A MORE FUNDAMENTAL PLANE

Adam S. Bolton, Scott Burles, Tommaso Treu, Léon V. E. Koopmans, and Leonidas A. Moustakas

ApJ Letters, in press

ABSTRACT

We combine strong-lensing masses with SDSS stellar velocity dispersions and HST-ACS effective (half-light) radii for 36 lens galaxies from the Sloan Lens ACS (SLACS) Survey to study the mass dependence of mass-dynamical structure in early-type galaxies. We find that over a 180–390 km s$^{-1}$ range in velocity dispersion, structure is independent of lensing mass to within 5%. This result suggests a systematic variation in the total (i.e., luminous plus dark matter) mass-to-light ratio as the origin of the tilt of the fundamental plane (FP) scaling relationship between galaxy size, velocity dispersion, and surface brightness. We construct the FP of the lens sample, which we find to be consistent with the FP of the parent SDSS early-type galaxy population, and present the first observational correlation between mass-to-light ratio and residuals about the FP. Finally, we re-formulate the FP in terms of surface mass density rather than surface brightness. By removing the complexities of stellar-population effects, this mass-plane formulation will facilitate comparison to numerical simulations and possible use as a cosmological distance indicator.

Subject headings: gravitational lensing — galaxies: elliptical

1. INTRODUCTION

The fundamental plane (FP; Dressler et al. 1987; Djorgovski & Davis 1987) is a well-known scaling relationship between the size $R$, surface brightness $I$, and velocity dispersion $\sigma$ of elliptical galaxies, expressed in the form

$$R \propto \sigma^a I^b,$$

that indicates an underlying regularity within the population. Crudely speaking, the exponents of the FP are $(a, b) = (1.5, -0.8)$ (e.g., Bernardi et al. 2003), differing significantly from the most naive constant mass-to-light dimensional-analysis expectation of $(a, b) = (2, -1)$. This so-called tilt of the FP (relative to the virial plane) can be attributed to either a systematic variation in the mass-dynamical structure of ellipticals (structural non-homology), a systematic variation of the stellar mass-to-light ratio, or a systematic variation in the central dark-matter fraction with other quantities. This ambiguity is difficult to resolve, since neither mass structure (as opposed to light structure), nor mass-to-light ratio, nor dark-matter fraction are directly and independently observable (see e.g., Ciotti, Lanzoni, & Renzini 1996). As a result, no definite consensus has emerged as to the underlying explanation of the FP.

Strong gravitational lensing can break some of this degeneracy observationally, since the total mass within the Einstein radius $R_{\text{Ein}}$ is directly observable in gravitational lens galaxies independent of any dynamical modeling. The main impediment to this strong lensing approach has been the lack of a large and homogenous sample of strong lenses for which the traditional FP observables $R$, $I$, and $\sigma$ can all be reliably measured. This limitation has recently been overcome by the Sloan Lens ACS (SLACS) Survey (Bolton et al. 2006; Treu et al. 2006; Koopmans et al. 2006; Gavazzi et al. 2007; hereafter Papers I–IV respectively; see also Bolton et al. 2004, 2005), an ongoing survey for strong gravitational lens galaxies combining spectroscopic lens-candidate selection from the Sloan Digital Sky Survey (SDSS; York et al. 2000) with high-resolution follow-up imaging with the Advanced Camera for Surveys (ACS) aboard the Hubble Space Telescope (HST). In this Letter, we investigate the dependence upon mass of early-type galaxy mass-dynamical structure by adding strong-lensing information to the traditional FP observables. We also construct the FP itself for the SLACS sample, show that the residuals about the best fitting FP are significantly correlated with mass-to-light ratio, and present a new formulation of the FP using lensing data to replace surface brightness with surface mass density.

2. OBSERVATIONS AND MEASUREMENTS

The imaging data for all analysis presented in this Letter were collected with single 420-s exposures through the F814W $(I$-band) filter under HST programs 10174 (PI: Koopmans) and 10587 (PI: Bolton). As of 2006 July, 89 systems were successfully observed with ACS-WFC by these two Snapshot programs, yielding 44 strong lenses with redshifts in the range $z_{\text{lens}} \approx 0.1$–0.4. Full details of the final SLACS Snapshot sample will be presented in a forthcoming paper (Bolton et al. 2007, in preparation; hereafter B07). To generate lens-galaxy-subtracted images suitable for gravi-
tional lens modeling and to measure lens-galaxy flux within an arbitrary radial aperture, we fit a PSF-convolved elliptical b-spline model to the surface brightness profile of the lensing galaxies (see Paper I). We also fit a PSF-convolved elliptical deVaucouleurs surface brightness model to the image of each lens galaxy, to measure intermediate-axis half-light (effective) radii \( R_e \) and brightnesses \( I_e = 0.5L_e/\pi R_e^2 \) for use in the FP analysis. Lastly, we make lensing mass measurements by fitting singular isothermal ellipsoid (SIE; e.g. Kormann et al. 1994) mass models to the extended multiple images of lensed background galaxies. We correct the HST I-band photometry with the Galactic dust corrections of Schlegel, Finkbeiner, & Davis (1998), synthetic k-corrections to rest-frame V-band based on SDSS spectral templates for each galaxy, an evolution correction of \( d \log \Omega_0 / dz = -0.4 \) (Kelson et al. 2000, Treu et al. 2001, Moran et al. 2005), and distance moduli computed for an \( (\Omega_M, \Omega_L, h) = (0.3, 0.7, 0.7) \) FRW universe. Throughout this Letter, the aforementioned FRW cosmology is assumed, magnitudes are in the AB system, masses and luminosities are in solar units, sizes are expressed in kpc, velocities are in km s\(^{-1}\), and logarithms are base 10.

In order to achieve a uniform physical aperture with as little extrapolation and artificial covariance as possible, we correct all lensing mass measurements to an aperture of \( R_e/2 \) using the isothermal mass model, since the median ratio of \( R_e/2 \) to \( R_e \) within our lens sample is 0.55. The isothermal model is preferred by the lens-dynamical analysis of Paper III, and is also favored by statistical studies of lensed quasars (e.g. Rusin & Kochanek 2005) and by dynamical analysis of nearby ellipticals (e.g. Gerhard et al. 2001). To assess the sensitivity of our results to the isothermal assumption, we derive alternate aperture-mass corrections using a light-traces-mass (LTM) model determined from the b-spline photometry. The mean difference between isothermal and LTM aperture masses within \( R_e/2 \) is \(-3\%\), with an RMS difference of \( \pm 9\%\). To compute central mass-to-light ratios (which we denote by \( \gamma_{e2} \)), luminosities within \( R_e/2 \) are measured from the b-spline models. We also correct the observed velocity dispersions from the SDSS fiber radius of \( 1.5 \) to \( R_e/2 \) (giving \( \sigma_{e2} \)) using the empirical relation of Jørgensen, Franx, & Kjærgaard (1995). These velocity corrections are small: \( 1.4\% \pm 1.3\% \).

We reject 8 lenses based upon (i) prominent spiral arms, (ii) an SDSS spectral SNR per pixel of less than 7, or (iii) significant disagreement between the model \( R_e \) and the radius of an aperture containing one-half of the model flux. These cuts leave us with a sample of 36 early-type strong lens galaxies with absolute evolution-corrected magnitudes \( M_V \) in the range \(-20.8 \) to \(-24.0 \) and velocity dispersions \( \sigma_{e2} \approx 180-390 \) km s\(^{-1}\). Quoted errors on all fitted parameters are 68\% limits from bootstrap re-sampling of these 36 lenses.

3. THE MASS (IN)DEPENDENCE OF STRUCTURE

Dimensional analysis of the Jeans equation (e.g., Binney & Tremaine 1987) shows that

\[ M = \sigma^2 R / G, \]

where \( R \) is a scaling radius, \( \sigma \) is an average stellar velocity dispersion within that radius, \( M \) is the mass interior to that radius, \( G \) is Newton’s constant, and \( c \) is a dimensionless structure constant. Note that \( R \) and \( \sigma \) pertain to the luminous (i.e., stellar) component, while \( M \) refers to the total mass (i.e. stellar and dark): this follows from the Jeans equation, and matches well with the quantities that we actually measure with photometry, spectroscopy, and lens modeling. The value of \( c \) will in general depend upon the anisotropy of the stellar orbits, the overall shape of both the luminous- and dark-matter density profiles, and the relative fraction of luminous to dark matter in the region of interest. In the SLACS sample, a systematic variation of \( c \) with galaxy mass will be apparent in the relationship between the lensing-determined total mass \( M_{\text{Lens}} \) within \( R_e/2 \) on the one hand and the dimensional mass variable \( M_{\text{dim}} = G^{-1} \sigma^2_{e2} (R_e/2) \) on the other, which we parameterize as

\[ \log M_{\text{lens}} = \delta \log M_{\text{dim}} + \log c_0. \]

A systematic trend of \( c \) with mass thus corresponds to a value of \( \delta \) different than 1. Minimizing the scatter orthogonal to the best-fit relation, we find \( \delta = 0.986 \pm 0.034 \) (\( \delta = 0.956 \pm 0.042 \)) and \( \log c_0 = 0.58 \pm 0.16 \) (\( \log c_0 = 0.74 \pm 0.19 \)) for isothermal (LTM) aperture mass corrections. This relationship is shown in the left-hand panel of Fig. 1. We see that—whatever the underlying details—the SLACS lens population is empirically consistent with no variation of the structure constant \( c \) with mass. This result is closely related to the nearly one-to-one relation between stellar and isothermal lens-model velocity dispersions shown for the initial SLACS sample in Treu et al. (2006). By casting this result in terms of nearly model-independent aperture masses, the current analysis emphasizes the strong evidence for the mass independence of early-type galaxy structure in the range \( \sigma_{e2} = 180-390 \) km s\(^{-1}\), independent of any assumed underlying mass-dynamical model.

4. PLANES FUNDAMENTAL

To place the above result in the context of the FP, we must first verify that the SLACS sample does indeed define the same FP as non-lenses. Paper II showed the original SLACS sample of 15 lenses to be consistent with the locally determined FP when corrected for luminosity evolution; the current, larger sample allows us to directly constrain the FP of the lenses. We perform this fit in the orthogonal sense, defining the best-fitting plane as that which minimizes the total squared perpendicular distance from all data points in the space spanned by \( \log R_e, \log I_e \) and \( \log \sigma_{e2} \). Defined in this way, the coefficients of the FP do not change with the choice of dependent variable. Expressing the FP in the form

\[ \log R_e = a \log \sigma_{e2} + b \log I_e + d, \]

we find \( a = 1.50 \pm 0.32 \), \( b = -0.78 \pm 0.13 \), and \( d = 3.9 \pm 1.7 \). The given errors are the square-root diagonal entries of the covariance matrix of a set of bootstrap-sampled coefficient fits; off-diagonal correlations are \( \rho_{ab} \approx 0.6 \), \( \rho_{ad} \approx -0.8 \), and \( \rho_{bd} \approx -0.9 \). The residual logarithmic orthogonal scatter about the best-fit plane is 0.041 dex. The FP is shown in edge-on projection with respect to \( R_e \) in the center panel of Fig. 1. The scaling coefficients \( (a \text{ and } b) \) of the FP defined by the SLACS lens sample are consistent with the orthogonal FP fits of Bernardi et al. (2003) for early-type galaxies.
from the SDSS (with somewhat different selection and conventions).

As an aside, the addition of lensing data allows us to make the first direct observation of a correlation between the residual scatter about the FP and the total mass-to-light ratio $τ_{e2}$ as determined from lensing, shown in the right-hand panel of Fig. 1. The correlation has a linear (Pearson) coefficient of $-0.58$, giving a formal significance of $99.98\%$ for a sample size of 36. The significance of the correlation is similar under the LTM assumption (i.e. no correction of $\tau$ from $R_{Ein}$ to $R_e/2$). Furthermore, the FP residuals do not have any significant correlation with mass or with luminosity separately, nor any correlation with redshift or with the ratio $R_{Ein}/R_e$. We are thus drawn to the conclusion that this correlation is intrinsic, and not introduced through a correlation of measurement errors. Though they did not observe it directly, such a correlation of FP residuals with mass-to-light ratio was deduced by Faber et al. [1987] to be the most likely explanation for the intrinsic thickness of the FP. (Also see Jørgensen, Franx, & Kjærgaard [1996] for an extensive observational analysis of FP residual correlations and intrinsic thickness.)

We now use the strong-lensing data to formulate an analogous plane in mass space, which we will refer to as the mass plane (MP). Following the traditional form of the FP, we define the MP by replacing surface brightness $I_e$ with surface mass density within $R_e/2$, denoted by $Σ_{e2}$ (in $M_\odot$ kpc$^{-2}$):

\[
\log R_e = a_m \log \sigma_{r2} + b_m \log Σ_{e2} + d_m .
\]

Note that in going from $I_e$ to Σ_{e2}, the sensitivity to luminosity evolution with redshift is removed. Fitting as for the FP above, the MP coefficients are $a_m = 1.77 \pm 0.14$, $b_m = -1.16 \pm 0.09$, and $d_m = 7.8 \pm 1.0$. Off-diagonal correlations are $ρ_{ab,m} \simeq 0.1$, $ρ_{ad,m} \simeq -0.4$, and $ρ_{bd,m} \simeq -0.9$. The RMS orthogonal logarithmic scatter about the MP is 0.026dex. Fitting for the MP with mass densities computed using the LTM assumption rather than the isothermal model gives $a_m = 1.86 \pm 0.17$, $b_m = -0.93 \pm 0.09$, and $d_m = 5.4 \pm 0.9$, with comparable parameter correlations and an orthogonal logarithmic scatter of 0.030dex. The MP thus appears to be tighter than the FP in the sense of having smaller residual scatter. This scatter is consistent with the ~7% fractional velocity-dispersion errors in the current data.

The significant difference between the FP and the MP is most easily seen by considering the parameterization of the FP tilt in terms of a relationship of the form $L \propto M^δ$, (e.g. Dressler et al. [1987]; Ciotti et al. [1996]; Trujillo, Burkert, & Bell [2004]; Treu et al. [2005b]). While this form does not exactly reproduce the best-fitting FP exponents of the current study, it is a convenient physically motivated approximation. Fitting in log-space by minimizing the orthogonal scatter, we find $δ = 0.82 \pm 0.05$ for the SLACS sample. This translates into FP coefficients of $a = 1.39$ and $b = -0.85$ in the form of Eq. (4). Comparing this with the result that $δ = 0.98 \pm 0.034$ from §3—which amounts to an analogous parameterization of the MP—we see that in going from the FP to the MP, the tilt relative to the virial relation is essentially eliminated.

5. DISCUSSION

Previous studies have constructed the FP of gravitational lens galaxies (Kochanek et al. [2006]; van de Ven et al. [2003]; Rusin & Kochanek [2005]), but have taken their velocity dispersions from the strong lensing data rather than from stellar dynamics. By combining independent measurements of mass and velocity, we have found direct evidence that the total mass-dynamical structure of early-type galaxies is independent of mass. What, then, does this result tell us about the underlying explanation for the tilt of the FP? The straightforward binary answer is that the FP must be due to a systematic variation in the total central mass-to-light ratio—either through the stellar population or through the central dark-matter fraction—and not due to any systematic variation of mass-dynamical structure with mass. If mass-dynamical structure effects were responsible for the FP, they should also manifest as a systematic variation with mass of the structure constant $c$ of §3 and a similar tilt in the MP as in the FP, whereas we see neither of these two effects. This conclusion is most notably consistent with those of Padmanabhan et al. [2004] and Cappellari et al. [2006]; the agreement is reassuring given the diversity of the methods employed between these studies and ours.

Our conclusions are at variance with those of Trujillo et al. [2004], who point to non-homology in the luminous component of early-type galaxies (specifically, the systematic variation in Sérsic index with galaxy luminosity) as being largely responsible for the FP. A plausible explanation is that, motivated by the results of Romanowsky et al. [2003], Trujillo et al. [2004] do
not allow for the presence of dark matter. Other lines of evidence suggest a “bulge-halo conspiracy” in early-type galaxies, whereby the combined luminous and dark-matter profiles generate a more uniformly flat rotation curve than either component alone (e.g. Gerhard et al. 2001). Such an effect could offset non-homology in the luminous component, leading us back to systematic mass-to-light variation as the explanation for the FP.

As mentioned above, our observations do not distinguish between stellar mass and dark mass: the two physically very distinct possibilities of a variation in the stellar mass-to-light ratio and a variation in the central dark-matter fraction are (in principle) equally allowed. Previous studies have shown that variations in stellar mass-to-light must be responsible for some (but not all) of the tilt of the FP, as seen through the systematic decrease in tilt at redder wave-bands (Pahre et al. 1998), detailed stellar population modeling (Thomas et al. 2003), and the galaxy-mass-dependent average rate of luminosity evolution with redshift (Trenkner et al. 2005a,b). At this stage, the main diagnostic available to us to quantify stellar populations effects in the SLACS sample is the strength of the 4000˚A break in lens-galaxy continuum flux $D_n(4000)$, which should correlate with stellar mass-to-light ratio (Bruzual 1983; Hamilton 1985; Balogh et al. 1999; Kauffmann et al. 2003). No significant correlation with $Y$ is found, although the sensitivity of $D_n(4000)$ may not be sufficient to detect the small age differences ($\Delta t/t \sim 2/10$) expected for early-type galaxies in this range of velocity dispersion (Thomas et al. 2003). Taken at face value, the result suggests that most of the variation in $T_{e2}$ is due to dark matter content. We will quantify this statement in future work with the aid of more sophisticated stellar population diagnostics.

In the process of investigating the mass dependence of early-type galaxy structure and the genesis of the FP, we have made the first observational correlation of the thickness of the FP with mass-to-light ratio, and we have introduced an analogous plane in mass space that is both tighter and less tilted than the FP relative to the virial scaling relation. This observational mass plane is a fundamental dynamical scaling relation for early-type galaxies; though it requires a measurement of galaxy size, it makes no reference to galaxy luminosity, and therefore it can be tracked across cosmic time without regard to stellar evolution. The MP thus offers great promise as a cosmological standard ruler, particularly if the relation can be calibrated locally by masses from detailed dynamical models of nearby elliptical galaxies. (Though structural evolution may still occur: e.g. van der Marel & van Dokkum 2006a,b.) By removing the need for stellar-population modeling, the MP is more robust for comparison with the results of numerical simulations.

This Letter has not addressed possible biases introduced through our gravitational-lens selection procedure. We defer a full discussion of selection effects to B07, but note that Papers I and II showed the original SLACS sample to be statistically consistent with the parent sample of non-lens SDSS galaxies from which they were selected.

The analysis presented here has been made possible only recently by the SLACS Survey gravitational lens sample. Existing and forthcoming deep HST imaging will permit more accurate mass, luminosity, and color measurements, while ongoing spectroscopy with the VLT and Keck telescopes will provide more robust velocity dispersion measurements and stellar-population diagnostics. These data will soon enable a greater precision in the type of analysis described in this Letter.

The authors thank G. Bertin, L. Ciotti, A. Renzini, and the anonymous referee for valuable comments. ASB, TT, LVEK, and LAM acknowledge the support and hospitality of the Kavli Institute for Theoretical Physics at UCSB, where a significant part of this work was completed. This research was supported in part by the NSF under Grant No. PHY99-07949. TT acknowledges support from the NSF through CAREER award NSF-0642621, and from the Sloan Foundation through a Sloan Research Fellowship. LVEK is supported in part through an NWO-VIDI program subsidy (project #639.042.505). The work of LAM was carried out at JPL/Caltech, under a contract with NASA. Support for HST programs #10174 and #10587 was provided by NASA through a grant from STScI, which is operated by AURA, Inc., under NASA contract NAS 5-26555. Funding for the SDSS has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the NSF, the U.S. D.O.E., NASA, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. The SDSS is managed by the Astrophysical Research Consortium for the Participating Institutions.

REFERENCES

Balogh, M. L., Morris, S. L., Yee, H. K. C.,Carlberg, R. G., & Ellingson, E. 1999, ApJ, 527, 54
Bernardi, M., et al. 2003, AJ, 125, 1866
Binney, J., & Tremaine, S. 1987, Galactic dynamics (Princeton, NJ, Princeton University Press, 1987, 747 p.)
Bolton, A. S., Burles, S., Koopmans, L. V. E., Treu, T., & Moustakas, L. A. 2005, ApJ, 624, L21
Bolton, A. S., Burles, S., Koopmans, L. V. E., Treu, T., & Moustakas, L. A. 2006, ApJ, 638, 703
Bolton, A. S., Burles, S., Schlegel, D. J., Eisenstein, D. J., & Brinkmann, J. 2004, AJ, 127, 1860
Bruzual, G. 1983, ApJ, 273, 105
Cappellari, M., et al. 2006, MNRAS, 366, 1126
Ciotti, L., Lanzoni, B., & Renzini, A. 1996, MNRAS, 282, 1
Djorgovski, S., & Davis, M. 1987, ApJ, 313, 59
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42
Faber, S. M., Dressler, A., Davies, R. L., Burstein, D., & Lynden-Bell, D. 1987, in Nearly Normal Galaxies. From the Planck Time to the Present, ed. S. M. Faber, 175–183
Gerhard, O., Kronawitter, A., Saglia, R. P., & Bender, R. 2001, AJ, 121, 1936
Hamilton, D. 1985, ApJ, 297, 371
Jørgensen, I., Franx, M., & Kjærgaard, P. 1995, MNRAS, 276, 1341
—. 1996, MNRAS, 280, 167
Kauffmann, G., et al. 2003, MNRAS, 341, 33
Kelson, D. D., Illingworth, G. D., van Dokkum, P. G., & Franx, M. 2000, ApJ, 531, 184
Kochanek, C. S., et al. 2000, ApJ, 543, 131
Koopmans, L. V. E., Treu, T., Bolton, A. S., Burles, S., & Moustakas, L. A. 2006, ApJ, 649, 599
Kormann, R., Schneider, P., & Bartelmann, M. 1994, A&A, 284, 285
Moran, S. M., Ellis, R. S., Treu, T., Smail, I., Dressler, A., Coil, A. L., & Smith, G. P. 2005, ApJ, 634, 977
Padmanabhan, N., et al. 2004, New Astronomy, 9, 329
Pahre, M. A., de Carvalho, R. R., & Djorgovski, S. G. 1998, AJ, 116, 1606
Romanowsky, A. J., et al. 2003, Science, 301, 1696
Rusin, D., & Kochanek, C. S. 2005, ApJ, 623, 666
Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, ApJ, 500, 525
Thomas, D., Maraston, C., Bender, R., & Mendes de Oliveira, C. 2005, ApJ, 621, 673
Treu, T., Ellis, R. S., Liao, T. X., & van Dokkum, P. G. 2005a, ApJ, 622, L5
Treu, T., Koopmans, L. V., Bolton, A. S., Burles, S., & Moustakas, L. A. 2006, ApJ, 640, 662
Treu, T., Stiavelli, M., Bertin, G., Casertano, S., & Møller, P. 2001, MNRAS, 326, 237
Treu, T., et al. 2005b, ApJ, 633, 174
Trujillo, I., Burkert, A., & Bell, E. F. 2004, ApJ, 600, L39
van de Ven, G., van Dokkum, P. G., & Franx, M. 2003, MNRAS, 344, 924
van der Marel, R. P., & van Dokkum, P. G. 2006a, ApJ, submitted (astro-ph/0611571)
—. 2006b, ApJ, submitted (astro-ph/0611577)
York, D. G., et al. 2000, AJ, 120, 1579