EARLY-TYPE HALO MASSES FROM GALAXY-GALAXY LENSING

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We present measurements of the extended dark halo profiles of bright early-type galaxies at redshifts $0.1 < z < 0.9$ obtained via galaxy-galaxy lensing analysis of images taken at the CFHT using the UH8K CCD mosaic camera. Six 0.5×0.5 degree fields were observed for a total of 2 hours each in I and V, resulting in catalogs containing ~ 20000 galaxies per field. We used $V-I$ color and I magnitude to select bright early-type galaxies as the lens galaxies, yielding a sample of massive lenses with fairly well determined redshifts and absolute magnitudes $M \sim M_* \pm 1$. We paired these with faint galaxies lying at angular distances $20'' < \theta < 60''$, corresponding to physical radii of $26 < r < 77$ h^{-1} kpc ($z = 0.1$) and $105 < r < 315$ h^{-1} kpc ($z = 0.9$), and computed the mean tangential shear $\gamma_T(\theta)$ of the faint galaxies. The shear falls off with radius roughly as $\gamma_T \propto 1/\theta$ as expected for flat rotation curve halos. The shear values were weighted in proportion to the square root of the luminosity of the lens galaxy. Our results give a value for the average mean rotation velocity of an $L_\star$ galaxy halo at $r \sim 50 - 200$ h^{-1} kpc of $v_\star = 238^{+27}_{-30}$ km s^{-1} for a flat lambda ($\Omega_{\rm m0} = 0.3, \Omega_{\lambda 0} = 0.7$) cosmology ($v_\star = 269^{+34}_{-39}$ km s^{-1} for Einstein-de Sitter), and with little evidence for evolution with redshift. We find a mass-to-light ratio of $M/L_B \simeq 121 \pm 28h(r/100$ h^{-1} kpc) (for $L_\star$ galaxies) and these halos constitute $\Omega \simeq 0.04 \pm 0.01(r/100$ h^{-1} kpc) of closure density.

1 Introduction

Galaxy-galaxy lensing (the distortion of shapes of typically faint background galaxies seen near typically brighter foreground galaxies) offers a clean probe of the dark matter halo around galaxies. Here we shall restrict attention to smaller scales where it is reasonable to interpret the results as probing relatively stable and virialized halos of individual galaxies. Clusters of galaxies have traditionally been the primary target of weak lensing studies. Individual galaxy masses are far more difficult to measure due to their being less massive and hence yielding a smaller lensing signal relative to the noise. However, by stacking pairs of galaxies it is possible to beat down the noise and measure the total average halo mass (characterized here by rotation velocity).

2 THE DATA AND GALAXY SAMPLES

2.1 Data Acquisition and Reduction

The data were taken at the 3.6m CFHT telescope using the 8192×8192 pixel UH8K camera at prime focus. The field of view of this camera is $\sim 30'$ with pixelsize $0.207''$. Six pointings were acquired as part of an ongoing project whose principle aim is to investigate the cosmic shear pattern caused by gravitational lensing from the large-scale structure of the Universe. This article is based on the second in a series of papers describing results from that project and focuses on properties of massive galaxy halos at radii of $20'' < \theta < 60''$ or $50 - 200\ h^{-1}$ kpc (Wilson, Kaiser, Luppino & Cowie [2] [Paper II]). Kaiser, Wilson and Luppino [1] [Paper I] presented estimates of cosmic shear variance on $2' - 30'$ scales, and Wilson, Kaiser & Luppino [3] [Paper III] investigated the distribution of mass and light on galaxy group and cluster scales.

2.2 Lens and Source Galaxy Samples

Our analysis differed from other groups in that we used $V - I$ color to select a sample of bright early-type lens galaxies with reasonably well determined redshifts. As shown in § 2.2 of Paper II, with fluxes in 2 passbands and a judicious cut in red flux, one can reliably select bright early type galaxies and assign them approximate redshifts.

To investigate the evolution of halo mass with redshift, the lenses were firstly subdivided into three slices of width $dz = 0.3$ centered on redshifts 0.2, 0.5 and 0.8 (Table 1). Secondly, a wider slice of width $dz = 0.5$ centered on redshift 0.5 was analyzed.

3 GALAXY DARK MATTER HALO MASSES

3.1 Observed Tangential Shear Signal

For each lens, the mean tangential shear of faint 'source' galaxies averaged over lens-source pairs binned by angular separation is given by

$$\gamma_T(\theta) = -\frac{\sum\limits_{\rm pairs} W_l W_s M_{\alpha ij} \theta_i \theta_j \hat{\gamma}_\alpha / \theta^2}{\sum\limits_{\rm pairs} W_l W_s} \tag{1}$$

where $\hat{\gamma}_\alpha$, for $\alpha = 1, 2$, is the shear estimate for the source galaxy, θ is the projected angular separation of the lens and source, W_l, W_s are weights for the lens and source, and the two constant matrices M_1, M_2 are

$$M_{1lm} \equiv \begin{bmatrix} 1 & 0 \\ 0 & -1 \end{bmatrix}, \; M_{2lm} \equiv \begin{bmatrix} 0 & 1 \\ 1 & 0 \end{bmatrix}. \tag{2}$$

However, not all lens galaxies will contribute equally to the shear signal. To optimize the signal to noise, the shear contribution from each lens-source pair should be weighted by the mass of the lens. We assume here that the Faber-Jackson relation ($M \propto \sqrt{L}$) continues to larger radii and weight each lens accordingly. At each redshift, the resultant mean tangential shear signal falls off with radius roughly as $\gamma_T \propto 1/\theta$, as expected for flat rotation curve halos.

3.2 Inferred Rotation Velocity

For a flat rotation curve object the shear is given by

$$\gamma_T(\theta) = \pi(v/c)^2\langle\beta(z_l)\rangle/\theta \tag{3}$$

This equation allows one to convert between measured shear values and an equivalent rotation velocity (the dimensionless quantity $\langle\beta(z_l)\rangle$ is calculated, assuming a source galaxy redshift distribution based on spectroscopic data from Len Cowie's ongoing Hawaii Deep Fields Survey).

As a result of the magnitude cut discussed in § 2.2 the inferred rotation velocity is for some effective luminosity $L_{\rm eff}$ galaxy. The equivalent mean rotation velocity, $v_\star$, for an $L_\star$ lens galaxy is computed using $v_\star^2 = v^2/(L_{\rm eff}/L_\star)^{1/2}$.

Column 2 of Table 1 shows $v_\star$ at each redshift for a flat lambda ($\Omega_{\rm m0} = 0.3, \Omega_{\lambda 0} = 0.7$) cosmology. We obtained values of $v_\star = 255^{+36}_{-42}$ km s^{-1} for $z = 0.2 \pm 0.15$, 253^{+30}_{-35} for $z = 0.5 \pm 0.15$, and 228^{+53}_{-70} for $z = 0.8 \pm 0.15$. Thus, it appears that there is little evolution in the mass of dark matter halos with redshift. We then binned the signal for lens galaxies between $z = 0.25$ and $z = 0.75$ and concluded a rotation velocity of $v_\star = 238^{+27}_{-30}$ for $z = 0.5 \pm 0.25$.

For comparison, column 3 again shows $v_\star$ but for an Einstein-de Sitter cosmology. The inferred rotation velocity increases to $v_\star = 275^{+42}_{-50}$, 285^{+38}_{-44} and 278^{+65}_{-85} for the same three intervals. The increase in $v_\star$ in such a universe is primarily caused by smaller $\langle\beta\rangle$ values. We would conclude an overall rotation velocity of $v_\star = 269^{+34}_{-39}$ km s^{-1} for $z = 0.5 \pm 0.25$ in this cosmology.

3.3 M/L and Contribution to Ω_0

An $L_\star$ galaxy halo with $v_\star = 238$ contains $1.31 \times 10^{12}(r/100\ h^{-1}\ \mathrm{kpc})h^{-1}M_\odot$ within a radius of r (since $M(r) = v_\star^2 r/G$). An $L_\star$ galaxy has a luminosity of $1.09 \times 10^{10}h^{-2}L_\odot^B$, so the mass to light ratio is $M/L_B = 121 \pm$

Table 1. Rotation velocity, $v_\star$, of an $L_\star$ galaxy as a function of redshift and cosmology.

Lens Redshift	$\Omega_{m0}=0.3$ $\Omega_{\lambda 0}=0.7$	$\Omega_{m0}=1.0$ $\Omega_{\lambda 0}=0.0$
	$v_\star$	
0.2 ± 0.15	255^{+36}_{-42}	275^{+42}_{-50}
0.5 ± 0.15	253^{+30}_{-35}	285^{+38}_{-44}
0.8 ± 0.15	228^{+53}_{-70}	278^{+65}_{-85}
0.5 ± 0.25	238^{+27}_{-30}	269^{+34}_{-39}

$28h(r/100\ h^{-1}\ \mathrm{kpc})$, or about $M/L_B \sim 250h$ at the outermost points we can reliably measure.

The contribution of these early-type halos to the total density of the Universe (again assuming that $M \propto \sqrt{L}$, so $M(r) = M_\star(r)\sqrt{L/L_\star}$) is then $\rho = M_\star(r) \int dL\ \phi_E(L)\sqrt{L/L_\star} = M_\star(r)\phi_{E\star}\Gamma(\alpha + 3/2)$. This constitutes $\Omega = 0.04 \pm 0.01(r/100\ h^{-1}\ \mathrm{kpc})$ of closure density.

4 Conclusions

We used colors and magnitudes to cleanly select bright early-type galaxies. By measuring a weighted mean tangential shear which decreased roughly as $1/\theta$ we concluded that early-type galaxies have approximately flat rotation curve halos extending out to several hundred h^{-1} kpc. By assuming a M $\propto \sqrt{L}$ relationship we inferred a rotation velocity for an $L_\star$ galaxy of $v_\star = 238^{+27}_{-30}$ km s^{-1} for $\Omega_0 = 0.3, \lambda_0 = 0.7$ ($v_\star = 269^{+34}_{-39}$ km s^{-1} for Einstein-de Sitter). We sub-divided the galaxies and found little evidence for evolution with redshift. Finally, we determined a mass-to-light ratio for early-type halos of $M/L_B = 121 \pm 28h(r/100\ h^{-1}\ \mathrm{kpc})$ (for $L_\star$ galaxies) and found that these halos constitute $\Omega \simeq 0.04 \pm 0.01(r/100\ h^{-1}\ \mathrm{kpc})$ of closure density.

References

1. Kaiser, N., Wilson, G., & Luppino, G. 2001, paper I, cosmic shear paper, ApJL, in press, (astro-ph/0003338)
2. Wilson, G., Kaiser, N., Luppino, G., & Cowie, L. L. 2001, paper II, galaxy-galaxy paper, ApJ, in press, (astro-ph/0008504)
3. Wilson, G., Kaiser, N., & Luppino, G. 2001, paper III, mass and light paper, ApJ, in press, (astro-ph/0102396)