MAGNIFICENT MAGNIFICATION: EXPLOITING THE OTHER HALF OF THE LENSING SIGNAL

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Received 2013 August 16; accepted 2013 November 6; published 2013 December 16

ABSTRACT

We describe a new method for measuring galaxy magnification due to weak gravitational lensing. Our method makes use of a tight scaling relation between galaxy properties that are modified by gravitational lensing, such as apparent size, and other properties that are not, such as surface brightness. In particular, we use a version of the well-known fundamental plane relation for early-type galaxies. This modified “photometric fundamental plane” uses only photometric galaxy properties, eliminating the need for spectroscopic data. We present the first detection of magnification using this method by applying it to photometric catalogs from the Sloan Digital Sky Survey. This analysis shows that the derived magnification signal is within a factor of three of that available from conventional methods using gravitational shear. We suppress the dominant sources of systematic error and discuss modest improvements that may further enhance the lensing signal-to-noise available with this method. Moreover, some of the dominant sources of systematic error are substantially different from those of shear-based techniques. With this new technique, magnification becomes a useful measurement tool for the coming era of large ground-based surveys intending to measure gravitational lensing.

Key words: cosmology: observations – gravitational lensing: weak – methods: observational

Online-only material: color figures

1. INTRODUCTION

Weak gravitational lensing is the most direct method for characterizing the distribution of dark matter over a wide range of scales. The astronomical community is investing heavily in current and future imaging surveys, designed at least in part around weak lensing science, e.g., the Dark Energy Survey, the Kilo-Degree Survey, the Hyper Suprime Cam for the Subaru Telescope, the Large Synoptic Survey Telescope, and the Euclid space mission.

Lensing measurements have played a significant role in astrophysics in the last two decades over a range of scales and physical regimes (e.g., Sheldon et al. 2004; Hoekstra et al. 2004; Seljak et al. 2005; Mandelbaum et al. 2006b; Heymans et al. 2013; Huff et al. 2011a). These measurements are currently made almost exclusively by studying spatially correlated distortions in the ellipticities of background galaxies due to the shear component of gravitational lensing.

Lensing also magnifies background sources, but the intrinsic variance in the distribution of galaxy sizes and luminosities—those properties perturbed by magnification—is much larger than that of galaxy shapes. Historically, magnification measurements making use of number counts alone have necessarily had to average over much larger galaxy samples to obtain signal-to-noise ratio (S/N) equivalent to shear measurements (cf. Hildebrandt et al. 2011; Ménard et al. 2010; Scranton et al. 2005). Recently, some authors have achieved S/Ns only a factor of a few less than shear measurements by exploiting the joint distribution of sizes and magnitudes (Schmidt et al. 2012), or using background sources with atypical luminosity functions (Ménard et al. 2010; Morrison et al. 2012; Umetu et al. 2011).

In this Letter, we make use of a photometry-only version of the well-known fundamental plane (FP) for early-type galaxies (Djorgovski & Davis 1987; Dressler et al. 1987) to substantially narrow the scatter in size for a set of source galaxies. This permits an additional reduction in the noise in the magnification signal that is independent of that explored in other techniques.

A thorough description of our implementation will be presented in a forthcoming paper (hereafter Paper II). Here, we describe the core concepts, present a detailed outline of the method, and demonstrate its effectiveness. Throughout, we assume a ΛCDM cosmology with $\Omega_M = 0.274$, $\Omega_\Lambda = 0.726$, and $H_0 = 100$ km s$^{-1}$ Mpc$^{-1}$.

2. THE PHOTOMETRIC FUNDAMENTAL PLANE

The FP is an observed correlation between galaxy effective radius ($R_{\text{eff}}$), which is magnified by gravitational lensing, and two galaxy properties which are not: galaxy surface brightness ($\mu$) and the stellar velocity dispersion ($\sigma$). The intrinsic scatter in the FP is ~0.08 dex (Jorgensen et al. 1996; Bernardi et al. 2003), or 20%. Thus the FP makes it possible to predict the intrinsic value of $R_{\text{eff}}$ from observations of $\mu$ and $\sigma$, which can then be compared with the observed values of $R_{\text{eff}}$ to measure magnification.

The FP was in fact proposed as a tool for this purpose by Bertin & Lombardi (2006), but to our knowledge has never been used as such. Placing galaxies on the FP requires $\sigma$ measurements. Even with the tight scatter in the FP, a statistically viable measurement would require high-resolution spectroscopic measurements for tens of millions of galaxies.

Identifying a photometric analog to the FP (a photoFP) with comparable scatter would solve this problem. Such a relation has already been identified by Graham (2002), where the Sérsic index replaces $\sigma$. This works in part because concentration and velocity dispersion are both strongly correlated with galaxy mass, and in part because at fixed mass, galaxies with more concentrated mass profiles have higher velocity dispersions.

For this work, we have identified a similar scaling relation in the Sloan Digital Sky Survey (SDSS) imaging data, which is described entirely by quantities measured in the SDSS photometry pipeline. The SDSS galaxies can be shown to lie on a two-dimensional (2D) plane within the three-dimensional parameter space of half-light radius ($R_c$), central surface brightness...
(μ), and light-profile concentration (C), with scatter of 0.15 dex in the $R_e$ direction (see the next section). This scaling relation is similar in spirit to the one in Graham (2002), but is derived independently from the SDSS data.

2.1. Background Sources

To define a photoFP for this work, we use a sample of galaxies drawn from the SDSS-III Eighth Data Release (DR8; Aihara et al. 2011). We limit the sample to resolved sources that meet basic quality cuts (e.g., are not saturated). For these, we estimate photometric redshifts (photo-$z$’s) based on the SDSS ugri$z$ photometry using the public code ZEBRA (Feldmann et al. 2006) run with the default templates, allowing interpolation between the standard templates without template optimization. We estimate the uncertainties in our photometric redshifts by cross-matching the source population to galaxies with secure redshifts in the PRIMUS and VVDS surveys; the typical rms photo-$z$ error for our sources is $σ_z = 0.06$. The effect of these errors on $R_{\text{eff}}$ is roughly equal to the errors in the measured effective radii. To select a sample of early-type background galaxies, we exclude the $\sim 2/3$ of the galaxies with best-fitting templates inconsistent with that of a passive stellar population. The sample selection for background sources will be described in greater detail in Paper II.

The SDSS photometric pipeline does not measure Sérsic index. Here, we substitute for it the SDSS Petrosian concentration

$$C = R_{90}/R_{50},$$

defined as the ratio of the radii containing 90% and 50% of the Petrosian flux (e.g., Shimasaku et al. 2001). Reported quantities are measured in the $r$ and $i$ bands.

We fit a photoFP of the form

$$\log R_{\text{eff}} = αμ + β log C + γ,$$

where $R_{\text{eff}}$ is the half-light radius of the best-fit de Vaucouleurs light profile converted into physical units using the ZEBRA sources that should lie on the photoFP, we exclude the effective radii. To select a sample of early-type background galaxies, we exclude the $\sim 2/3$ of the galaxies with best-fitting templates inconsistent with that of a passive stellar population. The sample selection for background sources will be described in greater detail in Paper II.

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where $R_{\text{eff}}$ is the half-light radius of the best-fit de Vaucouleurs light profile converted into physical units using the ZEBRA photo-$z$, $μ$ is the mean de Vaucouleurs surface brightness within $R_{\text{eff}}$, and $α$, $β$, and $γ$ are free parameters. To avoid errors resulting from a redshift-dependent selection function, evolution in the photoFP; and morphological $K$-corrections, we divide our galaxy sample into redshift bins with width $Δz = 0.01$ and fit the photoFP separately in each bin. The best-fit coefficients are chosen to minimize the dispersion in effective radius at fixed $μ$ and $log C$, taking into account only the errors in $R_{\text{eff}}$. Correlated measurement errors and an impure galaxy selection will increase the scatter in the $κ$ estimates, but without a spatially varying component they cannot bias the measurement.

Figure 1 shows an edge-on view of the photoFP for our source sample. The dispersion around the photoFP in the direction of effective radius is 0.15 dex, or 35%.

2.2. Magnification using the PhotoFP

A line-of-sight matter overdensity at lens redshift $z_l$ will produce an image convergence $κ$ of amplitude:

$$κ = \frac{Σ(d_Ω)}{Σ_{\text{crit}}},$$

where $Σ_{\text{crit}}$ is the characteristic surface density of matter required for lensing. $Σ_{\text{crit}}$ is defined by the lensing geometry, such that

$$Σ_{\text{crit}} = \frac{c^2}{4πG} \frac{d_s}{d_l d_{ls}} (1 + z_l)^2,$$

where $d_s$, $d_l$, and $d_{ls}$ are the angular diameter distances from the observer to the lens, from the observer to the source, and from the lens to the source, respectively. The factor of $(1 + z_l)^2$ arises from our use of comoving coordinates.

In the weak lensing limit the light profile is rescaled by a factor of $(1 + κ)$. The radius and luminosity increase, but the concentration is unchanged. Given the scaling relation described above, this implies an estimator $κ$ of

$$κ = \frac{log (1 + κ) = Δ(log R_{\text{eff}})}{log R_{\text{eff}} - (αμ + β log C + γ)}.$$

If the errors in the observables are uncorrelated, the variance in our estimator $κ$ is just the variance in the photoFP in the direction of $R_{\text{eff}}$ (if the errors are correlated, then the variance in $κ$ achieved by this method could be reduced by an optimized estimator). We extract a galaxy–galaxy lensing signal by cross-correlating $κ$ with positions of foreground lenses.

3. A MAGNIFICATION MEASUREMENT

3.1. Lens Sample

The lens sample is selected from the New York University (NYU) Value-Added Catalog (Blanton et al. 2005) version of the SDSS Data Release 7 (DR7) spectroscopic survey (Abazajian et al. 2009), using only luminous red galaxy (LRG) sample targets (Eisenstein et al. 2003). In order to compare with the results of Mandelbaum et al. (2008a), we limit the sample to massive galaxies with absolute $r$-band magnitudes

\begin{figure}
\centering
\includegraphics[width=0.5\textwidth]{figure1}
\caption{Photometric fundamental plane for our source sample of 8.4 million galaxies, shown edge-on. Gray points show a random subset of 100,000 galaxies from the source catalog, while the solid line shows the one-to-one relation.
}
\end{figure}
−21.5 > M_{hi} > −22.6 and redshifts 0.15 < z < 0.35. The magnitudes are k-corrected and evolution corrected to z = 0.0 as in Mandelbaum et al. (2006a, hereafter M+06). Finally, to exclude satellite galaxies that are not at the centers of their dark matter haloes, we remove galaxies with brighter nearby LRGs, again following M+06. This gives a sample of ~55,000 lenses that have comparable properties to the combined LRG sample of M+06.

3.2. Correcting Biases due to Photometric Redshift Errors

In the presence of photo-z errors, the overdensity of sources clustered near a lens will produce an excess of source galaxies with incorrect photo-z (z_s) along the line of sight to the lens. As a result, when we average Δlog R_{eff} over the foreground or background source galaxies, we systematically mis-estimate the residuals from the plane associated with a lens due to the "shadow" cast by photo-z errors.

To deal with this bias, we calculate the magnitude of this spurious signal directly from the data, and subtract it from our measured signal. We first estimate the error in Δlog R_{eff} induced by a galaxy being assigned the wrong z_s (Δlog R_{eff}^err), then calculate what fraction f_i of the galaxies at each z_s have been scattered in from z_l. In these terms, the observed mean photoFP residual is

$$\Delta \log R_{\text{eff}}^\text{obs} = (1 - f_i) \log (1 + \kappa) + f_i \Delta \log R_{\text{eff}}^\text{err},$$

(5)

where κ is the true convergence.

$\Delta \log R_{\text{eff}}^\text{err}$ can be estimated by assuming that the galaxy lies on the photoFP at z_l but is incorrectly assigned to z_s. The inferred effective radius of a galaxy with true redshift z_l that is mistakenly assigned to z_s will be off by a factor of $d_s(z_s)/d_s(z_l)$, and the surface brightness will be $\mu_s = \mu_l - 10 \log [(1 + z_l)/(1 + z_s)]$. Finally, the photoFP fits differ between redshift bins. A galaxy with an incorrect photo-z will therefore lie off the photoFP at z_s by

$$\Delta \log R_{\text{eff}}^\text{err} = \log \left( \frac{d_s(z_s)}{d_s(z_l)} \frac{R_{\text{eff}}^l(\mu_l, C)}{R_{\text{eff}}^l(\mu_l, C)} \right).$$

(6)

The expressions $R_{\text{eff}}^l(\mu_l, C)$ and $R_{\text{eff}}^l(\mu_l, C)$ are the radii that would be predicted by the photoFP for that galaxy’s surface brightness and concentration in the bins corresponding to z_s and z_l, respectively.

The quantity f_i can be estimated by cross-correlating the positions of sources at z_s with lenses at z_l. We assume that the positions of galaxies in widely separated redshift bins are uncorrelated and that any observed excess of sources far behind a lens is due to scattering from z_l. This means that

$$f_i = \frac{w_{sl}(\theta)}{1 + w_{sl}(\theta)},$$

(7)

where $w_{sl}(\theta)$ is the angular cross-correlation between the positions of sources at z_s and lenses at z_l. To calculate the cross-correlations, we use a random catalog created by sampling the full SDSS DR7 mask described in Blanton et al. (2005; J. Tinker 2011, private communication), and cross-correlate the positions of these random sources with our lens catalog. We estimate $w_{sl}(\theta)$ in bins as the ratio of the number of random pairs in each θ bin to the number of source galaxies in the same bin, normalized by the relative sizes of the random and sources catalogs.

The cross-correlations for 0.20 < z_l < 0.25 with a range of z_s bins are shown in Figure 2. f_i is computed using the binned correlation function estimates. The overdensity of galaxies at the lens redshift cannot produce an excess of galaxies scattered to z_l from z_s, so we enforce $w \geq 0$.

As a final step in dealing with photo-z biases, we exclude from the measurement all galaxies in angular and photo-z bins with a large inferred contamination fraction, $f_i \geq 0.5$. This step removes a very large fraction of otherwise usable early-type galaxies at angular scales where the magnification signal is strongest (more than half at $\theta < 1'$). We have tested the effects of changing $f_i$, and find that for the range of values between 0.5 and 0.8 (inclusive) there is no statistically significant effect on the final signal.

In addition to the effects of galaxy clustering on photometric redshift errors, a mean offset between the true and photometric redshifts in a z_s bin will cause an incorrect estimation of the critical density $\Sigma_{\text{crit}}$ for all of the galaxies in that bin. This error depends on the distribution of foreground lens redshifts. Using the method of Mandelbaum et al. (2008b), we estimate the effect of a mean shift in our photo-z’s on the signal of no more than 10%. This uncertainty is small relative to the other corrections discussed here, so we defer this calculation to Paper II.

3.3. Proximity Bias Correction

The SDSS photometric pipeline, photo, produces known proximity effects, where the photometry of objects near bright stars or galaxies is systematically biased (cf. Aihara et al. 2011). This can induce a systematic bias in the estimated radii, surface brightnesses, and concentrations that contaminates the lensing signal.

We directly measure these effects using the SHERA suite of image simulations based on the software described in Mandelbaum et al. (2012). SHERA modifies high-resolution galaxy images from the Hubble Space Telescope (HST) to simulate their appearance in lower-resolution surveys using the point-spread function (PSF) of the lower-resolution survey.
Figure 3. Red solid line: the fractional change in the flux and size for simulation galaxies selected as described in Section 2.1. Black solid line: the same quantities, but for the subset of the above with half-light radii above 1′′. Note that the photometric quantities are entirely unreliable at lens–source separations below 0′′.6, but that the magnitude of the biases are less than 1% in the former case. The vertical dotted lines shows the smallest source–lens separation used for the measurement.

(A color version of this figure is available in the online journal.)

Photo uses a principal component decomposition of the images of bright stars to build a model of the SDSS PSF and its variation across each imaging field. This model, which has been used and validated in numerous weak lensing studies with SDSS data (cf. Sheldon et al. 2004; Mandelbaum et al. 2005; Huff et al. 2011b), can be reconstructed at an arbitrary position in each image.

We simulate the effects of proximity bias by placing SHERA-generated galaxy images convolved with the appropriate SDSS PSF model in single-epoch SDSS imaging near our lenses, at 10 fixed angular separations from lens galaxies, with random azimuthal angles. Once each image is added to the SDSS image, we rerun photo, select the nearest object within 1′′ in the resulting catalog that passes source selection cuts described in Section 2.1, and record that object’s photometric properties. The results are shown in Figure 3. The HST images used by SHERA are only available for a single band (F814W), so we cannot assign them spectral types. The proximity effects in our simulations are greatest for the smallest simulated galaxies. We therefore make additional cuts in half-light radius that result in an acceptable level of bias for this measurement.7 We postpone an exhaustive discussion of the simulations until Paper II.

3.4. Halo Mass Profile

After controlling for the systematic errors described above, we calculate the line-of-sight surface matter density Σ by

7 The residual proximity biases shown in Figure 3, with our FP coefficients, correspond to biases in the magnification signal of order Σ(R) ≃ 5 M⊙ pc−2.

weighting each lens—background source pair by the critical surface density Σcrit(zs,zl). Shear measurements constrain the enclosed projected mass (∆Σ), while magnification measures the projected mass profile (Σ). Figure 4 shows the M+06 shear measurements and their best-fit Navarro–Frenk–White (NFW) ∆Σ profile (black points and line). The Σ profile derived from this NFW profile is also shown (shaded gray band), which accurately predicts the magnification signal from this work.

One benefit of showing both Σ and ∆Σ together is that the errors can be compared directly in physical units. This is most easily done in the bottom panels of Figure 4, which have a linear mass scale. From the figure, it is evident that the magnification-derived halo constraints have lower S/N than the shear-derived constraints, but only by a modest factor. The error bars in this figure are estimated from the variance in the measured κ in angular bins, and so are conservative upper limits on the statistical noise in the measurement. A proper treatment of correlated errors would reduce the scatter in the final measurement.

4. DISCUSSION: THE WAY FORWARD

The magnification technique demonstrated above, while substantially less noisy than traditional number-count measurements, still faces several major challenges that shear measurements do not. First, the convergence dispersion resulting from the measured photoFP width is 35% (1.8 times larger than the intrinsic shear dispersion of 20%). Second, we have not attempted to identify a usable photometric scaling relation for the two-thirds of the sample composed of blue galaxies. Finally, we
Figure 4. Colored line with errors in each panel shows the mass profile from this measurement. The black points with errors show the measured shear profile for the same lens selection from M+06. The black line shows the best-fit $\Delta\Sigma$ profile from that work, while the gray band shows the expected $\Sigma$ profile from the shear signal. Left panels show the $r$-band magnification signal, and the right two panels show that for the $i$ band.

(A color version of this figure is available in the online journal.)

could only immunize our measurement against photo-$z$ biases by removing a large fraction of the sources from our sample in the regions with highest magnification. This impact of photo-$z$ contamination is likely to be lessened somewhat with deeper surveys, where a smaller fraction of the source galaxies are physically associated with the lenses themselves, but it is clear that photo-$z$ errors are a greater concern for this method than for shear measurements.

Despite these issues, magnification by this method represents a substantial increase in the available signal for weak lensing analysis. The magnification signal identified here is not subject to the same systematic biases that challenge shear measurements. For instance, the intrinsic galaxy alignment signal on large scales should not affect galaxy sizes, concentrations, and mean surface brightnesses in same the manner in which it affects shapes. We expect that this technique will also prove useful in extracting and removing instrumental systematics, such as those arising from variations in the telescope PSF, and will investigate this prospect in a subsequent paper.

The authors are deeply grateful to Rachel Mandelbaum and Reiko Nakajima for their help in understanding several of the systematic errors, to Jeremy Tinker for help with producing the SDSS random catalog, and to Chris Hirata and Uros Seljak for many useful and productive discussions related to this work. The authors are also grateful to the PRIMUS team for allowing the use of their spectroscopic catalog in estimating photometric redshift calibration errors.

Funding for SDSS-III has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, and the U.S. Department of Energy. The SDSS-III Web site is http://www.sdss3.org/.

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