WEAK-LENSES STUDY OF LOW-MASS GALAXY GROUPS: IMPLICATIONS FOR $\Omega_m$

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ABSTRACT

We report on the first measurement of the average mass and mass-to-light ratio of galaxy groups by analyzing the weak-lensing signal induced by these systems. The groups, which have velocity dispersions of 50–400 km s$^{-1}$, have been selected from the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC2). This survey allows the identification of a large number of groups with redshifts ranging from $z = 0.12$ to 0.55, ideal for a weak-lensing analysis of their mass distribution. For our analysis we use a sample of 50 groups that are selected on the basis of a careful dynamical analysis of group candidates. We detect a signal at the 99% confidence limit. The best-fit singular isothermal sphere model yields an Einstein radius $\theta_E = 0.72 \pm 0.29$. This corresponds to a velocity dispersion of $(\sigma^2)^{1/2} = 274 \pm 50$ km s$^{-1}$ (using photometric redshift distributions for the source galaxies), which is in good agreement with the dynamical estimate. Under the assumption that the light traces the mass, we find an average mass-to-light ratio of $191 \pm 83 M_\odot/L_{B,0}$ in the rest-frame $B$ band. Unlike dynamical estimates, this result is insensitive to problems associated with determining group membership. After correction of the observed mass-to-light ratio for luminosity evolution to $z = 0$, we find $254 \pm 110 M_\odot/L_{B,0}$, lower than what is found for rich clusters. We use the observed mass-to-light ratio to estimate the matter density of the universe, for which we find $\Omega_m = 0.19 \pm 0.10$ ($\Omega_\Lambda = 0$), in good agreement with other recent estimates. For a closed universe ($\Omega_m + \Omega_\Lambda = 1$), we obtain $\Omega_m = 0.13 \pm 0.07$.

Subject headings: cosmology: observations — dark matter — gravitational lensing

1. INTRODUCTION

Galaxy groups, such as the Local Group, are common structures in the universe. Although numerous, groups are difficult to identify because the contrast with the smooth background of galaxies is quite low and their galaxy properties are similar to that of the field. To date most systems have been studied using the results of large-redshift surveys (e.g., Turner & Gott 1976; Ramella, Geller, & Huchra 1989; Huchra, Geller, & Corwin 1995) or X-ray observations (Mulchaey et al. 1996). Unfortunately, X-ray observations are available for only very few groups.

Measuring the amount of matter locked up in these typical systems is interesting, but a measurement of the average mass-to-light ratio of galaxy groups may be even more important, as it provides a good measure of the MIL ratio of the field, i.e., the universe as a whole (e.g., Gott & Turner 1977). Subsequently, this result can be used to obtain an estimate for the matter density $\Omega_m$ (Oort 1958; Gott & Turner 1977), similar to what has been done for rich clusters of galaxies (e.g., Carlberg, Yee, & Ellingson 1997; Carlberg et al. 1999).

However, measuring the mass or MIL ratio of groups selected from redshift surveys is difficult. Nolthenius & White (1987) showed that the dynamical masses inferred from such surveys depend on the survey parameters, the group selection procedure, and the way galaxies cluster. Consequently, an independent measure of the group mass is needed. In this Letter we study galaxy groups by their weak-lensing effect on the shapes of the images of the faint background sources.

Weak lensing enables us to measure the projected mass surface density, without any assumption about the geometry or dynamical state of the system under investigation. The technique has been applied successfully to rich clusters of galaxies (for a review see Mellier 1999).

The amplitude of the weak-lensing signal is proportional to the mass of the lens, and as a result the expected signal from an individual galaxy group is very low. To circumvent this problem, we study the properties of the ensemble-averaged group by stacking the signals of many groups at intermediate redshifts, where the lensing signal is maximal.

Galaxy groups identified in the Canadian Network for Observational Cosmology Field Galaxy Redshift Survey (CNOC2; Lin et al. 1999; Yee et al. 2000; Carlberg et al. 2001) are ideal for a weak-lensing study of their mass distribution: the survey provides a large sample of groups at intermediate redshifts, which can be imaged efficiently by wide-field imaging.

The observations, data reduction, and weak-lensing analysis are outlined in § 2, and the group selection is discussed in...
The results of the weak-lensing analysis are given in § 4. In § 5 we present our estimate of Ω_m.

2. OBSERVATIONS AND ANALYSIS

The CNOC2 survey targeted four widely separated patches on the sky to study the dynamics of galaxy clustering at intermediate redshifts. Redshifts of approximately 5000 galaxies down to \( z = 21.5 \) have been measured, resulting in a large sample of galaxies at intermediate redshifts (\( z = 0.12 \pm 0.55 \)). A detailed description of the survey and the catalogs is given in Yee et al. (2000).

We have observed the central parts of the two patches 1447+09 and 2148–05 using the 4.2 m William Herschel Telescope at La Palma. The data were taken using the prime focus camera, equipped with a thinned 2k × 4k pixel E2V10 chip, and a pixel scale of 0.237 pixel\(^{-1}\). To cover the central regions of the patches, a mosaic of six pointings was observed, resulting in a field of view of 31′ × 23′.

The typical total integration time per pointing is 1 hr in \( R \). The seeing ranged from 0′6 to 1′0, with a median seeing of 0′7 for the 1447 field and 0′85 for the 2148 field. The images were deblended and flat-fielded, and photometric calibration was performed using standard stars from Landolt (1992).

Our object analysis is based on the procedure developed by Kaiser, Squires, & Broadhurst (1995) and Luppino & Kaiser (1997), with a number of modifications that are described in Hoekstra et al. (1998) and Hoekstra, Franx, & Kuijken (2000).

The objects detected in the images are analyzed: sizes, apparent magnitudes, and shape parameters are determined. We correct the measurements for various observational distortions. We also tested how uncertainties in these corrections would affect our results and found that the results are very stable.

In the weak-lensing analysis we use galaxies with \( 22 < R < 26 \) as background sources. These catalogs contain some faint group members, which can lower the lensing signal at the group centers. We examined the average number density of sources around the groups and found that the contamination is negligible.

3. GALAXY GROUPS

Finding galaxy groups in a redshift survey such as CNOC2 is a difficult problem. The crucial step is to determine the group membership, which makes a reliable dynamical mass estimate difficult. The weak-lensing mass estimate is more robust against contamination by interlopers, as it relies only on the position of the overdensity.

Lensing in itself does not provide information as to whether the studied structures are gravitationally bound galaxy groups. The question whether the selected structures are genuine groups is less important when determining the average \( M/L \) ratio of these systems. As we will demonstrate in § 4.3, the \( M/L \) ratio from weak lensing is particularly stable against uncertainties in the determination of group membership. For the estimate of \( \Omega_m \) presented in § 5, it is sufficient to identify high-density regions.

For our analysis we use the groups presented by Carlberg et al. (2001). The groups are found using an iterative method, which is a variant of the often-used friends-of-friends algorithm. A detailed discussion of the algorithm is presented in Carlberg et al. (2001).

The resulting sample consists of 50 groups that are within the observed fields. The average redshift of the groups is \( z = 0.33 \), and they have velocity dispersions ranging from 50 to 400 km s\(^{-1}\). The redshift information is crucial because the contrast of the groups with the field is low: the average group corresponds to a 1.2 ± overdensity in number counts.

To estimate the light contents of the groups, we determine \( B_\star \), the rest-frame B-band magnitude. To this end, we use template spectra for a range in spectral types and compute the corresponding passband corrections as a function of redshift and galaxy color. The redshifts and colors of the galaxies are taken from the CNOC2 catalogs (e.g., Yee et al. 2000).

To account for the incompleteness of the redshift survey, each galaxy with a measured redshift is assigned a proper weight (Yee et al. 2000; Lin et al. 1999). These weights are used to correct the galaxy luminosities and the group luminosity profiles (the average correction factor is found to be 1.53 ± 0.02). We used the luminosity function derived by Lin et al. (1999) to estimate the correction factor for the missing faint galaxies, for which we find a value of 1.20 ± 0.07. We find that the average luminosity of the groups considered here is \( L_B = (6.3 \pm 0.6) \times 10^{10} \ h^{-2} \ L_{B,0} \), which corresponds to \( 5\sigma \) for the average distortion at a redshift \( z = 0.33 \) (see § 4.2).

We quantify the lensing signal by means of the tangential distortion, which is defined as \( g_T = -(g_r \cos 2\phi + g_\phi \sin 2\phi) \), where \( \phi \) is the azimuthal angle with respect to the assumed group center and \( g_r \) are the components of the distortion. The number of confirmed group members per group is rather low (3–7 members), and therefore the positions of the group centers are somewhat uncertain. Here we use the positions that are found from a virial analysis described in Carlberg et al. (2001). Simulations using SIS models indicate that the uncertainty in the group centers could result in an overestimate of the average lensing signal by at most 4%–8%. In addition, the groups are embedded in the large-scale structure, which tends to increase the weak-lensing mass estimate. The numerical results from Cen (1997) match well our observations and indicate that the bias is still small, on the order of 10%. We note, however, that our estimate for the average \( M/L \) ratio presented in § 4.3 does not suffer from either of the biases mentioned above.

The azimuthally averaged tangential distortion around the 50 groups is presented in Figure 1a. We detect a positive average tangential distortion of 0.00254 ± 0.0011, which is significant at the 99% confidence level. We tested the robustness of the signal in various ways. Figure 1b shows the result when the phase of the distortion is increased by π/2. In addition, other tests, such as randomizing the group positions or the ellipticities of the sources, yielded no significant signal. We therefore conclude that the observed signal is due to weak lensing by galaxy groups.

The best-fit singular isothermal sphere model \( \kappa(r) = r_\epsilon / 2[r] \) to the ensemble-averaged distortion from the sample of 50 galaxy groups from Carlberg et al. (2001) yields an Einstein radius of \( r_\epsilon = 0.72 \pm 0.29 \).
the filled circles), which has a velocity dispersion of $230 \pm 80$ km s$^{-1}$, is indicated by the solid line. (b) Signal when the phase of the distortion is increased by $\pi/2$: no signal should be present if the signal in (a) is due to lensing. The vertical error bars indicate the 1$\sigma$ errors.

4.2. Estimate of the Velocity Dispersion

The next step is to relate the Einstein radius to an estimate of the velocity dispersion. To do so we use photometric redshift distributions inferred from the Hubble Deep Fields (HDFs; Fernández-Soto, Lanzetta, & Yahil 1999; Chen et al. 1998), which generally work well (Hoekstra et al. 2000). We determine the R-band magnitudes of the galaxies in the HDFs and use these results to derive the average group velocity dispersion.

The strength of the lensing signal is characterized by $\beta$, which is defined as $\beta = \text{max} \begin{pmatrix} 0, D_e/D_s \end{pmatrix}$, where $D_e$ and $D_s$ are the angular diameter distances between the lens and the source and between the observer and the source. For each group-galaxy pair we compute the corresponding value of $\beta$ based on the R-band magnitude of the source and the redshift of the group. We find $\langle \beta \rangle = 0.393 \pm 0.006$, which results in an ensemble-averaged group velocity dispersion of $\langle \sigma^2 \rangle^{1/2} = 274^{+15}_{-11} \text{ km s}^{-1}$ (68% confidence; $\Omega_m = 0.2$, and $\Omega_{\Lambda} = 0$) for the sample of groups from Carlberg et al. (2001). For $\Omega_m = 0.2$ and $\Omega_{\Lambda} = 0.8$, it changes to $\langle \sigma^2 \rangle^{1/2} = 258^{+45}_{-29} \text{ km s}^{-1}$ (68% confidence). These results are in good agreement with the average velocity dispersion of 230 km s$^{-1}$ from the velocities of the group members.

4.3. Mass-to-Light Ratio

Under the assumption that the light traces the mass, we derive the expected tangential distortion as a function of radius. We use the ensemble-averaged group luminosity profile to calculate the expected signal for each group for a mass-to-light ratio of unity (taking into account the redshift) and average the result for all groups. To measure the MIL ratio, we scale the resulting tangential distortion to match the observed signal.

In Figure 2a the resulting profile (solid line) is shown. The ratio of the computed to the observed signal is presented in Figure 2b and is consistent with a constant MIL ratio with radius for which we find a value of $191 \pm 83 \, h \, M_{\odot}/L_{\odot}$ in the rest-frame $B$ band.

This measurement of the MIL ratio has not been corrected for luminosity evolution. If the luminosity evolution scales with redshift as $L_r \propto (1 + z)$ (e.g., Lin et al. 1999), we obtain a value of $254 \pm 110 \, h \, M_{\odot}/L_{\odot}$, corrected to $z = 0$. Carlberg et al. (1997) measured the MIL ratio of a sample of 15 rich clusters, for which they found an average value of $M/L_r = 237^{+41}_{-31} \, M_{\odot}/L_{\odot}$. To convert their result to an MIL ratio in the $B$ band, we assume an average color of the cluster of $B - r = 1.07$, which corresponds to the typical color of 50 galaxies (Jørgensen, Franx, & Kjærgaard 1995). Thus, we find that the average cluster MIL ratio is $438 \pm 76 \, h \, M_{\odot}/L_{\odot}$ (where we also corrected for luminosity evolution to $z = 0$). Thus, the average group MIL ratio in the $B$ band is lower than the value typically found for rich clusters.

We derived the expected lensing signal using only galaxies identified as group members. However, lensing is sensitive to the contribution of all matter along the line of sight. To examine the contribution of the remaining galaxies we recalculated the group light profile, using all galaxies with redshifts. Fitting the predicted distortion to the observations, we find an MIL ratio of $183 \pm 80 \, h \, M_{\odot}/L_{\odot}$, in excellent agreement with our measurement from group members only. An important consequence of this exercise is that the weak-lensing estimate of the MIL ratio is insensitive to the determination of group membership, unlike the dynamical estimators.
5. ESTIMATE OF $\Omega_m$

A well-known method to estimate the matter density of the universe was proposed by Oort (1958): $\Omega_m$ is the product of the universe’s mass-to-light ratio and its luminosity density. Carlberg et al. (1997) used the observed $M/L$ ratios of a sample of rich clusters to estimate $\Omega_m$, for which they found a value of $\Omega_m = 0.19 \pm 0.06$.

The galaxy properties of rich clusters are quite different from those of the field, and a large correction is needed to relate the cluster $M/L$ ratio to the $M/L$ ratio of the universe. However, we found a small difference of $\Delta(B-V) = 0.035 \pm 0.013$ between the average rest-frame colors of group galaxies and the field, which is caused by a small difference in stellar populations. We use stellar evolution models12 (Bruzual & Charlot 1993) to make a small correction for this effect. Under the assumption that the fraction of the mass in stars is the same for both groups and galaxies, we find that the $B$-band $M/L$ ratio of the field is lower by a factor 1.15 compared with the value found for the groups.

We combine our estimate of the $M/L$ ratio with the results from Lin et al. (1999), which are based on the same data. Convolving the redshift distribution of the groups with their redshift-dependent luminosity density yields $j = (3.2 \pm 0.6) \times 10^4 \ h Mpc^{-3}$ (assuming $\Omega_m = 0.2$ and $\Lambda = 0$).

We obtain $\Omega_m = 0.19 \pm 0.10$ for an $\Omega_m = 0$ cosmology. Our estimate for $\Omega_m$ decreases to a value of $\Omega_m = 0.13 \pm 0.07$ for $\Omega_m = 0.87$. The value for $\Omega_m$ is derived in a self-consistent way and therefore is independent of the cosmology assumed throughout the Letter. The error is dominated by the uncertainty in the weak-lensing signal due to the intrinsic ellipticities of the sources but also incorporates the uncertainties in the determination of the luminosity density and the group luminosities. The systematic uncertainty ($\sim 15\%$) introduced by the color difference between the group members and the field is not included in this error estimate.

Our results on $\Omega_m$ agree well with the result from Carlberg et al. (1997) and combined constraints from high-redshift supernovae (e.g., Perlmutter et al. 1999) and cosmic microwave background measurements (e.g., Efstathiou et al. 1999; De Bernardis et al. 2000).

Some caveats should be noted as well. Our measurement of the $M/L$ ratio is stable against changes in group membership but is correct only if the light traces the mass. If the dark matter is more extended than the light, our estimate for $\Omega_m$ should be interpreted as a lower limit. In addition, the correction for the color difference between group members and the field is somewhat uncertain.

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