MAGNIFICATION AS A PROBE OF DARK MATTER HALOS AT HIGH REDSHIFTS

L. Van Waerbeke\textsuperscript{1}, H. Hildebrandt\textsuperscript{2}, J. Ford\textsuperscript{1}, and M. Milkeraitis\textsuperscript{1}

\textsuperscript{1} University of British Columbia, Vancouver, BC V6T 2C2, Canada
\textsuperscript{2} Leiden Observatory, Leiden University, Niels Bohrweg 2, 2333CA Leiden, The Netherlands

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ABSTRACT

We propose a new approach for measuring the mass profile of dark matter halos by stacking the lensing magnification of distant background galaxies behind groups and clusters of galaxies. The main advantage of lensing magnification is that, unlike lensing shear, it relies on accurate photometric redshifts only and not on galaxy shapes, thus enabling the study of the dark matter distribution with unresolved source galaxies. We present a feasibility study, using a real population of $z \geq 2.5$ Lyman break galaxies as source galaxies, and where, similar to galaxy–galaxy lensing, foreground lenses are stacked in order to increase the signal-to-noise ratio. We find that there is an interesting new observational window for gravitational lensing as a probe of dark matter halos at high redshift, which does not require a measurement of galaxy shapes.

Key words: dark matter – galaxies: halos – gravitational lensing: weak

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1. INTRODUCTION

Dark matter halos can be used as a probe of both cosmological parameters and structure formation. Their statistical distribution as a function of mass and redshift is a strong probe of dark energy (Allen et al. 2004), and a comparison of the halo mass versus galaxy distribution within individual halos contains important clues about the role of dark matter in the baryonic mass buildup (Hoekstra et al. 2005). Any study using dark matter halos, statistically or individually, requires an estimate of the mass profile or the halo mass. Unfortunately, there are still practical difficulties with these measurements, particularly for high-redshift halos and a certain mass range. High-redshift clusters, for instance, are dynamically young objects, making velocity dispersion and X-ray temperature based mass estimates questionable. There is therefore a vivid interest in finding a reliable mass calibration tool: one that is unbiased and, as much as possible, independent of the dynamical state of the halo. In fact, the mass calibration issue is central to high-redshift cluster searches, such as the SpARCS/SWIRE survey (Muzzin et al. 2009) and Sunyaev–Zel’dovich surveys.

The most prevalent technique for estimating halo masses uses gravitational lensing, and more specifically the tangential shear measured from the shapes of background galaxies. The variation of the strength of the shear from the halo center is an estimate of the lens mass profile. Although this technique is formally unbiased and provides a mass estimate independent of the halo dynamical state and shape, it suffers from practical limitations. Accurate galaxy shape measurement requires good pixel resolution and a small point-spread function (PSF), which, for high-redshift sources, is generally not the case. Current ground-based surveys show that there is a limitation from shear calibration (Semboloni et al. 2009) and a low number density of galaxies at high redshifts which makes measurements of accurate shapes of galaxies at redshifts higher than $z \simeq 1.5$ very difficult. This upper bound automatically sets a maximum redshift for the lenses one can probe: roughly half of the source redshift. One concludes that it is unlikely that shear observations can probe the dark matter distribution at redshifts higher than $z \simeq 1$. Note that, in principle, space-based data should perform better than ground-based data, although a quantitative analysis of space-based over ground-based performance at these redshifts remains to be done under realistic observing conditions.

The alternative mass estimate we propose is based on lensing magnification instead of shear. Magnification relies solely on photometry instead of shapes, thereby removing any practical requirement on how large a source galaxy must be; technically one could measure lensing magnification on unresolved galaxies, well beyond the redshift limits imposed on shape measurement by the PSF. Magnification behind dark matter halos was pioneered by Broadhurst et al. (1995) and Taylor et al. (1998), but at that time, optical surveys were too small and shallow, severely limiting photometric redshift estimates. Moreover, the net loss in the signal-to-noise ratio with magnification compared with shear made the former less interesting for practical applications (Schneider et al. 2000).

On the other hand, recent wide and deep surveys are well suited for measuring the magnification signal. The measurement of cosmic magnification on Lyman break galaxies (LBGs; Hildebrandt et al. 2009a) already demonstrates that the lensing magnification signal on $z \geq 2.5$ galaxies is detectable. This Letter explores this new opportunity for the study of cluster/group-sized dark matter halos at high redshift.

Section 2 introduces the magnification technique, Section 3 uses the population of high-redshift galaxies detected in the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS) to demonstrate how accurately halo masses and shapes can be measured. The last section discusses the prospects for this new technique in light of current and forthcoming surveys.

2. GALAXY–HALO LENSING MAGNIFICATION

The gravitational lensing of the source galaxies is described by the amplification matrix, $A$, which is a function of shear, $\gamma$, and convergence, $\kappa$ (see Munshi et al. 2008 for a review). The magnification, $\mu(\theta)$, along a line of sight quantifies the change in flux of a distant object affected by gravitational lensing:

$$
\mu(\theta) = \frac{1}{(1 - \kappa(\theta))^2 - \gamma(\theta)^2},
$$

(1)
where $\theta = (\theta_1, \theta_2)$ is the position angle on the sky measured from a chosen reference point. The apparent magnitude, $m$, of a lensed object is $m + 2.5 \log(\mu)$, making it brighter ($\mu > 1$) or fainter ($\mu < 1$) depending on the amount of projected mass present in the direction $\theta$, as indicated in Equation (1). The magnification effect is measured by counting, for lines of sight at different $\theta$, the number of galaxies that appear in a magnitude bin $[m, m + dm]$ for a survey of limiting magnitude $m_{\text{lim}} > m$. The number of unlensed galaxies in $[m, m + dm]$ is $N_0(m) dm$ and the number of lensed galaxies in the same magnitude range is $N(m, \theta) dm$. Narayan (1989) showed that

$$N(m, \theta) dm = \mu^{2.5r(m)} N_0(m) dm,$$

where $s(m)$ is the slope of the logarithmic galaxy number counts at magnitude $m$. The magnification, $\mu$, can be directly obtained from a measurement of the galaxy counts contrast, $\delta_N(\theta)$:

$$\delta_N(\theta) = \frac{N(m, \theta) - N_0(m)}{N_0(m)} = \mu^{2.5r(m)} - 1.$$

Behind a dark matter halo, galaxies are expected to be magnified because both $\kappa$ and $\gamma$ are positive. A halo could also be located in an under-dense region, leading to a dimming of the background galaxies locally; however, with the average lensing effect over the entire sky being zero, this environmental effect vanishes and only contributes to the noise. Therefore, we can safely focus on the mass profile of a halo itself, embedded in a uniform background.

The strategy adopted in this work is to evaluate the constraints on dark matter halos described by the universal Navarro–Frenk–White (NFW) profile, $\rho_{\text{NFW}}$ (Navarro et al. 1997). The mass density profile is described by the simple formula:

$$\rho_{\text{NFW}}(r) = \frac{\delta_0}{(r/r_s)(1 + r/r_s)^2},$$

where $\rho_{\text{crit}}$ is the critical density, $r_s$ is a characteristic scale radius, and $\delta_0$ is the density parameter:

$$\delta_0 = \frac{200}{3} \ln(1 + c_{200}) - c_{200}/(1 + c_{200}).$$

The concentration parameter, $c_{200}$, at the virial radius, $r_{200}$, is simply given by $r_{200} = r_s / c_{200}$. The parametric model in Equation (4) effectively depends on only two parameters: the concentration, $c_{200}$, and the halo mass, $M_{200}$, both within the virial radius and related by $M_{200} = 4/3 \pi r_{200}^3 c_{200}^3 \rho_{\text{crit}}$. They are related to the velocity dispersion $v_{200}$ via

$$M_{200} = \frac{V_{200}^3}{\sqrt{4/3 \pi}} r_{200}^3 \rho_{\text{crit}} G^3$$

$\kappa$ and $\gamma$ are given by the second-order derivatives of the gravitational lensing potential, $\psi(\theta)$:

$$\kappa(\theta) = \frac{1}{r}(\psi_{11} + \psi_{22})$$
$$\gamma r(\theta) = \frac{1}{r}(\psi_{11} - \psi_{22})$$
$$\gamma_\psi(\theta) = \psi_{12}.$$

$\psi(\theta)$ essentially measures the projected gravitational lensing potential along the line of sight at $\theta$:

$$\psi(\theta) = \frac{4G}{c^2} \frac{D_{\text{ds}} D_{\text{os}}}{D_{\text{ls}}} \int d^2\theta' \Sigma_{\text{NFW}}(\theta') \ln |\theta - \theta'|,$$

where $\Sigma_{\text{NFW}}(\theta)$ is the projected mass of the NFW profile, and $D_{\text{ds}}$, $D_{\text{os}}$, and $D_{\text{ls}}$ are the angular diameter distances between the source, observer, and the lens. Analytical expression of the lensing potential for the NFW profile can be found in Meneghetti et al. (2003). One could in principle constrain the parameters $c_{200}$ and $v_{200}$ for each halo where the magnification is measured. In practice however, the signal-to-noise ratio per halo is too low and it is necessary to stack the signal from many foreground halos, a strategy similar to galaxy–galaxy lensing. This technique is described in detail in the following section.

3. HALO CHARACTERIZATION

Galaxy–galaxy lensing was initially developed as a probe of galactic-size dark matter halos, making use of the tangential shear around foreground galaxies (Brainerd et al. 1996; Hudson et al. 1998). Similar to the shear, the signal-to-noise ratio of the lensing magnification is low for most lenses, making the stacking of foreground lenses necessary in order to lower the noise of the average magnification as a function of distance from the lens centers. The stacking should rely on a proxy to group foreground lenses with similar mass (e.g., stellar mass). It can be applied to clusters, groups of galaxies, and individual galaxies.\[3\]

Constraints on the mass and concentration parameters, $M_{200}$ and $c_{200}$, of the average magnification profile are obtained from the likelihood:

$$\mathcal{L} \propto \exp \left[ (\delta_N(\theta) - \delta_N(\theta))^T C_{\delta_N \delta_N}^{-1} (\delta_N(\theta) - \delta_N(\theta)) \right],$$

where $\delta_N(\theta)$ is the galaxy count profile from Equation (3), circularly averaged for our purpose, and $\delta_N(\theta)$ is the galaxy count profile model. The covariance matrix, $C_{\delta_N \delta_N}$, is estimated as described below.

In Taylor et al. (1998), it was shown that for a given population of source galaxies, the net signal-to-noise loss for magnification is larger by roughly a factor of five compared with shear measurements. Ignoring the sampling variance and the effect of large-scale structures, there are two sources of noise for magnification: (1) the statistical, Poisson, noise due to discrete sampling of the source galaxies and (2) the clustering of the source galaxies leading to variations of number counts coherent over large angular distances. In order to test the feasibility of our approach under realistic observing conditions, the sampling and clustering sources of noise in $C_{\delta_N \delta_N}$ are measured from a real population of source galaxies. This population of source galaxies is the high redshift, $z \geq 2.5$, LBGs selected from the CFHTLS-Wide data set by the method described in Hildebrandt et al. (2009b); it contains $\sim 130,000$ $u$- and $g$-dropouts in the magnitude range $23.5 < i < 24.5$ selected from 156 deg$^2$ of the CFHTLS-Wide data set.

The slope of the number counts is such that $2.5s(m) - 1 = 1.4$, as measured on the CFHTLS-Deep data with a limiting magnitude approximately 2 magnitudes deeper than the CFHTLS-Wide (Hildebrandt et al. 2009a).

The estimate of the noise covariance matrix, $C_{\delta_N \delta_N}$, proceeds as follows: approximately 200 random positions are chosen to represent foreground lenses in each square degree of the 156 deg$^2$. Their angular positions are then cross-correlated to the LBGs for each square degree. The average cross-correlation is zero, and the dispersion around zero corresponds to the $C_{\delta_N \delta_N}$ expected for 200 foreground lenses. The amplitude of the noise

\[3\] Note that the most massive clusters generate a strong magnification signal where stacking is not necessary (Taylor et al. 1998).
The lensing signal strength varies only by a few percents. When on the signal because for source redshifts between 2.5 and 3.2, \( \sigma \sim 8 \) from the stacking of 6000 halos with \( V_{200} = 590 \text{ km s}^{-1} \) and \( c_{200} = 4.5 \) at redshift \( z = 1 \); on the right, the constraints from the stacking of 6000 halos with \( V_{200} = 650 \text{ km s}^{-1} \) and \( c_{200} = 5.5 \) are shown. The open triangle in the top panels shows the fiducial values. Bottom panels: left and right show the halo mass derived from the constraints \( (V_{200}, c) \) from the top left and top right panels, respectively.

marginalized over \( c_{200} \) with a flat prior, the uncertainty on the velocity dispersion is

\[
\frac{\Delta V_{200}}{V_{200}} = 0.02 \times \left( \frac{6000}{N} \right)^{0.5}.
\]

\[
\frac{\Delta V_{200}}{V_{200}} = 0.09 \times \left( \frac{135}{N} \right)^{0.5},
\]

where \( N \) is the number of halos of the specified velocity dispersion. Note that the scaling with the halo redshift is approximately, but not exactly, proportional to the angular diameter distance of the halo. However, the scaling with velocity dispersion is much more complicated because the projected mass density of an NFW profile does not simply scale like some power of \( V_{200} \). Also, it is worth mentioning that a simple profile model such as the singular isothermal sphere would lead to simple scaling relations and tighter constraints on \( V_{200} \), but these models are not recommended as they provide poor fits to realistic profiles (Wright & Brainerd 2009). Equation (9) shows that magnification of high-redshift galaxies can in principle probe dark halos well beyond the domain of applicability of the shear method with a good precision. The velocity dispersion shown in Figure 2 and Equation (9) translates into a mass uncertainty of 6% and 27%, respectively, for the low and high mass bins. For a full sky survey (200 times the area used in this work), these numbers become 0.4% and 2%, respectively. Precision measurement of dark halo mass profiles is therefore possible with future full sky lensing surveys.

The practical implementation of this technique requires a mass proxy, a measurement of the cluster redshift, and an estimate of the cluster/group center which coincides with the halo peak. The mass proxy is not specified at this stage, but it has to rely on external estimates such as the stellar mass, X-ray temperature/luminosity, cluster richness, or a combination of...
these. Mass proxies based on optical data can reach a precision of 10%–15% (Sheldon et al. 2009) up to 30% (Hilbert & White 2010) for the mass range considered in this work. This suggests that the mass calibration of halos can be further improved with lensing magnification, particularly in a redshift regime where shear measurements are difficult or impossible. A centroid misalignment would cause an additional spread in the mass profile, as shown in Mandelbaum et al. (2006) and Sheldon et al. (2004). A complete study of the impact of center misidentification is beyond the scope of this Letter, but note that for the two extremes of halo sizes, individual galaxies and massive clusters, the centroiding issue is nearly nonexistent.

An interesting aspect of magnification is the possibility of simultaneously measuring the lensing signal and the dust absorption by the lenses. Dust absorption by the lens induces a small chromatic angular scale-dependent cross-correlation between the background population and the lens (unlike lensing magnification which is achromatic). Ménard et al. (2010a, 2010b) showed that the dust absorption is a very negligible source of magnitude noise and that its contamination is only a few percent of the lensing signal. Only small angular scales are affected, where baryonic matter is concentrated and dust absorption is highest. The practical implementation of how dust absorption can be fully integrated into a magnification-based mass measurement is left for a forthcoming study.

4. CONCLUSION

We have shown that weak lensing magnification of $z \geq 2.5$ LBGs can reach a relatively high signal-to-noise ratio to enable the study of dark matter halos at high redshift, $z \geq 1$, where traditional shear measurements would fail because the source galaxies are unresolved. The performance of our method was quantified using a real LBGs distribution, from the CFHTLS-Wide data, as source galaxies. The steep number counts and the high redshift of the sources considerably help alleviating the low signal-to-noise found in previous magnification studies. The approach is similar to galaxy–galaxy lensing, where lenses are stacked according to a mass proxy, although no attempt was made to discuss which mass proxy should be used since it entirely depends on the data wavelength coverage.

The magnification technique as a probe of dark matter halos can be generalized to a larger sample of background galaxies over a wider magnitude and redshift range. It is interesting to note that, in principle, the halo shape can also be measured, which can be used to discriminate between various Cold Dark Matter models. The main limitations of our method lie in our ability to separate lensing from dust extinction in large surveys, which is dependent on the number and wavelength coverage of filters, and in identifying reliable mass proxies and determining the halo centers; although the latter two equally affect shear-based mass profile measurements, it is not specific to magnification. A quantitative estimate of the practical limitations for future lensing surveys such as LSST and JDEM would be particularly interesting, but is beyond the scope of this work.

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REFERENCES

Allen, S. W., et al. 2004, MNRAS, 353, 457
Brainerd, T. G., Blandford, R. D., & Smail, I. 1996, ApJ, 466, 623
Broadhurst, T., Taylor, A., & Peacock, J. 1995, ApJ, 438, 49
De Lucia, G., & Blaizot, J. 2007, MNRAS, 375, 2
Hilbert, S., & White, S. D. M. 2010, MNRAS, 404, 486
Hildebrandt, H., van Waerbeke, L., & Erben, T. 2009a, A&A, 507, 683
Hildebrandt, H., Pielorz, J., Erben, T., van Waerbeke, L., Simon, P., & Capak, P. 2009b, A&A, 498, 725
Hoekstra, H., Hsieh, B. C., Yee, H. K. C., Lin, H., & Gladders, M. D. 2005, ApJ, 635, 73
Hudson, M. J., Gwyn, S., Dahle, H., & Kaiser, N. 1998, ApJ, 503, 531
Kitchbichler, M. G., & White, S. D. M. 2007, MNRAS, 376, 2
Larson, D., et al. 2010, arXiv:1001.4635
Mandelbaum, R., Seljak, U., Cool, R. J., Blanton, M., Hirata, C. M., & Brinkmann, J. 2006, MNRAS, 372, 758
Ménard, B., Kilbinger, M., & Scranton, R. 2010a, MNRAS, 406, 1815
Ménard, B., Scranton, R., Fukugita, M., & Richards, G. 2010b, MNRAS, 405, 1025
Meneghetti, M., Bartelmann, M., & Moscardini, L. 2003, MNRAS, 340, 105
Milkeraitis, M., Van Waerbeke, L., Heymans, C., Hildebrandt, H., Dietrich, J. P., & Erben, T. 2010, MNRAS, 406, 673
Munshi, D., Valageas, P., van Waerbeke, L., & Heavens, A. 2008, Phys. Rep., 462, 67
Muzzin, A., et al. 2009, ApJ, 698, 1934
Narayan, R. 1989, ApJ, 339, L53
Navarro, J. F., Frenk, C. S., & White, S. D. M. 1997, ApJ, 490, 493
Schneider, P., King, L., & Erben, T. 2000, A&A, 353, 41
Semlodi, E., Tereno, I., van Waerbeke, L., & Heymans, C. 2009, MNRAS, 397, 608
Sheldon, E., et al. 2004, AJ, 127, 2544
Sheldon, E., & White, S. D. M. 2008, A&A, 486, 501
Taylor, A. N., Dye, S., Broadhurst, T. J., Benitez, N., & van Kampen, E. 1998, ApJ, 510, 539
Wright, C. O., & Brainerd, T. 2000, ApJ, 534, 34