MEASUREMENT OF THE HALO BIAS FROM STACKED SHEAR PROFILES OF GALAXY CLUSTERS

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Received 2014 January 22; accepted 2014 February 18; published 2014 March 14

ABSTRACT

We present observational evidence of the two-halo term in the stacked shear profile of a sample of \ approximately 1200 optically selected galaxy clusters based on imaging data and the public shear catalog from the CFHTLenS. We find that the halo bias, a measure of the correlated distribution of matter around galaxy clusters, has amplitude and correlation with galaxy cluster mass in very good agreement with the predictions based on the LCDM standard cosmological model. The mass–concentration relation is flat but higher than theoretical predictions. We also confirm the close scaling relation between the optical richness of galaxy clusters and their mass.

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

Online-only material: color figures

1. INTRODUCTION

A fundamental scope of the observational study of galaxy clusters, the most massive gravitationally bound systems in the cosmos, is testing models of structure formation and gaining insight into the complex physical interplay between the baryonic and dark components of matter. Currently, the most successful framework is based on the cosmological constant term and cold, collisionless dark matter (LCDM), the nature of which is still not understood. Numerical simulations have provided clear predictions for the structure of dark matter halos (e.g., the so-called mass–concentration relation; Bullock et al. 2001) and their clustering properties.

The halo power spectrum $P_h(k)$ describes the statistical properties of the spatial distribution of massive halos. Observed structures are in principle distributed differently from the underlying dark matter. The correlation between the halo density field and the underlying matter distribution is parameterized by the halo bias parameter, $b_h$. This is defined as the ratio of the halo power spectrum to the linear matter (Tinker et al. 2010; Oguri & Takada 2011):

$$b_h^2(k) = \frac{P_h(k)}{P_m(k)}. \quad (1)$$

Theoretical models of gravitational clustering of dark matter halos provide robust predictions for the bias (Mo & White 1996; Sheth et al. 2001). It is expected to be constant at large scales and an increasing function of the peak height. It is therefore of importance to compare such predictions with observations of galaxy clusters, as a function of mass and cosmic epoch.

The correlated matter distribution around galaxy clusters manifests itself as a two-halo term in the mass density profiles, at scales larger than \ approximately 10 Mpc, its contribution being proportional to $b_h$. The two-halo term describes the cumulative effects of the large scale structure in which galaxy clusters are located. Although weak gravitational lensing is a powerful tool to measure mass distribution in galaxy clusters (Kneib & Natarajan 2011), the lensing signal expected in the two-halo term is too low to be reliably detected in the outskirts of individual systems. Stacking the lensing signal of a large number of galaxy clusters enable us to detect at high S/N the two-halo term. Stacked shear profiles of galaxy groups and clusters have been used to study the average properties of radial profiles and the observable scaling relations (Sheldon et al. 2001; Dahle et al. 2003; Cacciato et al. 2009; Okabe et al. 2010; Leauthaud et al. 2010; Oguri et al. 2012; Sereno & Covone 2013; Shan et al. 2013).

Johnston et al. (2007) used \ approximately 1.3 $\times 10^5$ galaxy groups and clusters from the Sloan Digital Sky Survey (SDSS) to obtain stacked lensing signals and infer the relations between mass and optical richness and luminosity over a wide range of masses, and also to measure the halo bias and concentration as a function of mass. Oguri & Takada (2011) proposed a cosmological test based on the combination of stacked weak lensing of galaxy clusters with number counts and correlation functions, showing that this reduces systematic errors from poorly known redshift distributions and scaling relations.

Several studies have shown observational evidence for the two-halo term in the stacked galaxy–galaxy lensing profile (Brimioulle et al. 2013; Velander et al. 2014). In this work, we apply this technique at the galaxy cluster scale. We use public data from Canada–France–Hawaii Telescope Lensing Survey (CFHTLenS) to measure the lensing signal from a sample of optically selected galaxy clusters (Wen et al. 2012). As framework we use a spatially flat cosmological model with $\Omega_m = 0.7$, $\Omega_m = 0.3$, and $h = 0.7$, with $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$.

2. ANALYSIS

The radial shear profile $\gamma(\theta)$ of a galaxy cluster at redshift $z$ can be effectively described by the sum of two terms: $\gamma(\theta) = \gamma_{1h}(\theta) + \gamma_{2h}(\theta)$. The first term $\gamma_{1h}(\theta)$ accounts for the main dark matter halo and the associated baryonic component. The two-halo term $\gamma_{2h}(\theta)$ accounts for the correlated distribution of matter around the cluster. The tangential shear profile due to the two-halo term is (Oguri & Takada 2011;
Oguri & Hamana (2011) evaluated in each radial bin, taking into account the weight $w$ et al. (2012). We used the following region in the two-color space: of the associated shear measurement. of the linear matter power spectrum, and the baryon and neutrino density and scalar spectral index as measured by the Planck Collaboration et al. (2013). The uncorrelated matter distribution along the line of sight provides no contribution to the stacked shear signal, therefore the two-halo term is a function of the correlated matter distribution at the same cluster redshift (Oguri & Takada 2011).

We used the public shear catalog provided by the CFHTLenS (Heymans et al. 2012) containing the photometry, photometric redshifts, and ellipticity measurements from the four wide fields covering about 154 square degrees. Data have been collected within the CFHT Legacy Survey (CFHTLS; Erben et al. 2013). Photometric redshifts were determined from the available optical $ugriz$ observations (Hildebrandt et al. 2012; Benjamin et al. 2013), with accuracy $\simeq 0.04 (1 + z)$ and a catastrophic outlier rate of about 4%.

We used the catalog built by Wen et al. (2012) to identify galaxy clusters in the four fields. The catalog contains positions, photometric redshift, richness, and brightest cluster galaxy (BCG) magnitude for 132,684 optically selected galaxy clusters, up to $z = 0.8$. Galaxy clusters were identified in the SDSS-DR9 imaging data, with a detection rate of $\sim 75\%$ for masses larger than $0.6 \times 10^{14} M_{\odot}$. The false detection rate is less than 6% for the whole sample. The center of each galaxy cluster is identified with the position of the BCG. We selected galaxy clusters centered on the CFHTLS fields, with redshift in the range $0.1 \leq z \leq 0.6$ and at least one radial shear measurement in the inner 2 Mpc $h^{-1}$ (corresponding to about 7.5 arcmin at $z = 0.3$). The upper redshift limit was chosen in order to separate robustly the lensing and background galaxy populations. Our final sample contains 530, 89, 457, and 287 systems (1176 overall) in the four regions, respectively, with median redshift $z = 0.36$. No further selection is applied.

For each galaxy cluster, we determined the shear profile $\gamma_i(r)$ around its center as briefly outlined hereafter. The procedure leading to the shape measurements, based on the tool $\text{lencorrfit}$, is described in Miller et al. (2013). The CFHTLenS catalog provides the raw shear components, $e_1$, $e_2$. These quantities are still affected by a small multiplicative and additive bias: we performed the correction by applying two calibration parameters, $m$ and $c_1$, empirically derived from the data and provided in the shear catalog (Heymans et al. 2012). The calibration reads

$$e_{\text{true},i} = \frac{e_{m,i} - c_i}{1 + m} \quad (i = 1, 2),$$

where $e_{m}$ is the measured ellipticity. The average quantity $\bar{m}$ is evaluated in each radial bin, taking into account the weight $w$ of the associated shear measurement.

We selected background lensed sources behind each cluster by using a two-color selection (Medezinski et al. 2010; Oguri et al. 2012). We used the following region in the two-color space:

$$(g - r < 0.3) \text{ OR } (r - i > 1.3) \text{ OR } (r - i > g - r).$$

These criteria efficiently select galaxies at $z > 0.7$ (Medezinski et al. 2010). We did not select background sources on the basis of photometric redshifts, as the photometric redshift distribution of the faint galaxies show an artificial peak at $z_{\text{phot}} \sim 0.2$ (Hildebrandt et al. 2012). We note that these sources are mostly characterized by a low value of the $\alpha$ parameter that quantifies the relative importance of the most likely redshift (Hildebrandt et al. 2012), hinting at possible degeneracies in the redshift determination based only on optical colors. Finally, we also excluded all sources that were either not detected in one of the three $gri$ filters or did not satisfy the following requirements on the parameters of the CFHTLenS catalog: ellipticity weight larger than 0, mask smaller than or equal to 1, $S/N$ of the $\text{lencorrfit}$ measurement larger than 0, and $i$ magnitude brighter than the local limit magnitude. The final density of the background galaxies is about six galaxies per arcmin$^2$.

We determined the shear profile as a function of the physical length, up to about 20 Mpc $h^{-1}$ (corresponding to about 2 deg, at $z = 0.3$). We excluded the central region of angular radius 0.1 Mpc $h^{-1}$ around the BCG because of the low number of background sources and the low accuracy in the determination of the cluster center. The shear profile was determined in 23 log-spaced radial bins, with logarithm spacing $\log_{10} r = 0.1$ Finally, in each radial bin, we determined the weighted ellipticity of the background sources, and hence the tangential and cross components of the shear, $\gamma_t$, $\gamma_c$.

By using photometric redshifts measurements of the lens and source population, we calculated the excess surface mass density

$$\Delta \Sigma(R) = \Sigma_{\text{true}} g_t (R),$$

where $g_t (R)$ is the reduced tangential shear and then computed the mean in the given annular bin (McKay et al. 2001).

Finally, we obtained high-S/N radial profiles as a function of the physical length scale by stacking the signal of galaxy clusters grouped according to their optical richness. The optical richness is defined as $R_L = L_{200}/L_s$ (Wen et al. 2012), where $L_{200}$ is the cluster total luminosity within an empirically determined radius $r_{200}$ and $L_s$ is the evolved characteristic luminosity of galaxies in the $r$ band. Wen et al. (2012) have shown that there is a close correlation between the virial mass $M_{200}$ and the optical richness. Hence, we used the observable quantity $R_L$, to split the full galaxy cluster sample into six bins; see Table 1. Stacked radial profiles of the excess mass density $\Delta \Sigma$ are shown in Figure 1.

We fitted each stacked profile with a double mass component. The galaxy cluster halo is fitted with the smoothly truncated Navarro–Frenk–White (NFW) profile proposed by Baltz et al. (2009),

$$\rho_{\text{NFW}} = \frac{\rho_s}{r_t (1 + \frac{r_t}{r_s})^2 \left( \frac{r_t^2}{r^2 + r_s^2} \right)^2},$$

where we set the truncation radius $r_t = 3 \, r_{200} r_s$. This modification of the original NFW profile removes the unphysical divergence of its total mass. Moreover, Oguri & Hamana (2011) used a set of ray-tracing $N$-body simulations to show that this parametric model gives a less biased estimates of mass and concentration with respect to the NFW profile, and also better describes the density profile beyond the virial radius, where the transition between the cluster and the two-halo term occurs. As discussed above, the two-halo term describes the outer profile. The shear signal at large radii is proportional to the halo power spectrum, and hence to the product $b_y \sigma_y^2$, where $\sigma_y$ is the rms mass fluctuation amplitude in spheres of size $8h^{-1}$ Mpc.

A relevant source of error is given by the halo centering offset, as the BCG (which defines the cluster center in our
sample) might be misidentified (Johnston et al. 2007) or not coincide with the matter centroid (Zitrin et al. 2012). The misidentification of the BCG can lead to an underestimate of $\Delta \Sigma(R)$ at small scales and bias low the measurements of $c_{\text{200}}$. Therefore, we fitted an offset mass component (Yang et al. 2006), distributed according to an azimuthally symmetric Gaussian distribution, with mass fraction and scale length of the Gaussian distribution as free parameters (Johnston et al. 2007). The contribution of the main cluster halos is given by the sum of two terms, a central term and an offset component. The off-diagonal terms of the covariance matrix does not significantly change the results. For consistency across the different richness bins, we only considered diagonal elements to perform the analysis.

Free fitting parameters are the mass and the concentration of the main cluster halo, the term $b_h \sigma_h^2$, the fraction of off-centered halos, $0.5 < f_h < 1$, and the scale length of the spatial distribution this additional component is extracted from $0 < \Delta < 1 \text{ Mpc} h^{-1}$. We performed radial fits using data points between 0.5 and 15 Mpc $h^{-1}$, beyond which annuli are largely incomplete due to the limited field of view. The choice of the lower limit for radial range is a compromise between minimizing the systematic errors due to the contamination of cluster galaxies, and minimizing the statistical error on $c_{\text{200}}$ (Mandelbaum et al. 2008). The number of degrees of freedom is 10 in each fit. Errors were determined with a standard bootstrap procedure with replacement.

In order to determine residual systematic effects affecting the stacked $\gamma_r$, $\gamma_s$ profiles, we built a random catalog of 5000 lenses with the same redshift distribution as the real galaxy clusters and we determined the lensing signal around the random positions using the same procedure described above. The systematic signal was then subtracted from the measured quantity. Errors on the stacked random cluster shear profiles have been estimated with a bootstrap procedure with replacement (5000 resamplings) and then added in quadrature. The stacked lensing signal $\Delta \Sigma$ from the random pointings is consistent with zero up to $\sim 5 \text{ Mpc} h^{-1}$. At larger radii, there is a spurious signal at about the 1$\sigma$ level, in agreement with Miyatake et al. (2013) who pointed to residual systematics in the shear measurements at the edges of the detector.

Due to stacking, shear observations at different radii are correlated. The off-diagonal terms of the covariance matrix are very noisy (Mandelbaum et al. 2013) and can be reliably computed only in the most populated bins at small optical richness, where we verified that the use of the covariance matrix does not significantly change the results. For consistency across the different richness bins, we only considered diagonal elements to perform the analysis.

The unbiased profiles were then analyzed using an MCMC procedure to explore the parameter space. Results are listed in Table 1. The mass fraction of the offset component is not strongly constrained by our data; however, it is important to

![Figure 1](image-url) Radial profiles of the excess surface mass density $\Delta \Sigma$ for the six samples of galaxy clusters, binned according to their optical richness $R_{L*}$. Black points are our measurements. The green line is the main galaxy cluster halo, the blue line is the contribution from the two-halo term. The black line is the overall fitted radial profile. Dashed lines are extrapolation from the best fit model. (A color version of this figure is available in the online journal.)

| Richness Bin $R_{L*}$ | $N_{\text{clus}}$ | $c_{\text{200}}$ | $M_{\text{200}}^{10^{14} M_{\odot} h^{-1}}$ | $b_h \sigma_h^2$ | $\chi^2$ |
|-----------------------|------------------|-----------------|-------------------------------|-----------------|-------|
| $12 \leq R_{L*} < 16$ | 476              | 13.8 ± 1.1      | 0.48 ± 0.09                   | 8.6 ± 5.8       | 1.76 ± 0.39 | 11.9  |
| $16 \leq R_{L*} < 21$ | 347              | 18.1 ± 1.4      | 0.51 ± 0.11                   | 4.3 ± 5.3       | 1.20 ± 0.49 | 10.7  |
| $21 \leq R_{L*} < 30$ | 216              | 24.7 ± 2.6      | 0.81 ± 0.13                   | 9.3 ± 5.5       | 1.77 ± 0.56 | 4.45  |
| $30 \leq R_{L*} < 40$ | 90               | 34.2 ± 2.7      | 1.52 ± 0.24                   | 1.8 ± 1.1       | 1.87 ± 0.94 | 18.8  |
| $40 \leq R_{L*} < 70$ | 37               | 47.8 ± 6.7      | 1.95 ± 0.30                   | 10.1 ± 5.6      | 2.14 ± 1.15 | 16.2  |
| $70 \leq R_{L*} < 100$| 10               | 85.6 ± 10.3     | 3.21 ± 0.54                   | 10.4 ± 5.2      | 5.45 ± 2.31 | 14.3  |

Notes. Reported central values and uncertainties were obtained as bi-weight estimators of the marginalized probability distributions. The $\chi^2$ value refers to the best fit model. The number of dof is 15–5 = 10.
include it the fitting procedure as this leads to a less biased measurement of the concentration, which would otherwise be significantly underestimated. The modeling provides good fits to the data.

3. SCALING RELATIONS

We analyzed scaling relations between cluster observables. Linear fits were performed using the BCES method, an implementation of the ordinary least squares estimator (Akritas & Bershady 1996). Errors were estimated by means of a bootstrap resampling with replacements.

We confirm the strong correlation between the optical richness $R_L$ and the virial mass of the stacked galaxy clusters (see Figure 2):

\[
\log \frac{M_{200}}{10^{14} M_\odot h^{-1}} = 0.035 \pm 0.028 + (1.18 \pm 0.12) \log \frac{R_L}{30} \tag{7}
\]

in excellent agreement with Wen et al. (2009).

Theoretical models of the hierarchical growth of structures in the LCDM model present two clear predictions on the mass scale of galaxy clusters: the mass–concentration relation and the dependence of the halo bias term on the parent halo mass. We find that the stacked galaxy clusters follow a flat $c(M)$-relation (see Figure 3):

\[
\log c_{200} = (0.75 \pm 0.13) + (0.09 \pm 0.33) \log \frac{M_{200}}{10^{14} M_\odot h^{-1}}. \tag{8}
\]

Although the slope is consistent with theoretical predictions by Duffy et al. (2008), the normalization differs at the 1σ level. We note that neglecting the offset component would decrease the normalization, without changing the slope of the relation.

The two-halo term is evident in each individual $R_L$ bin (Figure 1), and it is strongly dependent on the parent halo mass (Figure 4). Our results are remarkably consistent with theoretical predictions (Tinker et al. 2010; Bhattacharya et al. 2011). Quantitative analysis can be performed in terms of a $\chi^2$ function,

\[
\chi^2 = \sum_{i=1}^{6} \left( \frac{b_i \sigma_i^2 - \left[ b_i \sigma_i^2 \right]_T}{\delta M_{200}^2 + \delta (b_i \sigma_i^2)} \right)^2. \tag{9}
\]

We get $\chi^2 = 2.6$ assuming the theoretical bias from Tinker et al. (2010) and the value $\sigma_8 = 0.83$ measured by the Planck collaboration from the CMB temperature anisotropy and the lensing-potential power spectra (Planck Collaboration et al. 2013). The associated probability is $P(\chi^2 > 2.6) = 86\%$.

In an attempt to constrain $\sigma_8$, we can adopt the bias model from Tinker et al. (2010). We obtain $\sigma_8 = 0.7 \pm 0.3$.

4. CONCLUSIONS

We used the CFHTLenS public shear catalog to obtain the stacked weak lensing signal of 1176 galaxy clusters in the redshift range $0.1 < z < 0.6$. With respect to previous observational studies of the galaxy cluster halo bias based on SDSS imaging data, we used shear measurements derived from the deeper and higher quality data from the CFHTLS. We built high-S/N profiles in six bins in optical richness $R_L$, the average masses of which span the range from 0.5 to $\sim 3 \times 10^{14} M_\odot h^{-1}$.

We confirm that the cluster mass robustly correlates with the optical richness, with parameters in agreement with those found by Wen et al. (2012). Our result supports the use of the
stacking method in weak lensing to calibrate galaxy clusters scaling relations, e.g., Oguri & Takada (2011).

We studied the $c(M)$ and the $b_h(M)$ relations, and we found in both cases an agreement with theoretical predictions based on the LCDM cosmological models. While consistent at the 1σ level with the predictions from Duffy et al. (2008), we find evidence for an over-concentration of the $c(M)$–relation, in closer agreement with recent simulations by Bhattacharya et al. (2013).

Our results partially reconcile present tension between observed $c(M)$ relations and theoretical predictions. On one hand, studies of single clusters found very steep and over-concentrated relations (Oguri et al. 2012; Fedeli 2012; Sereno & Covone 2013). On the other hand, previous stacked analyses found flat relations of the expected amplitude (Mandelbaum et al. 2008). We found an alternative scenario in a middle ground: an over-concentrated but still flat relation. Analysis of individual clusters might be affected by low S/N and high correlation, as well as by selection effects, whereas previous SDSS stacked analysis might suffer from contamination and off-set effects.

The large scale shear profile is a degenerate function of the halo bias and the power spectrum normalization, therefore our measurement of the halo bias term is not independent of $\sigma_8$. Our measurement of the quantity $b_h(M)\sigma_8^2$ as a function of the average halo mass is in very good agreement with theoretical predictions by Tinker et al. (2010) and systematically higher than the ones by Johnston et al. (2007), Figure 4. As shown by Rozo et al. (2010), shear measurements in Johnston et al. (2007) are underestimated by $\sim 20\%$ due to the diluted lensing signal by foreground galaxies. This systematic error might explain the discrepancy with our measurements.

Our analysis is also consistent with measurements from the correlation function of galaxy clusters. Veropalumbo et al. (2013) analyzed a spectroscopic sample of 25,226 clusters of richness $R_{\ast} \geq 12$ at $z \sim 0.3$ and obtained $b_h = 2.06 \pm 0.04$ for $\sigma_8 = 0.8$.

Our results open the possibility of verifying further physical effects on the clustering properties of massive halos: Villasacausa-Navarro et al. (2013) used N-body simulations to show that cosmological models with massive neutrinos show a scale-dependent bias on large scales, while Dalal et al. (2008) have shown that the non-Gaussianity of primordial fluctuations brings a strongly scale-dependent bias.

We thank Keiichi Umetsu for stimulating discussions and the referee for clarifying comments. G.C. acknowledges financial support from the grant PRIN-INAF 2011 “Galaxy Evolution with the VLT Survey Telescope”; M.S. and V.F.C. acknowledge financial support from agreement ASI/INAF/L/023/12/0. This work is based on observations obtained with MegaPrime/ MegaCam, a project of CFHT and CEA/IRFU, at the CFHT, operated by the Canadian NRC, the Institut National des Sciences de l’Univers of the CNRS of France, and the University of Hawaii. This research used the facilities of the Canadian Astronomy Data Centre operated by the NRC of Canada with the support of the Canadian Space Agency. CFHTLenS data processing was made possible thanks to computing support from the NSERC Research Tools and Instruments grant program.

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