TWO-DIMENSIONAL GALAXY-GALAXY LENSING: A DIRECT MEASURE OF THE FLATTENING AND ALIGNMENT OF LIGHT AND MASS IN GALAXIES

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ABSTRACT

We propose a new technique to directly measure the shapes of dark matter halos of galaxies using weak gravitational lensing. Extending the standard galaxy-galaxy lensing method, we show that the shape parameters of the mass distribution of foreground galaxies can be measured from the two-dimensional shear field derived from background galaxies. This enables the comparison of the ellipticity of the mass distribution with that of the light in galaxies, as well as an estimate of the degree of alignment between the stellar component and dark matter. We choose the specific case of an elliptical, isothermal profile and estimate the feasibility and significance of the detection of this signal. The prospects for applying this technique are excellent with large on-going surveys like the Sloan Digital Sky Survey. The expected signal is smaller, but comparable in significance to that of the mass in standard galaxy-galaxy lensing analyses. Since shapes of halos depend on the degree of dissipation and the transfer of angular momentum during galaxy assembly, constraints obtained from our analysis will provide an important input to models of galaxy formation.

Subject headings: gravitational lensing, galaxies: fundamental parameters, halos, methods: numerical

1. INTRODUCTION

Current observations require the existence of dark matter halos for galaxies. However, fundamental parameters such as their total mass and spatial extent are not well constrained. The mass distribution in galaxies is primarily probed via dynamical tracers of the galactic potential on various scales: stars in the inner regions, HI gas in regions outside the optical radius, and orbital motions of bound satellites in the outer-most regions (e.g. Zaritsky & White 1994). However, the implications of these studies for the precise nature and composition of halos remains unclear. Probes of halo structure at radii devoid of any luminous tracers are therefore needed – weak gravitational lensing offers precisely that.

Galaxy-galaxy lensing, the preferential tangential alignment of the images of background galaxies around bright foreground ones, is statistically detected by stacking the contribution from many individual galaxies. It can be used to place constraints on halo masses and sizes. The technique, is, by construction, an effective measure of the mass at large radius, since the detected polarization signal is well outside the light distribution of the lens. The first observational attempt to look for weak tangential alignment of faint galaxies around bright galaxies was made by Tyson et al. (1984). The inability to measure galaxy shapes with the required accuracy from photographic data precluded detection. Recent studies have, however, been more successful, and detection of a signal at the 95% confidence level was first reported by Brainerd, Blandford & Smail (1996) using deep ground-based CCD data. Several subsequent studies using Hubble Space Telescope images as well as ground-based data (Griffiths et al. 1996; Dell’Antonio & Tyson 1996; Hudson et al. 1998; Casertano 1999; Ebbels et al. 2000; Fischer et al. 1999 [Sloan Digital Sky Survey (SDSS hereafter) commissioning data]) report unambiguous detection of a galaxy–galaxy lensing signal in field survey images.

In the method proposed in this letter, additional information that is available but not exploited in current galaxy-galaxy lensing studies is utilized, namely, the light distribution of galaxies selected to be foreground lenses. The general results derived by Schneider & Bartelmann (1997) are used to relate the shear field to the mass multipoles. We show that the shapes and orientations of the foreground galaxies (probes of the light) can be compared statistically to that of the shear field (probe of the mass), thus providing a direct method to compare the ellipticity of the light to that of the mass as well any potential misalignments between them reliably.

These parameters offer an important clue to the galaxy formation process, since they provide a quantitative measure of the importance of dissipation in the assembly of galaxies. Any variation of the flattening of the total mass (predominantly the dark matter component) with radius is a probe of the efficiency of angular momentum transfer to the dark halo and might provide insights into the structure and composition of galaxy halos. With regard to the relative orientation of the light and mass in galaxies, the two components are likely to be aligned on average and any misalignments might occur in the event of extreme circumstances, for instance, as an aftermath of a violent merger.

The outline of the paper is as follows: in \S 2, the current status of modeling in galaxy-galaxy lensing studies is reviewed. In \S 3 the formalism used to extract the shape of the mass distribution is presented, with the application to an elliptical isothermal mass model in \S 4. The feasibility of detection of the flattening of the mass is examined in \S 5, and a measure of the alignment of mass and light is discussed in \S 6. We conclude in \S 7 with a discussion of the importance of studying shapes of dark halos for un-
understanding key issues in the formation and structure of galaxies and the relation between the luminous and dark component in galaxies.

2. CURRENT STATUS OF GALAXY-GALAXY LENSING

The galaxy-galaxy signal is measured ideally from a deep image by selecting a population of brighter (assumed to be foreground, since typically the redshift is unknown) galaxies as lenses and measuring the induced shape distortion in the fainter (background) galaxies. The shear signal obtained from direct averaging in radial bins around the bright foreground galaxies is then stacked to obtain the radial profile of the shear $\gamma$ as a function of distance from the lens (see Fig. 1). In order to extract quantitative measures of the galaxy mass distribution, a parametric model, typically, the singular isothermal sphere is adopted and the observationally measured shear signal is compared to that expected from the assumed theoretical galaxy mass model. Such a comparison seems to provide reasonable constraints expected from the assumed theoretical galaxy mass model.

Schneider & Bartelmann (1997) have shown that the multipole moments of $\kappa(x)$ can be derived from the observed quantity, namely the shear $\gamma(x)$ field. In particular, the quadrupole moments (Eq. [3]) can be expressed as

$$Q = \int d^2x \ e^{2i\varphi} [g_t(x) \gamma_t(x) + i \ g_x(x) \gamma_x(x)],$$

where the rotated shear components $\gamma_t$ and $\gamma_x$ correspond, respectively, to a tangential and curl-type shear pattern about the center of mass of the lens (see Rhodes, Refregier & Groth 2000 for an illustration). They are related to the unrotated components by,

$$\gamma_r = -[\cos(2\varphi)\gamma_1 + \sin(2\varphi)\gamma_2],$$

$$\gamma_x = [-\sin(2\varphi)\gamma_1 + \cos(2\varphi)\gamma_2]$$

where $\varphi$ is the polar angle from the x-axis. The associated aperture functions $g_t(x)$ and $g_x(x)$ are given by

$$g_t(x) = 2V_2(x) - x^2 w(x), \quad g_x(x) = -2V_2(x),$$

where $V_n(x) = x^{-2} \int_0^x \ dx' x'^{n+1} w(x')$.

Similarly, the trace part $T$ and the mass $M$ can also be written as

$$T = \int d^2x g_t(x) \gamma_t(x), \quad M = \int d^2x h_t(x) \gamma_t(x),$$

where $h_t(x) = 2V_0(x) - w(x)$.

4. APPLICATION TO THE ELLIPTICAL ISOThERMAL MODEL

We consider an isothermal model with concentric elliptical equipotentials (Natarajan & Kneib 1996). The projected potential for this model is $\psi = \alpha r$, where $\alpha$ is the Einstein radius and $r$ is a generalized elliptical radius. If the x-axis is aligned with the major axis of the potential, the generalized radius is given by $r^2 = \frac{x^2}{1+\epsilon^2} + \frac{z^2}{1-\epsilon^2}$, where $\epsilon$ is the ellipticity of the equipotentials. The Einstein radius is related to the velocity dispersion of the galaxy $\sigma_v$ by $\alpha = 4\pi(\frac{\sigma_v}{c})^2(\frac{D_{ls}}{D_{ds}})$, and is of the order of 1″ for galaxies.

For a weakly elliptical model ($\epsilon \ll 1$), the potential has the form

$$\psi(x) \simeq \alpha x [1 - \frac{\epsilon}{2} \cos 2(\varphi - \varphi_0)]$$

where $\varphi_0$ is the position angle of the potential, and reduces to that of a singular isothermal sphere in the circular limit ($\epsilon = 0$). We restrict our analysis to the weak regime, which is the appropriate approximation for galaxy-galaxy lensing, such as that planned for the SDSS. In this case, the ellipticity of the mass $\epsilon_\kappa$ is then simply

$$\epsilon_\kappa = \frac{Q}{T} = \frac{(a_\kappa^2 - b_\kappa^2)}{(a_\kappa^2 + b_\kappa^2)} e^{i\epsilon_\kappa},$$

where $a_\kappa$ and $b_\kappa$ are, respectively, the major and minor axes of the mass distribution, and $\varphi_\kappa$ is its position angle relative to the positive x-axis.
MEASURING THE FLATTENING OF THE MASS DISTRIBUTION

We now show how these results can be used to measure the flattening of the mass distribution. As in ordinary galaxy-galaxy lensing, the galaxy catalog is first separated into a foreground and a background subsample, using magnitude, colors or photometric redshifts. The ellipticity of the galaxies in both subsamples is then measured in the usual fashion as is done for the sheared faint background galaxies by taking second moments of the light distribution. The ellipticities of the foreground sample yields the ellipticity of the light \( \epsilon_l \) associated with each lens. While \( \epsilon_l \) is ignored in ordinary galaxy-galaxy lensing (Fig. 1, top panel), we instead align the foreground galaxies along their major axes before stacking (Fig. 1, bottom panel). We then measure the average ellipticity of the mass \( \epsilon_K \) as described above, by replacing the integrals in equations (5) and (8) by sums over the sheared background galaxies. This yields a measurement of the component of the average ellipticity of the mass, \( \epsilon_{K||} \) parallel to the that of the light, i.e.

\[ \epsilon_{K||} = \text{Re}(\epsilon_l^* \epsilon_l) \]

where the ellipticities are taken to be complex numbers with \( \epsilon = \epsilon_1 + i \epsilon_2 \), * denotes complex conjugation, and \( \epsilon_l = \epsilon_l/|\epsilon_l| \) is the unit ellipticity of the light.

We now compute the uncertainty in measuring \( \epsilon_{K||} \), by taking the square of the mean of the discrete estimators for \( M, T \) and \( Q_l = \text{Re}(Q) \), and converting back into integrals (Schneider & Bartelmann 1997). In the absence of lensing, we find

\[ \sigma^2[M] = \frac{\sigma^2}{n_b n_f A} \int d^2 x \ h^2(x), \]

\[ \sigma^2[Q] = \frac{\sigma^2}{n_b n_f A} \int d^2 x \ [g^2(x) + g^2(x)], \]

where \( \sigma^2 = \langle \epsilon^2 \rangle = \langle \epsilon^2 \rangle \) is the variance of the intrinsic ellipticity distribution of galaxies (\( \sim 0.3^2 \)), \( n_b \) and \( n_f \) are respectively the number density of background and foreground galaxies, and \( A \) is the area covered by the survey.

For the elliptical isothermal model with the gaussian weight function, we can evaluate these integrals and find,

\[ \sigma^2[M] = \frac{\sigma^2}{4\pi n_b n_f A/2^2}, \]

\[ \sigma^2[Q] = \frac{3\sigma^2}{4\pi n_b n_f A} \]

By propagating these errors in the definition of the ellipticity of the mass (Eq. [4]), we can compute the signal to noise ratio \( (S/N)_{\epsilon_K} = \epsilon_{K||}/\sigma[\epsilon_{K||}] \) for measuring \( \epsilon_{K||} \), and find, to first order in \( \epsilon \),

\[ \left( \frac{S}{N} \right)_{\epsilon_K} \simeq 4.6 \left( \frac{\epsilon_{K||}}{0.3} \right) \left( \frac{\alpha}{0.5^2} \right) \left( \frac{n_b}{1.5\text{arcmin}^{-2}} \right) \left( \frac{n_f}{0.035\text{arcmin}^{-2}} \right) \left( \frac{T}{0.3} \right) \left( \frac{\sigma_{\epsilon}}{\text{arcsec}} \right) \left( \frac{A}{1000\text{deg}^2} \right)^{1/2}. \]

In these scalings, we have used the survey specifications (ellipticity dispersion, number of foreground lenses and number of background galaxies, and approximate observed Einstein radius) quoted for the SDSS commissioning run provided in a recent preprint by Fischer et al. (1999), with a modestly expanded area (1000 deg\(^2\)) from the current area of 225 deg\(^2\). Note that these numbers are conservative since the commissioning data suffered from very poor seeing. The shape parameters of the mass will therefore be easily detectable with SDSS in the near future. For the total SDSS area of 10\(^4\) deg\(^2\), the significance rises to 15\(\sigma\). This in fact implies that potentially, even the radial dependence of the flattening can be studied by considering annuli-shaped weight functions (for instance, the difference of two gaussians). Moreover, we will be able to study the degree of flattening as a function the morphological type of galaxies.

It is interesting to compare the \( (S/N)_{\epsilon_K} \) expected for measuring \( \epsilon_{K||} \) estimated above with that of the usual galaxy-galaxy lensing \( (S/N)_M = M/\sigma[M] \) which measures the mass enclosed within an aperture. For the model considered here, we find the following relation,

\[ \left( \frac{S}{N} \right)_{\epsilon_K} = 0.17 \left( \frac{\epsilon_{K||}}{0.3} \right) \left( \frac{S}{N} \right)_M. \]

Therefore, shape parameters can be measured with a significance which is smaller but comparable to that of the enclosed mass. Note that for the current SDSS survey area of \( A = 225 \text{ deg}^2 \), we find \( (S/N)_M \simeq 13 \) which agrees roughly with the significance of the reported Fischer et al. (1999) results, when averaged over all radial bins.
6. MEASURING THE ALIGNMENT OF LIGHT AND MASS

Given the good prospects expected from the above results, one can be more ambitious and try to characterize the alignment of mass and light in more details. We can make use of the amplitude of the light ellipticity $\epsilon_l$, which we have not used until now. This can be done by grouping the lens galaxies into several $\epsilon_l$-bins, and computing $\epsilon_{\ell}^*$ separately for each bin. A more direct approach would be to consider the correlation function of the ellipticities of the mass and light, defined as

$$C_{\ell} = \text{Re}(\epsilon_{\ell}^* \epsilon_l).$$

This correlation function could also be computed for several annuli, and, would therefore, yield a direct measure of the alignment of mass and light.

7. DISCUSSION

The shapes of dark matter halos (see Sackett (1995) for a more comprehensive review) have been probed via many techniques and the consensus from these studies is that the precise shapes offer important clues to both the galaxy formation process and perhaps, even to the nature of dark matter.

Cosmological N-body simulations suggest that dark matter halos are triaxial and that dissipation plays an important role in determining their shape. High resolution simulations find that the effect of dissipation (Katz & Gunn 1991; Dubinski 1994) is to transform an initially triaxial halo from prolate-triaxial to oblate-triaxial, while preserving the degree of flattening, yielding on average rounder and more oblate dark halos than those in dissipationless simulations.

Comparing the shape of the mass profile inferred from X-ray data for a sample of ellipticals with that of the light, Buote & Canizares (1994; 1998) find that the dark matter is at least as flattened as the light and is definitely more extended. The origin of the X-ray isophotal twist in the case of NGC720, they argue, reflects an intrinsic misalignment of the stars with the dark matter. Keeton, Kochanek & Seljak (1997) incorporate the shape of the light distribution as a constraint in modeling individual lenses (that produce multiple images of background quasars) and find that an additional component of shear is required to match the observations. They speculate that this component could arise from a misalignment between the luminous galaxy and its dark matter halo. Our proposed technique will provide highly reliable measurements of the shape and orientation of light and mass in galaxies, thereby aiding in the understanding of the coupling of baryons with the dark matter.

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REFERENCES

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Fig. 1.— Schematic of standard galaxy-galaxy lensing (top) and of the proposed technique (bottom).