mean density of the universe \( \rho = \bar{\rho} \xi_{cm} \). On small scales this is a measure of the mean density profile, but on large scales, where the density approaches the background, it can only be interpreted in terms of the correlation function.

We measure the light using a stacking technique directly comparable to the lensing measurements. We include light from all galaxies surrounding clusters with luminosity above a threshold, and then subtract the measurements around random points in order to remove the uniform background. This means we measure the luminosity density above the mean \( \Delta \ell = \ell(r) - \bar{\ell} \), so it is a correlation function just like the mass measurement. The excess mass within radius \( r \) divided by the excess luminosity within radius \( r \) is the ratio of integrals of the correlation functions:

\[
\frac{\Delta M}{\Delta L} < r = \frac{\int_0^r dr [\rho(r) - \bar{\rho}] \ell^2}{\int_0^r dr [\ell(r) - \bar{\ell}] \rho^2} = \frac{\int_0^r dr \bar{\rho} \xi_{cm} r^2}{\int_0^r dr \bar{\ell} \xi_{cr} r^2}. \quad (1)
\]

On the scale of virialized halos, defined where the mean density is a few hundred times the mean, Equation (1) can be interpreted as the mean cluster \( M/L \) in a straightforward way. On very large scales, as the density approaches the mean, Equation (1) becomes proportional to the mean \( M/L \) of the universe. The proportionality constant is related to the particulars of the correlation function measurements. For example, the light and mass may be clustered differently, and this difference may depend on the properties of the galaxies chosen as tracers of the light. Thus we expect this measurement to depend on the “bias” of the light tracers relative to the mass. This bias depends primarily on the mass of the halos hosting these tracers. The bias also depends on the variance of the mass density field \( \sigma_\ell \) as the larger the variance in that field the smaller the bias at a fixed mass (Kaiser 1984).

Full theoretical models of this measurement on all scales will require substantial effort. For this paper we will parametrize our ignorance at large scales in terms of the bias. We will write the asymptotic \( M/L \) as

\[
\langle \frac{\Delta M}{\Delta L} \rangle_{\text{asy}} = \langle M/L \rangle b_{M/L}^2,
\]

\[
b_{M/L}^2 = \frac{1}{b_{\ell m}} \frac{\xi_{cm}}{\xi_{cr}}. \quad (2)
\]

Here \( \langle M/L \rangle \) is the mean \( M/L \) of the universe, but it is multiplied by a bias factor \( b_{M/L}^2 \). This factor depends on the bias of the galaxy tracers relative to the mass \( b_{\ell m} \), which should be of order unity for tracers near \( L_s \) since these galaxies are expected to be only slightly anti-biased (Sheth & Tormen 1999; Seljak & Warren 2004). This term also depends on the ratio of the bias of clusters relative to mass and light \( b_{\ell c}/b_{\ell m} \), which should also be near unity for the same reasons. The cluster bias is likely to cancel from this equation because the cluster terms appear in a ratio \( b_{\ell m}/b_{\ell c} \).

On large enough scales, \( \Delta M/\Delta L \) should approach a constant value independent of the halo mass as long as the bias of the light tracers, and thus \( b_{M/L}^2 \), is equivalent in all cases. This appears to be the case, as we will demonstrate.

We assume a Friedman–Robertson–Walker cosmology with \( \Omega_M = 0.27, \Omega_\Lambda = 0.73, \) and \( H_0 = 100 \) km s\(^{-1}\) Mpc\(^{-1}\) and distances are measured in physical, or proper units, rather than in comoving units.

2. METHODS

2.1. Lensing Methods

We will briefly describe the lensing measurements as these were described in detail in Sheldon et al. (2009) and Johnston et al. (2007b). We measure the tangential shear in background galaxies by a set of foreground clusters and convert that shear to a redshift-independent density contrast \( \Delta \Sigma \):

\[
\gamma_T(R) \times \Sigma_{cm} = \bar{\Sigma}(<R) - \bar{\Sigma}(R) \equiv \Delta \Sigma, \quad (3)
\]

where \( \bar{\Sigma} \) is the projected surface mass density at radius \( R \) and \( \bar{\Sigma}(<R) \) is the mean-projected density within radius \( R \). In using this equation, we assume the shear is weak. This is not always
the case for the largest clusters on the smallest scales, as was discussed in Johnston et al. (2007b).

We average \( \Delta \Sigma \) for an ensemble of clusters in radial bins from 25 h\(^{-1}\) kpc to 30 h\(^{-1}\) Mpc, using the brightest cluster galaxy (BCG) as the center for all measurements (see Section 3.1 for a description of the cluster selection). The \( \Delta \Sigma \) is linear in the density and so averaging \( \Delta \Sigma \) averages the density directly (again assuming weak shear).

A number of corrections were made to the profile, as discussed in detail in Sheldon et al. (2009). Using random points, corrections were applied for contamination of the background source sample with cluster members that are not sheared; this correction is large but well determined on small scales, and negligible on large scales. We also corrected for residual additive biases in the shear. These result from imperfect correction for biases in the galaxy shapes caused by point-spread function (PSF) anisotropy. We use random points for this correction as well, as the additive biases will appear in random points as well as around clusters. This correction is negligible on small scales but significant on large scales.

There are remaining uncertainties in the overall calibration of the mean \( \Delta \Sigma \). These come primarily from uncertainties in photometric redshift determinations for the background source galaxies and correction for blurring of the galaxy shapes by the PSF. Simulations of the PSF correction suggest that it is good to a few percent under simplified circumstances (Massey et al. 2008). The photometric redshift calibrations are probably less well constrained. Comparisons with studies using Luminous Red Galaxies as sources, for which the redshift is better determined, suggest that the calibrations are good to about 10% (Mandelbaum et al. 2005), although that study used a different photometric algorithm than this work. Simulations of the algorithm used in this study also suggest \( \sim 10\% \) errors given the size of the training set (Lima et al. 2008).

In Section 8.5, we will present inversions of \( \Delta \Sigma \) to the integrated excess mass. These mass profiles are model independent, but as with the light measurements presented in Section 2.2, only the excess above the mean can be measured with lensing.

2.2. Cluster–Light Correlations

We used the method of Masjedi et al. (2006) to estimate the mean number density and luminosity density of galaxies around clusters. This method is essentially a correlation function with units of density; corrections are made for random pairs along the line of sight as well as pairs missed due to edges and holes. We also used this method in Hansen et al. (2009), and much of the following is also presented in that work.

Two samples were defined, the primary sample which we denote as \( p \) and the secondary sample which we denote as \( s \). In our case, the primaries are galaxy clusters with redshift estimates and the secondaries are the imaging sample with no redshift information, but in what follows we will use a more general notation. For example, the counts of real data secondaries around real data primaries are denoted \( D_pD_s \), while the counts of real secondaries around random primaries are \( R_pD_s \). If instead of counting “1” for each object, we count some other quantity such as the luminosity of the secondary, we say we have weighted the measurement by luminosity.

The mean luminosity density of secondaries around primaries is given by

\[
\bar{\ell} \equiv \frac{D_pD_s}{D_pR_s} \quad \text{and} \quad \bar{\ell} \equiv \frac{R_pD_s}{R_pR_s},
\]

where \( \bar{\ell} \) is the mean luminosity density of the secondary sample, averaged over the redshift distribution of the primaries, and \( w \) is the projected correlation function. This is the estimator from Masjedi et al. (2006) where the weight of each primary–secondary pair is the luminosity of the secondary. We have written the measurement as \( \ell w \) to illustrate that the estimator gives the mean density of the secondaries times the projected correlation function \( w \). Only the excess luminosity density with respect to the mean can be measured. Using a weight of unity gives the number density.

The first term in Equation (4) estimates the total luminosity density around the clusters including everything from the secondary imaging sample projected along the line of sight, and the second term corrects for the random pairs along the line of sight. Note, the same secondary may be counted around multiple primaries (or random primaries).

The numerator of the first term in Equation (4), \( D_pD_s \), is calculated as

\[
D_pD_s = \frac{\sum p,s L_s}{N_p} = \langle L_{\text{pair}} \rangle + \langle L_{\text{random}} \rangle = f A \bar{\ell} (w + 1),
\]

where the sum is over all pairs of primaries and secondaries, weighted by the luminosity of the secondary. The secondary luminosity is calculated by \( K \)-correcting each secondary galaxy’s flux assuming that it is at the same redshift as the primary (see Section 3.4 for details of the \( K \)-corrections). The total luminosity is the sum over correlated pairs \( (L_{\text{pair}}) \) as well as random pairs along the line of sight \( (L_{\text{random}}) \). By the definition of \( w \), this is the total luminosity per primary times \( w + 1 \). This can be rewritten in terms of the luminosity density of the secondaries \( \bar{\ell} \) times the area probed \( A \). Some fraction of the area searched around the lenses is empty of secondary galaxies due to survey edges and holes. The factor \( f \) represents the mean fraction of area around each primary actually covered by the secondary catalog. An example measurement of \( f \) is shown in Figure 1. It is a function of pair separation, with a mean value close to 1 on small scales but then dropping rapidly at large scales.

Again, a single secondary may be counted around multiple primaries and \( K \)-corrected to different redshifts. Statistically
they will only contribute when paired with a physically associated object due to the background subtraction described below. In fact most of the calculations involved in this measurement are for pairs that are not physically associated, which is part of the reason this is computationally difficult.

The denominator of the first term in Equation (4) calculates the factor $f_A$, the actual area probed around the primaries. This term in the denominator corrects for the effects of edges and holes. Also, because it has units of area, we recover the density rather than just the correlation function:

$$D_p R_s = \frac{N^{\text{pair}}_{\text{DR}}}{\sum_p \left( \frac{d\Omega}{d\ell} \right)_p \frac{d\Omega}{d\Omega}} = f_A. \quad (6)$$

The numerator is the pair counts between primaries and random secondaries, and the denominator is the expected density of pairs averaged over the redshift distribution of the primaries, times the number of primaries. The ratio is the actual mean area used around each primary $f_A$.

The second term in Equation (4) accounts for the random pairs along the line of sight. The numerator and denominator are calculated the same way as the first term in Equation (4), but with fake primaries distributed randomly over the survey geometry. The redshifts are chosen such that the distribution of redshifts smoothed in bins of $\Delta z = 0.01$ matches that of the clusters:

$$R_p D_s = \frac{\sum_{pr,s} L_s}{N_p} = \langle L_{\text{pair}} \rangle = f^R A^R \tilde{c} \quad (7)$$

$$R_p R_s = \frac{N^{\text{pair}}_{\text{RR}}}{\sum_{pr} \left( \frac{d\Omega}{d\ell} \right)_p \frac{d\Omega}{d\Omega}} = f^R A^R. \quad (8)$$

The ratio of these two terms, $R_p D_s/R_p R_s$, calculates the mean density of the secondaries after correcting for the survey geometry.

The density measured with this technique could be tabulated in various ways, typically as a function of projected radial separation $R$. We tabulate in a cube which represents bins of separation $R$, luminosity $L$, and color $g-r$. This facilitates the study of the radial dependence of the luminosity function and the color–density relation.

These profiles can be inverted to the three-dimensional excess density and integrated to get the total excess light. We will present this formalism in Section 8.4.

3. DATA

The data used for lensing were described in detail in Paper I (Sheldon et al. 2009) and the cluster sample is described in Koester et al. (2007a, 2007b) with the modifications detailed in Sheldon et al. (2009). We will briefly describe relevant details of the cluster sample and give a full description of the galaxies used as light tracers in the cluster-light cross-correlation measurements. All the primary data in this study come from the Sloan Digital Sky Survey (SDSS; York et al. 2000) data release 4 (Adelman-McCarthy et al. 2006).

3.1. Cluster Sample

Full details of the cluster finder and catalog can be found in Koester et al. (2007b, 2007a). The cluster finder is a red-sequence method, limited to the redshift range 0.1–0.3. The basic galaxy count $N_{200}$ is the number of galaxies on the red sequence with rest-frame $i$-band luminosity $L > 0.4L_*$ within $r_{200}^{\text{gal}}$. The $i$-band $L_*$ used in the cluster finder is the $z = 0.1$ value from Blanton et al. (2003b), corresponding to $M_* -5 \log_{10} h = -20.82 \pm 0.02$. The radius $r_{200}^{\text{gal}}$ is determined from the size-richness relation presented in Hansen et al. (2005). Note, this relation gives roughly a factor of 2 larger radius than the $r_{200}^{\text{mass}}$ determined from the mass in Paper II (Johnston et al. 2007b) (see Section 7 for details about the various richness measures). The published catalog contains clusters with $N_{200} \geq 10$, and we augment this catalog with $N_{200} \geq 3$ objects. The cluster photometric redshifts are accurate to 0.004 over our redshift range with a scatter of $\Delta z \sim 0.01$ for $N_{200} \geq 10$; the scatter degrades to $\Delta z \sim 0.02$ for $N_{200} \geq 3$, with the same accuracy.

3.2. Galaxy Sample

For the cluster-light cross-correlations we separated galaxies from stars using the Bayesian techniques developed in Scranton et al. (2002). The primary source of confusion in star–galaxy separation at faint magnitudes is shot noise. Stars scatter out of the stellar locus and galaxies scatter into the stellar locus. This technique uses knowledge of the true size distribution of stars and galaxies as a function of apparent magnitude to assign each object a probability of being a galaxy.

We characterized the distribution of star and galaxy sizes as a function of magnitude and seeing using the deeper southern SDSS stripe. The SDSS southern stripe has been repeatedly scanned. We chose regions of sky which were scanned at least 20 times and chose the 20 best-seeing observations for each object. We then simply added the flux at the catalog level to increase the S/N. Thus, the selection is close to that of single scans but with a better measurement; S/N at a given magnitude is higher, and the distribution of measured sizes is closer to the truth. For a range of seeing values, we then calculated the probability that an object in a single-epoch image with a given magnitude and size is truly a galaxy, and applied this to all objects in the survey. The resulting distribution is highly peaked at probabilities 0 and 1, such that our chosen probability cut at $p > 0.8$ results in a sample $\geq 99\%$ pure within our magnitude limit.

We chose to $K$-correct to bandpasses shifted to the mean cluster redshift 0.25 rather than redshift 0 to minimize the corrections. We will refer to all such magnitudes with a superscript, e.g., $0.25i$. For a full discussion of the band-shifting process see Blanton et al. (2003a).

We chose a volume- and magnitude-limited galaxy sample for $L_{g25} > 10^{0.5} h^{-2} L_0$ (or $M_{g25} - 5 \log_{10} h < -19.08$) and $z < 0.3$. This corresponds to an apparent magnitude limit of $i < 21.3$, and color limits of $g - r < 2$ and $r - i < 1$. All magnitudes are SDSS model magnitudes.

3.3. Survey Geometry

We characterized the survey geometry using the SDSSPix code. This code represents the survey using nearly equal area pixels, including edges and holes from missing fields and “bad” areas near bright stars. We removed areas with extinction greater than 0.2 mag in the dust maps of Schlegel et al. (1998). This window function was used in the cluster finding and in defining the galaxy catalog for the cross-correlations. By including

14 http://dls.physics.ucdavis.edu/~scranton/SDSSPix/
objects only from within the window, and generating random catalogs in the same regions, we controlled and corrected for edges and holes in the observed counts as described in Section 2.

3.4. K-corrections

We calculated K-corrections using the template code kcorrect from Blanton et al. (2003a). This code is accurate but too slow to calculate the K-corrections for the billions of pairs found in the cross-correlations. To save time we computed the K-correction on a grid of colors in advance. We took galaxies from the SDSS main sample as representative of all galaxy types. We then computed their K-corrections on a grid of redshifts between 0 and 0.3, the largest redshift considered for clusters in this study. The mean K-correction in a 21 × 21 × 80 grid of observed g − r, r − i, and z was saved. We interpolated this cube when calculating the K-correction for each neighboring galaxy. This interpolation makes the calculation computationally feasible for this study, but is still the bottleneck.

4. CLUSTER GALAXY POPULATION MEASUREMENTS

4.1. Radial, Color, and Luminosity Binning

Using the estimator presented in Section 2.2, we measured the number and luminosity density of galaxies around the clusters as a function of radius R from the BCG, color 0.25(g − r), and luminosity Lg−25i. The bins in radius, color, and luminosity form a data cube with 18 bins in radius, 20 bins in color, and 20 bins in luminosity. The range in each variable is 0.02 h−1 Mpc < R < 11.5 h−1 Mpc, 0 < 0.25(g − r) < 2, and 9.5 < log_{10}(L_{g−25i}/L⊙) < 11.7. The initial cube before background correction was kept separately for each cluster to allow flexibility when later estimating the average profile. Two versions of this cube were kept, one with number counts and another with the total luminosity. In other words, in the first case we counted each galaxy and in the other we counted the luminosity. Another set of measurements was also performed to 30 h−1 Mpc, but binning only in radial separation to save resources. More detailed analysis of the full cube will be presented in Hansen et al. (2009); here we will present what is needed for the particulars of the M/L measurement.

4.2. Random Catalogs

We generated random catalogs uniformly over the survey area using the window function described in Section 3.3. We chose the redshift distribution to be that of constant density in comoving volumes over the redshift range of the clusters. We matched subsets of these redshifts to the redshift distribution of each cluster subsample as described in Section 4.3.

We performed the same galaxy counting as described in Section 4.1 for a set of 15 million random points in order to correct for the random background. These are used in the RD term from the estimator described in Section 2 (Equations (4) and (7)). We also ran sets of 15 million random points for the DR and RR terms.

4.3. Histogram Matching

The redshifts used for random points must statistically match that of each cluster sample in order for the background subtraction to be accurate. The random primaries described in Section 4.2 were generated with constant comoving density. We drew random redshifts from this sample such that the distribution matched that of the cluster sample when binned with Δz = 0.01.

4.4. Cluster Richness Binning

Because the measurements before background correction were saved for each cluster separately, the clusters could be binned at a later time to produce mean density profiles. For this work we binned the clusters into 12 bins of N_{200} and 16 bins of i-band cluster luminosity L_{200}, where the luminosity is that of the N_{200} red galaxies counted within r_{200}^{gal} as described in Section 3.1. These bins were chosen to correspond with the binning presented in the lensing analysis of Sheldon et al. (2009). Some statistics of this sample are shown in Tables 1 and 2.

Table 1

| \(N_{200}\) | \(\Delta L_{200}\) | \(\Delta M_{200}\) | \(\frac{\Delta M}{\Delta L}_{200}\) | \(\frac{\Delta M}{\Delta L}_{\text{max}}\) | \(L_{\text{max}}\) | \(r_{1/2}\) | \(\alpha\) | \(\frac{\Delta M}{\Delta L}_{\text{asym}}\) |
|---|---|---|---|---|---|---|---|---|
| 3 | 3.84 ± 0.02 | 3.99 ± 0.16 | 101 ± 10 | 275 ± 313 | 0.98 ± 0.10 | 0.25 ± 0.07 | 1.34 ± 0.11 | 226 ± 33 |
| 4 | 4.86 ± 0.04 | 5.78 ± 0.26 | 108 ± 14 | 347 ± 229 | 1.02 ± 0.10 | 0.44 ± 0.15 | 1.05 ± 0.08 | 306 ± 42 |
| 5 | 5.98 ± 0.07 | 8.84 ± 0.44 | 166 ± 18 | 455 ± 234 | 1.02 ± 0.11 | 0.47 ± 0.16 | 1.06 ± 0.08 | 357 ± 44 |
| 7 | 7.22 ± 0.09 | 12.88 ± 0.64 | 170 ± 22 | 341 ± 183 | 0.93 ± 0.12 | 0.24 ± 0.05 | 1.46 ± 0.13 | 285 ± 28 |
| 9 | 7.99 ± 0.12 | 12.54 ± 0.78 | 122 ± 27 | 540 ± 231 | 1.10 ± 0.11 | 0.30 ± 0.31 | 1.02 ± 0.14 | 271 ± 59 |
| 11 | 8.96 ± 0.15 | 16.58 ± 1.20 | 179 ± 30 | 353 ± 157 | 1.10 ± 0.11 | 0.44 ± 0.12 | 1.16 ± 0.11 | 378 ± 41 |
| 23 | 10.36 ± 0.80 | 131.66 ± 5.02 | 333 ± 32 | 300 ± 175 | 1.27 ± 0.13 | 0.20 ± 0.04 | 1.35 ± 0.16 | 394 ± 26 |
| 50 | 53.82 ± 1.95 | 203.71 ± 9.57 | 379 ± 43 | 525 ± 307 | 0.94 ± 0.24 | 0.15 ± 0.02 | 2.19 ± 0.29 | 404 ± 21 |
| 92 | 104.33 ± 5.16 | 516.19 ± 38.78 | 489 ± 75 | 547 ± 332 | 0.93 ± 0.53 | 0.11 ± 0.01 | 3.91 ± 0.65 | 485 ± 33 |

Notes. M/L statistics for clusters binned by richness \(N_{200}\). \(\Delta L\) is the excess light over the mean luminosity density of the universe, and \(\Delta M\) is the excess mass over the mean mass density. Subscripts 200 and \(\text{max}\) indicate quantities within \(r_{200}\) and the maximum radius 22 h−1 Mpc, respectively. The subscript asym refers to an asymptotic value from fitting the model described in the text. Other parameters of this fit are \(r_{1/2}\), the radius at which the M/L reaches half its asymptotic value, and \(\alpha\), a power-law index. The model is not a physical model, so these uncertainties should be considered lower limits. \(L_{\text{max}}\) is the mean luminosity of the neighboring galaxies used to calculate \(\Delta L\). No attempt was made to account for mis-centering of the BCGs relative to the halo mass peak; this affects the \(\Delta M_{200}\) but should have little effect on \((\Delta M/\Delta L)_{200}\), and no effect on \((\Delta M/\Delta L)_{\text{asym}}\). The mean richness is shown but the ranges can be found in Sheldon et al. (2009).
4.5. Corrections for Edges and Holes

The terms $D_R R_i$ and $R_p R_i$ introduced in Section 2.2 correct for the survey edges and holes by measuring the actual area searched. An example DR is shown in Figure 1, generated for one of the richness bins described in Section 4.4. This is expressed as the mean fractional area searched relative to the area in the bin. For small separations, edges and holes make little difference so the fractional area is close to unity. On larger scales edges are important.

On small scales the number of pairs in each bin is relatively small so the correction is not as well constrained. However, we know that the fractional area must approach unity smoothly, and this can be seen from visual inspection. To smooth the result, we fit a fifth-order polynomial, constrained to be unity on small scales, to the fractional area as a function of the logarithmic separation. Due to the weighting, this results in a curve that approaches unity smoothly on small scales, yet matches intermediate separation points exactly. Points on larger scales are well constrained and do not need smoothing.

5. LUMINOSITY DENSITY AT $z = 0.25$

We are interested in the background luminosity density at $z = 0.25$, in the $0.25 i$ band, for comparisons with our luminosity measurements. We use an evolved version of the SDSS spectroscopic sample (whose median redshift is about $z \sim 0.1$). For this purpose, we use the DR4 version of the New York University Value-Added Galaxy Catalog (NYU-VAGC; Blanton et al. 2005). We select a subset of the galaxies in the redshift range $0.01 < z < 0.25$, in the apparent magnitude range $14.5 < m_r < 17.6$. The NYU-VAGC provides the angular completeness map necessary to calculate for each galaxy the quantity $V_{\text{max}}$, the maximum volume over which each galaxy could be observed. We do so using the same method as used by Blanton (2006), which accounts for the evolution and $K$-corrections within this redshift range. We use the $k$correct v4_1_4 code of Blanton & Roweis (2007) to estimate the $0.25 i$ band, Galactic extinction-corrected, $K$-corrected absolute magnitude of each galaxy, based on the model fluxes provided by the SDSS.

Finally, we evolution correct these magnitudes in the following way, based on the results of Blanton (2006). For each galaxy we apply a simple correction of the form:

$$M_{0.25}(z = 0.25) = M_{0.25}(z) + A(z - 0.25).$$

(9)

For galaxies on the blue sequence, based on their $0.25 (g - r)$ colors, we use $A = 0.65$. For galaxies on the red sequence we use $A = 0.35$. The red–blue split is defined by the line $0.25 (g - r) = 1.2 - 0.05 (M_{0.25} + 20)$. These values are calculated by evaluating the simple star-formation history models of Blanton (2006). These models explain the evolution of the blue and red sequences in the $0.1 g$ band well, and we use the corresponding predictions for the $0.25 i$ band. In practice, these corrections are quite small (at most 0.16 mag), and so the inevitable uncertainty in this correction is likely to be unimportant.

By using the evolution-corrected magnitudes and weighting each galaxy by $1/V_{\text{max}}$, we estimate the luminosity function using the method of Schmidt (1968). The resulting luminosity density for galaxies above our luminosity threshold $10^{9.5} h^{-2} L_\odot$ is $(1.61 \pm 0.05) \times 10^{8} h L_\odot \text{Mpc}^{-3}$ in comoving coordinates, or $(3.14 \pm 0.10) \times 10^{8} h L_\odot \text{Mpc}^{-3}$ in physical coordinates. Our luminosity limit is equivalent to $M_{0.25} - 5 \log_{10} h \sim -19.08$, where we use $M_\odot = 4.67$ in the $0.25 i$ band. The uncertainty is dominated by the absolute calibration of the SDSS. Fitting a single Schechter function to the luminosity function, we find that $M_\ast - 5 \log_{10} h \sim -20.9$ (with $\alpha \approx -1.21$), equivalent to $L_\ast = 1.7 \times 10^{10} h^{-2} L_\odot$. Thus the lower luminosity threshold corresponds to $0.19 L_\ast$.

6. SIMULATIONS

In order to study the impact of the MaxBCG algorithm on our conclusions, and in particular the differences between how our method operates on dark matter halos and on MaxBCG clusters, we have repeated the luminosity measurements on a mock catalog. These catalogs, which have been used in previous MaxBCG studies (Rozo et al. 2009; Koester et al. 2007b; Johnston et al. 2007b), populate a dark matter simulation with galaxies using the ADDGALS technique, to be described in
R. Wechsler et al. (2009, in preparation). This method is designed to populate large volume simulations with galaxies that have realistic luminosities, colors, clustering properties, and galaxy clusters.

The catalog is based on the light cone from the Hubble Volume simulation (Evrard et al. 2002), and extends from \(0 < z < 0.34\). Galaxies are assigned directly to dark matter particles in the simulation, with a luminosity-dependent bias scheme that is tuned to match local clustering data. First galaxy luminosities are generated in the \(z = 0.1\) shifted \(r\)-band, drawn from the luminosity function of Blanton et al. (2003b). The luminosity function is assumed to evolve passively, with galaxies with \(L\) drawn from the luminosity function of Blanton et al. (2003b), \(<z<0\)

The scheme that is tuned to match local clustering data. First galaxy Volume simulation (Evrard et al. 2002), and extends from and galaxy clusters.

that have realistic luminosities, colors, clustering properties, designed to populate large volume simulations with galaxies R. Wechsler et al. (2009, in preparation). This method is introduced in Section 3.1, is the same as Sheldon et al. (2009):

\[ M(z) = M_0(z = 0.1) - 1.3(z - 0.1) \]

Particles in the simulation are then assigned these luminosities based upon the following prescription.

We measure the local mass density around each dark matter particle, defined here as the radius enclosing a mass scale of \(\sim 1 \times 10^{13} M_{\odot}\). For sets of points binned by local mass density, we measure the auto-correlation function and the distance to the fifth nearest neighbor with the same local density. From galaxy surveys we know the correlation function as it depends on galaxy luminosity, so by finding the set of particles with a correlation function that matches that of galaxies in the real universe, we make a connection between the local mass density in the simulation and galaxy luminosity. We use this to parameterize the probability distribution of these dark matter densities as a function of luminosity, and constrain these parameters so that the resulting luminosity-dependent two-point clustering properties of the mock galaxies are in agreement with those measured in the SDSS (Zehavi et al. 2005).

Once placed on a dark matter particle according to this prescription, each mock galaxy is then assigned to a real SDSS galaxy that has approximately the same luminosity and local galaxy density, measured here as the distance to the fifth nearest neighbor. The color for each mock galaxy is then given by the spectral energy distribution (SED) of this matched galaxy transformed to the appropriate redshift. The matching of local galaxy density helps to ensure the relationship between color and density is preserved.

This procedure produces a catalog which matches several statistics of the observed SDSS population, including the location, width, and evolution of the ridgeline in color–luminosity characteristic of galaxy clusters. The luminosity limit for galaxies in these mocks is slightly lower than that of the MaxBCG cluster finder \(L > 0.4 L_*\), so the catalogs are well designed for testing the MaxBCG algorithm. However, this limit is higher than for our luminosity measurements, so the results cannot be compared at low luminosities. Therefore, in this paper the simulations are used strictly to understand the effects of cluster selection on our measurements (see Section 8.2).

7. NOTATION

The notation may get confusing due to the use of multiple methods and apertures in the course of cluster finding and lensing measurements. The basic notation for cluster variables, introduced in Section 3.1, is the same as Sheldon et al. (2009): the measures of richness and luminosity we will refer to as \(N_{200}\) and \(L_{200}\). These are the counts and \(i\)-band luminosity for galaxies with \(L_i > 0.4 L_*\), colors consistent with the cluster ridge-line, and projected separation less than \(r_{200}\) as calibrated in Hansen et al. (2005). Note, \(r_{200}\) was only used for \(N_{200}\) and \(L_{200}\), no other quantities in this paper use that aperture.

For more information about the richness measures see (Koester et al. 2007a, 2007b). This radius is different from the radius \(r_{200}\) calculated from the mass profile, which is typically half as big (Johnston et al. 2007b); this difference is primarily due to differences in convention between Hansen et al. (2005) and Johnston et al. (2007b); Hansen used projected overdensities relative to the mean luminosity density and Johnston used three-dimensional overdensities relative to the critical mass density. The \(L_{200}\) is only used for binning the clusters; because our results are essentially the same for \(L_{200}\) and \(N_{200}\) binning we will avoid using the \(L_{200}\) notation except where necessary.

We will refer to the total excess luminosity measured below, which includes the light of all types of galaxies above a luminosity threshold, as \(\Delta L(r)\). This luminosity and excess mass \(\Delta M(r)\) are the new measurements presented in this paper. The total excess mass and light within \(r_{200}\) are denoted \(\Delta M_{200}\) and \(\Delta L_{200}\). Projected two-dimensional radii are referred to as \(R\) and three-dimensional radii are referred to as \(r\).

8. RESULTS

In the following sections we show the results for clusters binned by \(N_{200}\). Similar results were obtained binning by \(L_{200}\), and we summarize all results in Tables 1 and 2, but for the sake of brevity we include plots only for the \(N_{200}\) binning.

8.1. The Radial Dependence of the Joint Luminosity–Color Function

Figure 2 shows the joint color–luminosity distribution function for each radial bin in the eighth cluster richness sample \((12 < N_{200} < 17)\). Similar distributions were created for each of the cluster richness bins used in this study. We will present detailed analyses of these type of data in Hansen et al. (2009), but we also present a sample here in order to demonstrate a few aspects important for the \(M/L\) study.

The first point is that the population is quite different at small scales relative to large scales. On small scales, near the BCGs, the galaxy population is dominated by red galaxies, while on large scales the color distribution looks more like the cosmological average. Similarly, on large scales the luminosity function looks more like that of the average, although they are poor fits to Schechter functions on large scales because we measure the ratio of correlation functions (see the following sections for more details). These facts are relevant to the \(M/L\) for a few reasons. We want to make sure that the population we see around clusters makes sense; that we, for example, are complete in the color–luminosity range we have probed. Again, detailed analysis will come in Hansen et al. (2009), but these color and luminosity trends are exactly what is expected. We will discuss the shape of the luminosity function in Section 8.2.

8.2. The Radial Dependence of the Luminosity Function

Projecting the two-dimensional color–luminosity plots from Figure 2 across the color axis produces the luminosity function in each radial bin. Recall that to produce these curves we have statistically subtracted the background, so the luminosity function is the luminosity function of galaxies minus that mean density of the universe. The value of these functions in a luminosity bin \(i\) is

\[ \phi_{\text{clus}}(R) = n(R) - \bar{n}_i = \phi_{\text{clus}}^i(R), \]

where \(n\) is the number density, \(w_{\text{clus}}(R)\) is the projected cross-correlation function between clusters and galaxies in luminosity
Figure 2. Joint galaxy $g - r$ and $i$-band luminosity densities as a function of projected separation from BCGs for the eighth cluster richness bin ($12 \leq N_{200} \leq 17$). The luminosities are expressed in the $z = 0.25$ shifted bandpass. Each frame corresponds to a different radial bin; the radius is indicated in the legend. The one-dimensional distributions for color and luminosity are also shown as the solid histograms along the left and bottom axes. The luminosity distribution is expressed as log of the number density as a function of log luminosity; the color distribution is linear density as a function of color. At small separations red galaxies dominate while on large scales there is a bivariate color distribution similar to the cosmological average. A smaller fraction of galaxies is highly luminous at small separations as compared to large.

bin $i$ at projected radius $R$ and $\phi_i$ is the value of the luminosity function of the universe in that luminosity bin $i$.

Because of the statistical subtraction, the value of the luminosity function in luminosity bin $i$ is weighted by the cross-correlation function of clusters with galaxies of that luminosity. This is important because galaxies of different luminosities correlate with clusters differently. An extreme example of this is demonstrated for the lowest $L_{200}$ bin in Figure 3, which shows $\phi_{c,i}$ in each radial bin. This figure shows that, near the virial radius, the inferred luminosity function for small groups is actually negative for galaxies with $L_{0.25} \sim 10^{10.7} L_\odot$. This is not because there is a negative number density of these galaxies around the groups, but because they are anti-correlated with the groups at this separation. This means that, near the virial radius, there are fewer of these high-luminosity galaxies relative to the background.

This effect is the strongest in our lowest $N_{200}$ bin, although there is a slight feature in the luminosity function at the virial radius for high-luminosity galaxies in the first few cluster bins.

In order to understand whether these effects are physical, due to selection effects of the cluster finder, or are artifacts of our method, we ran the MaxBCG algorithm and our cross-correlation code on the simulation-based mock catalogs described in Section 6. We performed this test twice, stacking on both cluster centers (BCGs) and halo centers. For the mock stacked on maxBCG clusters, a similar effect is seen, although it is suppressed relative to the effect in the real data. As in the data, the effect is strongest in the lowest richness bin. When the measurement is done around halo centers, there is no significant effect seen. This indicates that it is mostly an effect introduced by the selection criteria of the MaxBCG algorithm.

This lowest luminosity bin is peculiar in that it requires the close proximity of only three very luminous red galaxies, one of which has an extreme BCG-like luminosity. This is an unusual situation; BCGs of this luminosity are usually surrounded by many more galaxies. In order to find only two such galaxies within a few hundred kpc of a BCG-type galaxy, the algorithm selects objects embedded in slight underdensities. This can occur naturally in the MaxBCG algorithm due to the percolation step, which does not allow clusters to be embedded within larger clusters. This may limit low richness systems to very particular regions of space.
Figure 3. Excess luminosity functions for the first cluster richness bin $N_{200} = 3$. This is the integral across the color axis of the joint densities such as those shown for another richness bin in Figure 2. As in that figure, each panel is a radial bin with mean radius indicated in the legend. Each bin in the excess luminosity function is the amplitude of the projected cluster-galaxy cross-correlation function at that radial separation times the mean density. In some bins the galaxies are anti-correlated. This cluster richness bin was chosen as the extreme example of these anti-correlations; they are smaller or nonexistent in higher richness bins. As discussed in Section 8.2, this feature is a result of the MaxBCG selection function at low richness.

(A color version of this figure is available in the online journal.)

8.3. Radial Luminosity and Number Density

Further integrating the luminosity functions from Section 8.2 across the luminosity axis results in the excess number density of galaxies. We have also generated luminosity density profiles using the luminosity-weighted data cube rather than the cube of galaxy counts. These are shown in Figures 4 and 5, respectively. Each curve represents the excess density for each of the cluster $L_{200}$ bins. The errors come from jackknife resampling of the data following the same techniques used for the lensing analysis described in Sheldon et al. (2009). We will say more about errors in Section 9.

Again, it is important to remember that these curves are background subtracted, and are thus the number and luminosity densities above the mean. These terms can be written in terms of correlation functions:

$$n(R) - \bar{n} = \bar{n} w_{c,g}(R)$$  \hspace{1cm} (11)

$$\ell(R) - \bar{\ell} = \bar{\ell} w_{c,\ell}(R)$$  \hspace{1cm} (12)

where $\bar{n}$ and $\bar{\ell}$ are the mean number and luminosity density of galaxies over the explored luminosity range, and $w_{c,g}(R)$ and $w_{c,\ell}(R)$ are the projected cluster-galaxy and cluster-luminosity cross-correlation functions, averaged over all galaxies in the luminosity range at projected radius $R$, weighted by the luminosity function.

It is tempting to interpret the ratio of the excess luminosity to excess number densities as the mean luminosity as a function of radius. Given that there can be negative densities with respect to the mean at some luminosities when there are anti-correlations, as shown in Figure 3, this is not always the correct interpretation.

The curves in Figures 4 and 5 show a number of features expected for two-point correlation functions. In particular, there should be a transition radius between correlations within the halo and between different halos. The scale of this break should correspond to the size of the largest clusters in each bin. We present no detailed analysis here, but the radius of the break we see does increase with cluster richness as expected, with
values ranging from a few hundred kpc for the lowest richness bins to of order a Mpc for the richer systems, in agreement with the mass measurements shown in Johnston et al. (2007b). On small scales the profile is consistent with a universal profile and on large scales transitions to that expected for halo–halo correlations. We found in Johnston et al. (2007b) that the mass profiles of the clusters were good fits to models of this form. In this paper, we do not use any explicit modeling, preferring to focus on model-independent measurements, but these rich data should provide constraints for models of galaxy formation and evolution in a cosmological setting.

8.4. Integrated Luminosity Profiles

We will use integrated luminosity profiles to compute the mean $M/L$ within a given three-dimensional radius $r$. We invert the projected two-dimensional profile shown in Figure 5 using a standard Abel-type inversion (e.g., Plummer 1911):

$$\Delta \ell(r) = \ell(r) - \bar{\ell} = \frac{1}{\pi} \int_r^\infty dR \frac{-\ell'(R)}{\sqrt{R^2 - r^2}},$$

where we have re-used the notation for the excess luminosity density from Equation (11) but replaced the projected radius $R$ with three-dimensional radius $r$. We have been explicit here in indicating we measure the density minus the mean $\ell(r) - \bar{\ell}$. Thus the $\Delta \ell(r)$ is proportional to the cluster-light cross-correlation function:

$$\Delta \ell(r) = \Delta \xi_{c}(r).$$

The assumption behind the inversion in Equation (13) is that $\ell(R)$ is the line-of-sight projection of a spherically symmetric three-dimensional function $\ell(r)$. This follows from the isotropy of the universe as long as the cluster selection function does not select structures preferentially aligned relative to us. Results from simulations suggest such preferential alignment is not important for our cluster sample where the sample can be tested

$$N_{200} > 10.$$ A publication on these simulations is forthcoming (Hao et al. 2009)

Because the maximum separation we measure is $30 \, h^{-1}$ Mpc rather than infinity, we cannot accurately calculate $\Delta \ell(r)$ over the entire range. We lose the last point entirely, and the second to last point, at $22 \, h^{-1}$ Mpc, must be corrected slightly for the endpoint. We perform a power-law extrapolation of the profile and find this to be a 5% upward correction.

We then integrate the excess luminosity density to obtain the total luminosity within radius $r$. Because the profile only extends inward to $25 \, h^{-1}$ kpc, we miss some light interior to this radius. This light is dominated by the BCG however, so we can add that component back in as the average BCG luminosity for a given cluster sample:

$$\Delta L(< r) = \langle L_{BCG} \rangle + \int_{r_{\min}}^r 4\pi r^2 \Delta \ell(r),$$

where we have again been explicit in defining our measured quantity as $\Delta L(< r)$, the integrated excess luminosity above the mean density.

Figure 6 shows this quantity $\Delta L(< r)$ for the richness and luminosity cluster binning. There are two curves for each richness bin: one including the mean BCG luminosity $\langle L_{BCG} \rangle$ and one without. The light is dominated by the BCG on small scales. The luminosity within $r_{200}^{\text{mass}}$ is marked with an asterisk. The $r_{200}^{\text{mass}}$ is calculated from the mass profiles (see Section 8.5).

8.5. Integrated Mass Profiles

The cluster mass profiles were measured from the lensing measurements presented in Sheldon et al. (2009) and Johnston et al. (2007b). These measurements were performed for the same samples presented above. The basic lensing measurement is $\Delta \Sigma$. 

---

**Figure 4.** Excess radial number density for each of the cluster $N_{200}$ bins. These curves are the integral of the excess luminosity functions as shown in Figure 3. (A color version of this figure is available in the online journal.)

**Figure 5.** Excess radial $^{0.25}/$-band luminosity density for each of the cluster $N_{200}$ bins. These curves are the integral of luminosity-weighted luminosity functions. (A color version of this figure is available in the online journal.)
The inversion is a manifestation of the mass sheet degeneracy. The subtraction in this equation is a manifestation of the mass sheet degeneracy. The cluster mass is a projected quantity:

\[ \Delta \Sigma \equiv \bar{\Sigma}(< R) - \bar{\Sigma}(R), \]  

where \( \bar{\Sigma} \) is the projected surface mass density at radius \( R \) and \( \bar{\Sigma}(< R) \) is the mean projected density within radius \( R \). The subtraction in this equation is a manifestation of the mass sheet degeneracy.

In Johnston et al. (2007b), we inverted the projected profiles to the three-dimensional excess mass density using the techniques presented in Johnston et al. (2007a). This inversion is a procedure analogous to the inversion of the luminosity density presented in Section 8.4:

\[ -\frac{d\Sigma}{d R} = \frac{d \Delta \Sigma}{d R} + 2 \frac{\Delta \Sigma}{R}, \]

\[ \Delta \rho(r) \equiv \rho(r) - \bar{\rho} = \frac{1}{\pi} \int_r^{\infty} dR \frac{-d\Sigma/d R}{\sqrt{R^2 - r^2}}. \]  

Again, the assumption is that the profiles are projections of spherically symmetric three-dimensional functions. We can recover the total excess mass within radius \( r \), including that within our innermost radius, because \( \Delta \Sigma \) is itself a nonlocal measurement:

\[ \Delta M(< r) = \pi R^2 \Delta \Sigma(R) + 2\pi \int_r^{\infty} drr \Delta \rho(r) \times \left[ \frac{R^2}{\sqrt{r^2 - R^2}} - 2(r - \sqrt{r^2 - R^2}) \right]. \]  

As with the luminosity inversions, the last point must be thrown out and a 5% correction is applied to the second to last point. Figure 7 shows these excess mass profiles for the \( N_{200} \) binnings. The error bars are from jackknife resampling.

See Sheldon et al. (2009) for details about the error estimates, and Section 9 for more details about errors in this work. These data are the same as presented in Johnston et al. (2007b). We note that there could be a level of systematic error in these measurements, primarily from the photometric redshift errors on the background source galaxies used for the shear measurement. It is difficult to know this error, but simulations suggest the calibration is good to 10% (Lima et al. 2008).

In order to get a size scale for each cluster sample, we fit a simple model to the data. The model is that of an Navarro–Frenk–White (NFW) profile on small scales (Navarro et al. 1997) and linear correlations on large scales. This model was presented in detail in Johnston et al. (2007b). For this paper, we only use this fit in order to estimate a size \( r_{200}^\text{mass} \), from which we can also calculate the mass \( M_{200}^\text{mass} \). The \( r_{200}^\text{mass} \) is the radius where the mean mass density falls to 200 times the critical density, and \( M_{200}^\text{mass} \) is the mass contained within that radius. This radius \( r_{200}^\text{mass} \) will be a reference point for the \( M/L \) measurements. The fits for each richness bin are shown in Figure 7 and \( r_{200}^\text{mass} \) is marked for reference. Note, these values are somewhat different than those in Johnston et al. (2007b) where power-law interpolation between data points was used to extract \( r_{200}^\text{mass} \).

In Johnston et al. (2007b) it is shown that if a fair fraction of the BCGs are not centered on the peak of the halo mass distribution, the shape can be strongly effected. In that work an offset distribution was determined from simulations, and used to recover the underlying halo mass distribution. In this work we do not try to recover halo masses, but work directly with the observations around the BCGs chosen as centers. Thus it is important to keep in mind that these are the mass profiles (and light profiles) around BCGs, not necessarily peaks of the halo mass distribution. This is probably not a large effect for the \( M/L \) at the virial radius, and is negligible on the largest scales. On the other hand, for relatively small radii the shape of the \( M/L \) profile around BCGs may be different than that around halo centers.

### 8.6. Mass-to-Light Ratio Profiles

In order to generate \( \Delta M/\Delta L \) profiles we simply divide the integrated excess mass \( \Delta M \) by the integrated excess light \( \Delta L \) profiles. These profiles are shown for each cluster richness bin in Figure 8. These data are available for download and are summarized in Table 3.

The \( \Delta M/\Delta L \) is shown with and without the mean BCG luminosity. When the mean BCG luminosity is included the profile rises steeply and then flattens out at large radius. The \( r_{200}^\text{mass} \) is marked for reference. The mean \( \Delta M/\Delta L \) within \( r_{200}^\text{mass} \) is a strong function of cluster richness. However, the asymptotic \( \Delta M/\Delta L \) is nearly independent of cluster richness.

Without the mean BCG luminosity included, the \( \Delta M/\Delta L \) is relatively flat on intermediate to large scales, indicating that the relative amount of mass and light on those scales is not a strong function of radius. There is a turn up at small scales, however. This is partly due to the fact that we do not measure light on scales less than 25 h \(^{-1}\) kpc. However, there is also light not counted in our luminosity measurements. It is known that there is a significant amount of intra-cluster light (ICL), light not associated with galaxies, in many clusters (e.g., Gonzalez et al. 2005). There is also missing light from galaxies below the luminosity threshold 10\(^{9.5}\) h\(^{-2}\) L\(_{\odot}\) and the light not counted from the outskirts of detected galaxies (probably dominated by the outskirts of the BCG on these scales). Only by estimating...
Figure 7. Cumulative three-dimensional excess mass profiles for each cluster \( N_{200} \) bin derived from weak gravitational lensing. The solid curves show the best-fit NFW-linear bias model. The dotted curve is the corresponding linear model and the dot-dashed curve is the NFW only. The asterisk marks \( r_{\text{mass}}^{200} \). Note these models do not account for possible offsets between the BCG and the halo mass peak, which would alter the profile on small scales.

(A color version of this figure is available in the online journal.)

Table 3
Mass-to-Light Ratio Data for MaxBCG Clusters

| \( X \) \( (N \text{ or } L) \) | \( \langle X \rangle \) \( (\text{h}^{-1} \text{Mpc}) \) | \( r \) \( (\text{h}^{-1} \text{Mpc}) \) | \( L_{\text{BCG}}/\Delta L \) \( (h M_\odot/L_\odot) \) | \( \Delta M/\Delta L \) \( (h M_\odot/L_\odot) \) | \( \sigma(\Delta M/\Delta L) \) \( (h M_\odot/L_\odot) \) |
|---|---|---|---|---|---|
| N | 3.00e+00 | 2.433e–02 | 9.926e–01 | 9.846e+00 | 1.930e+00 |
| N | 3.00e+00 | 3.485e–02 | 9.786e–01 | 1.228e+01 | 2.580e+00 |
| N | 3.00e+00 | 4.987e–02 | 9.585e–01 | 2.137e+01 | 4.084e+00 |
| N | 3.00e+00 | 7.130e–02 | 9.314e–01 | 3.302e+01 | 4.682e+00 |
| N | 3.00e+00 | 1.018e–01 | 8.991e–01 | 6.066e+01 | 5.875e+00 |
| N | 3.00e+00 | 1.457e–01 | 8.546e–01 | 8.261e+01 | 7.354e+00 |
| N | 3.00e+00 | 2.084e–01 | 7.893e–01 | 9.543e+01 | 9.709e+00 |
| N | 3.00e+00 | 2.978e–01 | 7.062e–01 | 1.130e+02 | 1.314e+01 |
| N | 3.00e+00 | 4.257e–01 | 6.405e–01 | 1.520e+02 | 1.611e+01 |
| N | 3.00e+00 | 6.095e–01 | 6.208e–01 | 1.629e+02 | 2.268e+01 |
| N | 3.00e+00 | 8.708e–01 | 6.191e–01 | 2.070e+02 | 3.179e+01 |

Notes. \( M/L \) data corresponding to Figure 8. The first column indicates binning on either \( N_{200} \), labeled “N,” or \( L_{200} \), labeled “L.” The second column is the mean value of \( N_{200} \) or \( L_{200} \) for the bin, with units of either number or \( 10^{10} \text{h}^{-2}L_\odot \). Column 3 is the fraction of the total excess light \( \Delta L \) contained in the BCG. Note the fraction of light in the BCG can be slightly greater than unity due to noise.

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

In order to more quantitatively describe the shape of the \( \Delta M/\Delta L \) curves, we use a simple fitting function that captures the main features of our profiles. The function describes the ratio of two equal-index power laws in mass and light plus a delta function for the mean BCG luminosity.

\[
\frac{\Delta M}{\Delta L}(<r) = \frac{M_0(r/1 \text{h}^{-1} \text{Mpc})^\alpha}{L_{\text{BCG}} + L_0(r/1 \text{h}^{-1} \text{Mpc})^\alpha} = \left( \frac{(r/r_{1/2})^\alpha}{1 + (r/r_{1/2})^\alpha} \right) \left( \frac{\Delta M}{\Delta L} \right)_{\text{asym}},
\]

\( \text{asym} \)
Figure 8. Excess mass to excess light ratio profiles for each of the $N_{200}$ bins. Light is measured in the $0.25i$ bandpass. These curves are the ratio of the curves shown in Figures 6 and 7. The points with error bars include the mean BCG luminosity, while the dotted curves exclude the luminosity of the BCG. The asterisk marks $r_{\text{mass}}^{200}$. The curve through the data is a simple descriptive model as discussed in Section 8.6. (A color version of this figure is available in the online journal.)

where $r_{1/2} = (\langle L_{\text{BCG}} \rangle / L_0)^{1/\alpha}$ is the radius at which the $\Delta M/\Delta L$ reaches half its asymptotic value at infinity $(\Delta M/\Delta L)_{\text{asym}}$. A larger $r_{1/2}$ at fixed $\alpha$ implies a larger fraction of the total light is in the BCG, which results in a slower transition to the asymptotic $\Delta M/\Delta L$.

Although we know that the mass and light profiles are not pure power laws, they tend to deviate from a power law in similar ways, which partially cancels this error. However, this means that $\alpha$ should not be interpreted as the slope of the mass or light profile.

The best fits for Equation (19) are overplotted in Figure 8 for the $N_{200}$ binning. We use the full covariance matrix of the $\Delta M/\Delta L$, generated from the covariance matrices of $\Delta M$ and $\Delta L$, for the fits. Using the covariance matrix accounts for the strong correlations in the errors caused by the radial integration. The best-fit $r_{1/2}$, $\alpha$, and $(\Delta M/\Delta L)_{\text{asym}}$ are listed in Tables 1 and 2. There is a weak trend of decreasing $r_{1/2}$ with $N_{200}$, while $\alpha$ is relatively constant except for the highest richness bins. Recall that $r_{1/2} = (\langle L_{\text{BCG}} \rangle / L_0)^{1/\alpha}$, and thus a smaller $r_{1/2}$ at fixed $\alpha$ is indicative of a less dominant BCG relative to the overall cluster luminosity, which we had already seen to be true in Figure 6. However, at high masses the value of $\alpha$ increases also, weakening the change in $r_{1/2}$ somewhat. We will discuss the $(\Delta M/\Delta L)_{\text{asym}}$ values in Section 8.8.

8.7. Mass-to-Light Ratio Within $r_{\text{mass}}^{200}$

In Figure 9, we show the mean $\Delta M/\Delta L$ within $r_{\text{mass}}^{200}$, $(\Delta M/\Delta L)_{\text{200}}$, for each of the cluster richness and luminosity bins, plotted as a function of the mean $N_{200}$. The $\Delta M/\Delta L$ increases strongly with $N_{200}$ over two orders of magnitude in mass. The $\Delta M_{200}$ is also shown on the top axis, but note this is rough as the transformation is nonlinear. The $(\Delta M/\Delta L)_{200}$ versus $\Delta M_{200}$ is a good fit to a power law with index 0.33 ± 0.02. The $(\Delta M/\Delta L)_{200}$ versus $N_{200}$, however, is not a good fit to a power law due to the nonlinear relationship between mass and galaxy counts.

Over-plotted in Figure 9 is a prediction based on the models in Tinker et al. (2005) for $z = 0$ rest-frame $i$-band light rather than $0.25i$. The predicted $N_{200}$ have been scaled by a factor of 1.5 to pass over the points. We do not expect this prediction to match our data, which is in a different band and for which there are BCG centering effects. The point here is to show a rough expected trend with mass. There is qualitative agreement with the mass scaling of this prediction and our data. Note, it is tempting to think our data do not asymptote at high mass as expected from the model, but there is actually agreement at the 1σ level.

8.8. Asymptotic Mass-to-Light Ratio

The $\Delta M/\Delta L$ profiles shown in Figure 8 rise quickly and flatten at large separations. We measure this asymptotic value in two separate ways. First we use the last point in the $\Delta M/\Delta L$ curve at $r < 22 \ h^{-1} \text{ Mpc}$, which we will refer to as $(\Delta M/\Delta L)_{22\,\text{Mpc}}$. The $(\Delta M/\Delta L)_{22\,\text{Mpc}}$ for each richness bin is shown in Figure 10. Note, the value at $22 \ h^{-1} \text{ Mpc}$ should be insensitive to any offsets between the BCGs and the true
Figure 9. Mean ∆M/∆L within r_{200} as a function of N_{200}. Light is measured in the 0.25i bandpass. The mean ∆M_{200} within r_{200} centered on BCGs is shown on the top axis, although this is only rough since the transformation between ∆N_{200} and mass is nonlinear. No correction for offsets between the BCGs and the halo mass peaks is included. The (∆M/∆L)_{200} vs. ∆M_{200} is a good fit to a power law with index 0.33 ± 0.02; the (∆M/∆L)_{200} vs. N_{200} is not a good power law. The overplotted curve is a prediction based on the simulations of Tinker et al. (2005). This curve is not correctly matched to these data, but is rather intended to show the rough expected trend with mass.

Figure 10. Asymptotic excess M/L as a function of N_{200}. Light is measured in the 0.25i bandpass. This is simply the last point on the integrated ∆M/∆L curve at r = 22 h^{-1} Mpc. The mean ∆M within r_{200} centered on BCGs is shown on the top axis, although this is only rough since the transformation between N_{200} and mass is nonlinear. The mean ∆M/∆L = 362 ± 54 h, averaged over all samples, is plotted as the horizontal line.

We detect no trend in the (∆M/∆L)_{22} Mpc as a function of N_{200}. For the average value we get 362 ± 54 h for the richness binning and 349 ± 51 h for the luminosity binning. Note, these are not independent measures since the same clusters are used for both binning.

For the second method we examine the (∆M/∆L)_{asym} values measured from the fits in Section 8.6, which are listed in Tables 1 and 2. As with the (∆M/∆L)_{22} Mpc values, they are roughly constant with N_{200}. The errors on (∆M/∆L)_{asym} are much smaller than those on (∆M/∆L)_{22} Mpc because the model uses all data points rather than just the last data point to infer the asymptotic M/L. We will discuss the interpretation of these errors more in the discussion.

The average model asymptotic M/L's are 357 ± 9 h for the richness binning and 335 ± 9 h for the luminosity binning. Note, the two binning are not independent measures as the same clusters are used for both. Both are consistent with the values we get just taking the last point (∆M/∆L)_{22} Mpc.

9. ERRORS

As stated earlier, all errors come from jackknife resampling of the data. The method was discussed in Sheldon et al. (2004, 2009) in context of the lensing measurements. The same technique was used for the light measurements. The main difference between jackknifing in the lensing and luminosity measurements is that for the luminosity correlations we must jackknife all pieces of the estimator in Equation (4).

The systematics in the M/L measurements are dominated by calibration uncertainties in the lensing measurements, in particular the photometric redshift estimates for the background source galaxies. These errors were discussed in Section 2.1 and more detail can be found in Johnston et al. (2007b). Although it is difficult to know the absolute scale of the expected uncertainties, based upon the results of both simulations and real world tests shown in Lima et al. (2008), we estimate the overall level of systematics to be of order 10% for all contributing factors.

We want to stress again that the errors on the asymptotic M/L differ greatly for the two methods for a very simple reason: the (∆M/∆L)_{asym} is derived from the last point on the M/L curve and the (∆M/∆L)_{asym} is derived from fitting a simple descriptive model to all points. Because this model is not a physical model the points on small scales should not be expected to be constraining of the large scale M/L. So the errors on (∆M/∆L)_{asym} must be thought of as lower limits at this stage. The errors on (∆M/∆L)_{asym} can be thought as upper limits since there is certainly some information in points at smaller radius.

10. DISCUSSION

The integrated ∆M/∆L around MaxBCG clusters has a generic form. At 25 h^{-1} kpc, where the light of the cluster is dominated by the BCG, the ∆M/∆L is ∼ 10 h^{-2} M_{⊙}/L_{⊙}. There is a sharp rise and then the profile flattens out at large scales (22 h^{-1} Mpc). We fit a simple model to extract r_{1/2}, the radius at which the ∆M/∆L reaches half its value at infinity (see Section 8.6 for details).

For M_{200} < 10^{14} M_{⊙}, r_{1/2} is determined primarily by the relative amount of light in the BCG compared to the rest of the cluster. For higher masses, the ∆M/∆L asymptotes to (∆M/∆L)_{asym} more quickly relative to the lower masses, resulting in a smaller r_{1/2}.

The decreasing r_{1/2} with richness is partly due to the less dominant BCGs for higher richness clusters; the effect of the BCG on the integrated light is only important on small scales for very rich systems. But it is also partly because the measured ∆M/∆L within the large clusters is closer to the universal value. Figure 8 shows that the ∆M/∆L not including the BCG light is more flat for the high-richness clusters that have especially sharp transitions. The ∆M/∆L would be essentially equal to (∆M/∆L)_{asym} if it were not for the presence of the BCG. This is not true for the lower richness systems.
This difference between high- and low-richness systems leads us back to the discussion of uncounted light. Uncounted light is any light not counted in our measurements. This uncounted light is partly intra-cluster light (ICL), light not associated with galaxies. There is also light from galaxies less luminous than the threshold $10^{9.5} \, h^{-2} \, L_\odot$. The total luminosity of galaxies below this threshold is not dominant (see, e.g., Hansen et al. 2005), and the radial profile is similar to that of galaxies above the threshold, so including it would not change the profile dramatically. But the ICL has a steeper profile. It appears to follow a $\exp(-r^{1/4})$ law, with a scale length of order $100 \, h^{-1} \, kpc$, and contains many times more light than the BCG (Gonzalez et al. 2005). The total light in this component scales slowly with richness, and is more dominant on small scales in smaller systems. This could explain what appears to be a slower rise in $\Delta M/\Delta L$ relative to larger systems. We will explore the ICL for MaxBCG clusters in a future paper.

The $(\Delta M/\Delta L)_{200}$, the excess mass to light within $r_{200}^{mass}$, scales with richness and $M_{200}$. For lower richness systems, the $(\Delta M/\Delta L)_{200}$ is considerably smaller than $(\Delta M/\Delta L)_{asym}$, while for larger systems it is of order $(\Delta M/\Delta L)_{asym}$. This trend is probably a reflection of both a true difference in mean $\Delta M/\Delta L$ and the effect of the ICL, which may be more dominant for larger systems. The $(\Delta M/\Delta L)_{200}$ versus $N_{200}$ is not a good fit to a power law, but $(\Delta M/\Delta L)_{200}$ versus $M_{200}$ is well fitted by a power law with index $0.33 \pm 0.02$ (there is a nonlinear relationship between mass and galaxy counts). However, no attempt was made to model possible offsets between BCGs locations and the halo mass peaks. The $\Delta M/L$ will not be strongly affected because the luminosity roughly traces mass, the $\Delta M_{200}$ as a function of $N_{200}$ does change significantly (Johnston et al. 2007b). A fully model-dependent analysis for both the mass and light profiles following Johnston et al. (2007b) may imply different results for $(\Delta M/\Delta L)_{200}$ measured around dark matter halos as compared to MaxBCG clusters.

It is difficult to compare with the literature due to the many conventions and methods in use with regards to cluster selection, lower luminosity thresholds, galaxy aperture definitions, mass apertures and estimators, projected versus de-projected masses, luminosities with or without background subtraction, and the various bandpasses used for the exposures. With these caveats, we will say that there is broad agreement in the literature that $M/L \propto M^{0.2-0.3}$ (e.g., Girardi et al. 2000; Lin et al. 2004; Popesso et al. 2007). Below we compare the $\Omega_m$ calculated from the inferred global $M/L$, which may be less dependent on these factors.

We used two methods to extract the asymptotic $\Delta M/\Delta L$: the value with in $22 \, h^{-1} \, Mpc$, $(\Delta M/\Delta L)_{22Mpc}$, and the best-fit value from our fitting function, $(\Delta M/\Delta L)_{asym}$. Note, on these large scales, any offsets between the BCGs positions and the halo mass peak is irrelevant. We see no trend of either measure of the asymptotic $\Delta M/\Delta L$ with $N_{200}$.

As we discussed in the introduction, for any given cluster sample, the asymptotic $\Delta M/\Delta L$ is proportional to the $M/L$ of the universe. Repeating Equation (2) here for clarity,

$$\Delta M/L)_{asym} = (M/L)b_{M/L}^2,$$

$$b_{M/L}^2 = \frac{b_{cm}}{b_{cl}} \frac{1}{b_{bc}^2},$$

where $b_{M/L}^2$ depends primarily on the bias of the galaxy tracers relative to the underlying mass distribution, since the bias of the clusters likely cancels out in $b_{cm}/b_{cl}$.

Thus, if the $b_{M/L}^2$ is independent of cluster richness, then the lack of a trend of $(\Delta M/\Delta L)_{22Mpc}$ with $N_{200}$ means we have measured the same asymptotic $\Delta M/\Delta L$ for all richness bins. If $b_{M/L}^2$ is not independent of $N_{200}$, then by chance the variations in asymptotic $\Delta M/\Delta L$ were canceled by a corresponding change in the bias. So we need to determine whether this bias is constant.

The bias $b_{M/L}^2$ should primarily depend on the mass of the halos hosting the light tracers, and this should be related to the luminosity of those galaxies. Included in Tables 1 and 2 is the mean $i$-band luminosity of galaxies at $10 \, h^{-1} \, Mpc$ separations ($L_{10h}^{i\text{tot}}$). The value on larger scales was not well constrained for all richness bins. There is not a strong variation of this mean luminosity between the richness bins. The average, over all cluster richness bins, of the luminosity of galaxies within 10 Mpc is $L_{20z_{i}} = (1.10 \pm 0.04) \times 10^{10} \, h^{-2} \, L_\odot$ ($-20.43 \pm 0.04$ mag). Note, in Section 5 we saw that $L_{20z_{i}} = 1.7 \times 10^{10} \, h^{-2} \, L_\odot$. Given the small variation in luminosity, and the fact that the bias varies quite slowly for $L < L_\star$ galaxies (Tegmark et al. 2004), the bias $b_{M/L}^2$ should be roughly constant for each cluster sample. Thus, we will assume we are measuring the true asymptotic value at large separations, and average these values from all cluster richness bins.

In Section 8.8, we calculated this asymptotic value in two ways: first by taking the value of the integrated $\Delta M/L$ for the last radial bin 22 $h^{-1}$ Mpc to get $(\Delta M/\Delta L)_{22Mpc}$, and the second fitting a simple descriptive model to get $(\Delta M/\Delta L)_{asym}$. Averaging over all cluster luminosity bins gives

$$\langle M/L \rangle b_{M/L}^2 = \begin{cases} 362 \pm 54 & \text{within } 22 \, h^{-1} \, Mpc \\ 357 \pm 9 & \text{asymptotic fit} \end{cases}$$

in solar units, where the bias $b_{M/L}^2$ corresponds to that of $L_{20z_{i}} = 1.10 \times 10^{10} \, h^{-2} \, L_\odot$ galaxies at $z = 0.25$.

In Section 5, we calculated that the luminosity density in the $0.25_i$ band is $(3.14 \pm 0.10) \times 10^8 \, h \, L_\odot \, Mpc^{-3}$. Multiplying the above asymptotic $M/L$ by this, and dividing by the critical density, number we get an estimate of $\Omega_m$ that is independent of $h$:

$$\Omega_m b_{M/L}^2 = \begin{cases} 0.20 \pm 0.03 & \text{within } 22 \, h^{-1} \, Mpc \\ 0.194 \pm 0.008 & \text{asymptotic fit} \end{cases}$$

There is certainly more information than we have used in the 22 $h^{-1}$ Mpc values since points at smaller radius do contain independent information. So in principle a more precise measurement could be made, but the error within 22 $h^{-1}$ Mpc can be considered conservative. On the other hand, the error bar on the asymptotic fit is certainly an underestimate, as the fit is not based on a physical model. The errors are small simply because all the points in the curve are used rather than just the last, but in fact the points on small scales are not necessarily informative in interpreting the points on large scales in the absence of a physical model; this error should be thought of as a lower limit.

In addition, there is a level of systematic error not accounted for here. Although the level of systematic error is not precisely known, we expect it to be $\sim 10\%$, mostly due to errors in photometric redshifts of lensing source galaxies. See Johnston et al. (2007b) for a more complete discussion of systematic errors.

There have been numerous studies measuring $M/L$s of clusters. As discussed above with regards to the $(\Delta M/\Delta L)_{200}-M_{200}$ relation, there are a wide variety of techniques and conventions in place. Many of these studies use the $M/L$ to infer $\Omega_m$ by
assuming the value they get is equal to that of the universe. Although this is not always a well-justified assumption, converting to \( \Omega_m \) does remove most of the dependence on the bandpass, galaxy apertures, and mass aperture (as long as the mass aperture is not too small). Using the inferred \( \Omega_m \) may lead to a more robust comparison between the various results.

The series of papers by Bahcall et al. have consistently estimated \( \Omega_m \sim 0.2 \) from this technique, using various mass estimators. For example, using X-ray clusters, Bahcall & Comerford (2002) found \( 0.17 \pm 0.05 \) and SDSS clusters whose masses were calibrated from velocity dispersions gave \( 0.19 \pm 0.08 \) (Bahcall et al. 2003).

Cluster velocity dispersions in the CNOC data have also been used to calculate \( \Omega_m \). Using stacked velocity and B-band light profiles, Carlberg et al. (1997) found \( \Omega_m = 0.19 \pm 0.06 \). A recent analysis using individual masses and K-band light found \( 0.22 \pm 0.02 \) (Muzzin et al. 2007).

Using the “caustic” method for estimating masses and K-band light in the CAIRNS survey, Rines et al. (2004) inferred \( \Omega_m = 0.18 \pm 0.03 \). This method claims to yield more accurate masses by correctly modeling the infall regions around clusters. The study of CNOC2 groups by Parker et al. (2005) using weak lensing for group masses and B-band light found \( \Omega_m = 0.22 \pm 0.06 \). It should be noted that these are rather small groups; as we have shown in this work the \( M/L \) is less than universal within their virial radii. Using X-ray data for a set of Two Micron All Sky Survey (2MASS) clusters, and 2MASS K-band luminosities, Lin et al. (2003) find \( \Omega_m = 0.19 \pm 0.03 \).

Although there is general agreement when using \( M/L \) to infer \( \Omega_m \), these measurements give smaller values for \( \Omega_m \) than baryon fraction measurements, although baryon fraction measurements do have dependence on \( h \). This is noted, for example, by Lin et al. (2003) where they find a higher \( \Omega_m = 0.28 \pm 0.03 \) using the baryon fraction using their own data, and suggest that their \( M/L \) are too low.

In our analysis we demonstrated that the \( M/L \) reaches an asymptotic value at large radius, which removes one possible error in determining the global \( M/L \). The missed light, ICL and otherwise, will generally push the \( M/L \) even lower. It is possible that the \( b_{\text{ICL}}^{\text{Bg}} \) is considerably greater than unity, but this is not the theoretical expectation. The light tracers are \( L < L_* \) galaxies which reside in underbiased halos (Sheth & Tormen 1999; Seljak & Warren 2004).

Note, we have assumed a fiducial flat cosmology with \( \Omega_m = 0.27 \) when performing these measurements, and this has not been varied properly in order to constrain \( \Omega_m \) above. Thus the calculated \( \Omega_m \) could be slightly biased, and there could be some additional statistical error not accounted for here. Generally, decreasing the assumed \( \Omega_m \) increases the inferred \( \Omega_m \) using this technique, through its affect on the critical density for lensing. But at these redshifts such effects are secondary, well below our errors. In a future paper we will present a full cosmological analysis including these effects as well as a proper model for BCG displacements from the halo mass peak as carried out in Johnston et al. (2007b).

These results are a precise test for models of structure and galaxy formation. The \( M/L \) results, coupled with the galaxy color and luminosity distributions as a function of radius from clusters (Sections 8.1 and 8.3) show in detail how different types of galaxies are distributed in and around these clusters and how they are clustered relative to the underlying mass distribution (see also Hansen et al. 2009). These are the most basic cross-correlation statistics that can be addressed, and are perhaps the most precise and powerful statistics that can be measured by a photometric survey.

It is significant that these measurements were carried out in a purely photometric data set. Every step of the process uses photometric data only, from cluster finding, to galaxy cross-correlations, to lensing measurements. These types of measurements can be carried out in any high-quality survey with properly chosen bandpasses. Future surveys such as DES, SNAP, and LSST will greatly extend these measurements and further challenge our theories of cosmology and galaxy formation.

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