COMPARISON OF CLUSTER LENSING PROFILES WITH ΛCDM PREDICTIONS

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ABSTRACT

We derive lens distortion and magnification profiles of four well-known clusters observed with Subaru. Each cluster is very well fitted by the general form predicted for cold dark matter (CDM) dominated halos, with good consistency found between the independent distortion and magnification measurements. The inferred level of mass concentration is surprisingly high, \(8 < c_{\text{crit}} \leq 15\) (\(c_{\text{crit}} = 10.39 \pm 0.91\)), compared to the relatively shallow profiles predicted by the ΛCDM model, \(c_{\text{crit}} = 5.06 \pm 1.10\) (for \(M_{\text{vir}} = 1.25 \times 10^{15} M_{\odot} h^{-1}\)). This represents a 4 \(\sigma\) discrepancy, and includes the relatively modest effects of projection bias and profile evolution derived from N-body simulations, which oppose each other with little residual effect. In the context of CDM-based cosmologies, this discrepancy implies that clusters collapse earlier (\(z \geq 1\)) than predicted (\(z < 0.5\)), when the universe was correspondingly denser.

Subject headings: cosmology: observations — dark matter — galaxies: clusters: individual (A1689, A1703, A370, RX J1347−11) — gravitational lensing

1. INTRODUCTION

Dark matter (DM) is understood to comprise \(\approx 85\%\) of the material universe (Fukugita & Peebles 2004), in the form of massive halos around galaxies and clusters of galaxies. The density profile of a dark halo depends on the unknown nature of the DM and the way structure develops over cosmic time. Galaxy halos may be modified significantly when gas associated with the disk of a galaxy cools and condenses during its formation. In contrast, clusters are so massive that the virial temperature of the gas (typically 3–15 keV) is too high for efficient cooling and hence the cluster potential reflects the dominant DM.

Models for the development of structure now rest on accurate measurements of the power spectrum of mass fluctuations, the cosmological density of DM, and the contribution of a cosmological constant, \(\Lambda\) (Spergel et al. 2007; Komatsu et al. 2008). This framework is the standard “ΛCDM” cosmological model, with the added simple assumptions that DM is collisionless, reacts only gravitationally, was never relativistic (“cold”), and with initially Gaussian-distributed density perturbations. In this context, detailed N-body simulations have established a clear prediction that CDM-dominated cluster halos should have relatively shallow, low-concentration mass profiles, where the logarithmic gradient flattens continuously toward the center with a central slope tending toward \(r^{-1}\), interior to a characteristic radius, \(r_{\text{vir}} \approx 100–200 \text{kpc} h^{-1}\) (Navarro, Frenk, & White 1997, hereafter NFW; Bullock et al. 2001; Macciò et al. 2007; Henri et al. 2007; Neto et al. 2007; Duffy et al. 2008). This “NFW” profile is characterized by the (total) mass, \(M_{\text{vir}}\), within the virial radius, \(r_{\text{vir}}\), and by the concentration parameter, \(c_{\text{crit}} \equiv r_{\text{vir}}/r_s\).

Interaction between clusters indicates DM is collisionless, in particular the Bullet Cluster (Markevitch et al. 2002), where shocked gas lies between two substantial galaxy clusters, implying these clusters passed through each other recently (Markevitch et al. 2002). Here the weak-lensing signal follows the bimodal distribution of member galaxies reflecting substantial DM associated with each cluster component (Clowe et al. 2006) and that this DM is relatively collisionless like the galaxies. These observations disfavor the class of alternative gravity theories for which the lensing signal is expected to trace the dominant baryonic contribution of the gas (Clowe et al. 2006). Other cases of interaction show that in general displacement of the gas relative to the DM is typically related to interaction (Jee et al. 2005; Okabe & Umetsu 2008).

For many clusters no obvious evidence of recent interaction is seen as the gas and member galaxies follow a symmetric, structureless distribution. Measurements of the mass profiles of these relaxed clusters may help in understanding the nature of DM, preferably relying on gravitational lensing signals where model-dependent assumptions are not required. For A1689, over 100 multiply lensed images have been used to derive the inner mass profile (Broadhurst et al. 2005b), with the outer profile determined from weak lensing (Broadhurst et al. 2005a). Together, the full profile has the predicted NFW form, but with a surprisingly high concentration when compared to the shallow profiles of the standard ΛCDM model (Broadhurst et al. 2005a; Umetsu & Broadhurst 2008). Furthermore, good consistency is also found between the lensing-based mass profile and the X-ray and dynamical structure of this cluster in model-independent analyses (Lemze et al. 2008; D. Lemze et al. 2008, in preparation). A similar discrepancy is also indicated by lensing observations of other clusters, e.g., MS 2137–23 (Gavazzi et al. 2003) and CL 0024+16 (Kneib et al. 2003).

Here we examine a sample of relaxed, high-mass clusters, to test the distinctive prediction of ΛCDM, and to settle empirically whether the mass profile of A1689 is unusual. In § 2 we describe the data reduction, in § 3 we present the weak-lensing analysis and the magnification profiles derived from background number counts and make comparison with the prediction of the ΛCDM, and in § 4 we discuss our results and conclusions.

2. DATA REDUCTION

We analyze deep images of A1689, A1703, A370, and RX J1347−11 taken by the wide-field camera Suprime-Cam (34′ × 27′; Miyazaki et al. 2002) on Subaru (8.3 m), which are observed deeply in several optical passbands, listed in Table 1. These clusters are of interest due to the exceptional quality of the data, with exposures in the range 2000–10,000 s per pass.
band, with seeing ranging from 0.5° to 0.75°. We use either the R or J bands for our weak-lensing measurements (described below in § 3) for which the instrumental response, sky background, and seeing conspire to provide the best images. All the available bands are used to define colors with which we separate cluster members from the background in order to minimize dilution of the weak-lensing signal by unlensed objects.

The standard pipeline reduction software for Suprime-Cam (Yagi et al. 2002) is applied for flat-fielding, instrumental distortion correction, differential refraction, PSF matching, sky subtraction, and stacking. Photometric catalogs are constructed from stacked and matched images using SExtractor (Bertin & Arnouts 1996). We select red galaxies with colors redder than the color-magnitude sequence of cluster E/SO galaxies. The sequence forms a well-defined line due to the richness and relatively low redshifts of our clusters. These red galaxies are expected to lie in the background by virtue of k-corrections which are greater than for the red cluster sequence galaxies and convincingly spectroscopically by Rines & Geller (2008). We also include very blue galaxies falling far from the cluster sequence, >1.5–2.5 mag, depending on the passbands available for each cluster (listed in Table 1), to minimize cluster contamination (see Medezinski et al. 2007). Typically the proportion of blue galaxies used is around 50% of the red background. In addition, we adopt a conservative magnitude limit of m < 25.5–26.0, depending on the depth of the data for each cluster, to avoid incompleteness. Imposing these strict limits is a necessary precaution against the diluting effect that unlensed cluster and foreground galaxies will otherwise produce, leading to spuriously shallow central mass profiles, as shown in Broadhurst et al. (2005a) and Medezinski et al. (2007).

3. MEASUREMENTS OF LENSING EFFECTS

These data permit high-quality weak-lensing measurements, following established methods required to deal with instrumental and atmospheric effects following the formalism outlined in Kaiser et al. (1995), with modifications described in Erben et al. (2001). The mean residual stellar ellipticity after PSF correction is less than ~10⁻⁴ in all fields, averaged over 400–600 stars and consistent with the standard error on this measurement, ≈10⁻⁴. Note also the lack of any systematic deviation from zero in the B-mode, g, shown in Figure 2 (top). Full details of the methods are presented in Umetzu & Broadhurst (2008).

Figure 1 shows the gravitational shear field by locally averaging the corrected distortions of color-selected background galaxies of each cluster. This is compared to the distribution of color-selected cluster sequence galaxies. In each case, one large symmetric cluster is visible around which the lensing distortion pattern is clearly tangential, with little significant substructure. The derived radial profiles of the lensing distortion are seen to be very similar in form (Fig. 2, top), with differing amplitudes reflecting a range of mass.

The NFW profile fits well each cluster (Fig. 2; Table 1), but surprisingly the derived concentrations lie well in excess of the standard ΛCDM model (Fig. 3). For the derived masses of our clusters, the predicted mean concentration is c_e < ~5.06 ± 1.1 based on Duffy et al. (2008) using the improved WMAP5 (Komatsu et al. 2008). Our best-fitting values instead range over 8 < c_e < 15, with a mean value of ⟨c_e⟩ = 10.39 ± 0.91, representing a 4.8 σ discrepancy. Our measurements also imply A370 is the most massive cluster known, M_e = 2.93 × 10¹⁵ M⊙ h⁻³, with a virial mass twice that of RX J1347−11, the most X-ray-luminous cluster known. Our estimate of the virial mass of RX J1347−11 is in very good agreement with independent X-ray and lensing analyses (Miranda et al. 2008; Kling et al. 2005). For A1689, a somewhat lower concentration parameter is derived by Limousin et al. (2007), c_e = 9.6 ± 2.0, from independent weak-lensing measurements, which is consistent with our findings at the 1.5 σ level, whereas the observed Einstein radius of approximately 52″ is underpredicted by the NFW parameters obtained by Limousin et al. (2007), 24″ ± 11″ (see Umetzu & Broadhurst 2008).

Note, when model-fitting an estimate of the background depth is required. The mean depth is sufficient for our purposes as the variation of the lens distance ratio, D_e/D_o, is slow for our sample because the clusters are at relatively low redshift compared to the redshift range of the background galaxies. The estimated mean depth of the combined red+blue background galaxies is listed in the fifth column, which we obtain by applying our color-magnitude selection to Subaru imaging of the HDF region (Capak et al. 2004),

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**TABLE 1**

| Cluster | Filters | Filters | Filters | Filters |
|---------|---------|---------|---------|---------|
| A1689   | V/R/J  | V/R/J   | V/R/J   | V/R/J   |
| A1703   | g′/r′/i′ | g′/r′/i′ | g′/r′/i′ | g′/r′/i′ |
| A370    | B/R/c   | B/R/c   | B/R/c   | B/R/c   |
| RX J1347−11 | V/R/c | V/R/c   | V/R/c   | V/R/c   |

**Fig. 1.—Maps of the surface number-density distribution of color-selected cluster member galaxies, with the gravitational shear of background galaxies overlaid; 10% ellipticity is indicated top right, and the resolution of the distortion map is shown bottom right.**

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The table below lists the Einstein Radius combined with the Einstein-Radius Constraint.
where photometric redshifts are reliable for red galaxies, with a mean redshift close to $z = 1.2$ depending on the details of the color magnitude selection. For the blue galaxies we can rely on the zCOSMOS deep redshift survey (Lilly et al. 2007) where our mean depth is typically $z = 2.1$.

Lensing measures projected mass and so a statistical bias arises from the triaxiality of clusters in cases where the major axis lies along the line of sight. This leads to an $\sim 18\%$ increase in the mean value of lensing-derived concentrations based on ΛCDM (Oguri et al. 2005; Hennawi et al. 2007), and an overall discrepancy in $c_\text{vir}$ of 4.0 $\sigma$ with respect to the predictions. A larger bias is inferred for clusters selected by the presence of large arcs, $\sim 34\%$, representing the most triaxial cases (Hennawi et al. 2007).

Our sample is defined by the quality of available imaging and includes clusters observed for reasons other than lensing; hence it is unlikely that these clusters are all particularly triaxial with the long axes pointing to the observer. Even so, applying the maximum estimated bias ($\sim 50\%$; M. Oguri & R. Blandford, in preparation) cannot account for our measurements (Fig. 3). Multiply lensed images are visible in all our clusters, from which the inner mass distribution may be determined (Broadhurst et al. 2008).

Multiply lensed images are visible in all our clusters, from which the inner mass distribution may be determined (Broadhurst et al. 2005b; Halkola et al. 2008; Hennawi et al. 2008) and an equivalent Einstein radius derived by averaging azimuthally (Fig. 2) which for most cases is close to the observed radius. For A1703 and A370, the tangential critical curves are significantly elongated, for $r < 1'$ (Limousin et al. 2008; Kneib et al. 1993), although in general the mass distribution is always less elliptical than the critical curve. X-ray observations of A370 show that the inner region has some substructure (e.g., Shu et al. 2008), but beyond $r > 1'$ the weak-lensing pattern and the distribution of galaxies is symmetrical, as seen in Figure 1. For each cluster the NFW parameters derived with or without the Einstein radius constraint are found to be closely consistent and in combination they are more precisely determined; see Table 1.

We also examine the magnification profile, $\mu(r)$, via the surface number density of background galaxies (Broadhurst et al. 1995). At faint fluxes where the counts follow a power-law slope, $s = d \log N(< m)/dm$, lensing modifies the true density above the magnitude limit, $N_r(< m_{\text{lim}})$, by $N_r(< m_{\text{lim}}) = N_r(< m_{\text{lim}}) \mu(r)^{s-1}$, implying competition between the magnified sky, which reduces the surface density, and an increase of galaxies magnified above the flux limit. Here we use only gal-
axies lying redward of the cluster sequence because for these the intrinsic count slope of faint red galaxies is relatively flat, $s \sim 0.1$, so a net count depletion results, which we readily detect for each cluster, increasing toward the center (Fig. 2). For each cluster we calculate the depletion of the counts expected for the best-fitting NFW profile derived from the corresponding distortion measurements above (Fig. 2, bottom, with same color code), finding clear consistency, which considerably strengthens our conclusions, and also establishes the utility of the background red galaxies for measuring magnification. The variation in the total number of background counts seen in Figure 2 simply reflects the relative depth of the imaging data and also to some extent the redshift of the cluster, which lies redder in color space with increasing cluster redshift, thereby reducing the numbers of background galaxies which can be selected to lie redward of the sequence for our purposes. Note, absolute counts are not used here; the models are instead normalized to the observed density for each cluster, increasing toward the center (Fig. 2). For each cluster we calculate the depletion of the counts expected for the central region of clusters, diluting the central lensing signal. Without resorting to radical proposals regarding the nature of DM, our findings imply that the central region of clusters collapsed earlier than expected. Assuming the simple redshift relation $c_{\text{vir}}(z) = c_{\text{vir}}(1+z)$ (e.g., Wechsler et al. 2006), relating central cluster densities to the cosmological mean density, then the formation of clusters with $c_{\text{vir}}(1+z) = 10-15$ corresponds to $z \geq 1$, significantly earlier than in the standard ΛCDM, for which clusters form today with $c_{\text{vir}} \sim 5.6$. The presence of massive clusters at high redshift ($z \sim 2$), and the old ages of their member galaxies (Zirm et al. 2008; Blakeslee et al. 2003), may also imply clusters collapsed at relatively early times (Mathis et al. 2004), for which accelerated growth factors have been proposed, adopting a generalized equation of state (Sadeh & Rephaeli 2008). Alternatively, since clusters correspond to rare density maxima, then any non-Gaussianity in the early fluctuation spectrum may advance cluster formation (Mathis et al. 2004; Sadeh et al. 2007). Our results present a challenge to some of these models, since earlier cluster formation must not also enhance significantly the abundance of clusters.

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