THE BARYON FRACTIONS AND MASS-TO-LIGHT RATIOS OF EARLY-TYPE GALAXIES

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Received 2007 May 24, accepted 2007 August 16

ABSTRACT

We jointly model 22 early-type gravitational lens galaxies with stellar dynamical measurements using standard CDM halo models. The sample is inhomogeneous in both its mass distributions and the evolution of its stellar populations unless the true uncertainties are significantly larger than the reported measurement errors. In general, an individual system cannot constrain halo models, in the sense that the data poorly constrain the stellar mass fraction of the halo. An ensemble of systems, however, strongly constrains the average stellar mass represented by the visible galaxies to 0.026 ± 0.006 of the halo mass if we neglect adiabatic compression, rising to 0.056 ± 0.011 of the halo mass if we include adiabatic compression. Both estimates are significantly smaller than the global baryon fraction, corresponding to a star formation efficiency for early-type galaxies of 10%–30%. In the adiabatically compressed models, we find an average local B-band stellar mass-to-light ratio of \( (M/L)_0 \) = 7.2 ± 0.5 \( M_\odot/L_\odot \) that evolves as \( d \log (M/L)/dz = -0.72 ± 0.08 \) per unit redshift. Adjusting the isotropy of the stellar orbits has little effect on the results. The adiabatically compressed models are strongly favored if we impose either local estimates of the mass-to-light ratios of early-type galaxies or weak-lensing measurements for the lens galaxies on 100 kpc scales as model constraints.

Subject headings: galaxies: elliptical and lenticular, cD — gravitational lensing — stellar dynamics

Online material: color figures

1. INTRODUCTION

The presence of dark matter in early-type galaxies is clear on large scales, based on weak lensing (e.g., Kleinheinrich et al. 2006; Mandelbaum et al. 2006), X-ray studies (e.g., Humphrey et al. 2006), and dynamics analysis of the satellite galaxies (e.g., Conroy et al. 2007; van den Bosch et al. 2004; Prada et al. 2003). The distribution of the dark matter and the mass fraction represented by the stars are less well determined because of the difficulties in measuring early-type galaxy structure in the transition region between the stars and the dark matter. Stellar kinematic studies of the central regions, when compared to estimates of stellar mass-to-light ratios, have argued either that there is little dark matter inside the effective radius (e.g., Gerhard et al. 2001) or that there is a substantial dark matter fraction (e.g., Padmanabhan et al. 2004). The significance of these differences depends on the reliability of estimating the stellar mass from combinations of photometry, spectroscopy, and population synthesis models. Studies on larger scales using planetary nebulae have found examples of galaxies with falling rotation curves (Romanowsky et al. 2003), while the globular clusters in one of these systems show a flat rotation curve (Pierce et al. 2006). Surveys of structure with gravitational lenses (e.g., Rusin & Kochanek 2005; Treu et al. 2006a) indicate that the typical lens has a flat rotation curve on scales of \((1-2)R_e\), but the interpretation of the scatter around the mean structure has been used to argue for both inhomogeneity (e.g., Treu & Koopmans 2002; Kochanek et al. 2006) and homogeneity (e.g., Rusin & Kochanek 2005; Koopmans et al. 2006) in the mass distributions.

In this paper we reanalyze a sample of 15 lenses from the Sloan Lens ACS Survey (SLACS; Bolton et al. 2006) and seven lenses from the Lens Structure and Dynamics Survey (LSD; Koopmans & Treu 2003), which have both mass estimates from the lens geometry and central velocity dispersion measurements. Koopmans et al. (2006) analyzed the sample using a simple, global power-law model, \( \rho \propto r^{-\gamma} \), for the mass distribution to find a mean slope of \( \gamma = 2.01^{+0.02}_{-0.03} \), where \( \gamma = 2 \) corresponds to a flat rotation curve. With a nominal scatter in the slope of only 0.07, Koopmans et al. (2006) argue that the halo structures appear to be fairly homogeneous. It is difficult, however, to relate these power-law models to theoretical models of halos or to evaluate the significance of the scatter in the slope. In addition, the models are somewhat unphysical because they allow mass distributions more compact than the luminous galaxy.

Here we reanalyze the SLACS and LSD lens samples using a more physical mass model that combines a Hernquist (1990) profile for the stars with a Navarro et al. (1996, hereafter NFW) model for the dark matter. By comparing the mass inside the Einstein ring of the galaxies \([M(<R_E)]\) with the mass needed to produce the observed velocity dispersion, we can estimate the stellar mass fraction and the stellar mass-to-light ratio explicitly. We use a Bayesian formalism that allows us to quantitatively address the homogeneity of the sample. We review the data and describe our mass models and analysis techniques in \( \S \) 2. In \( \S \) 3 we discuss the models of the individual systems (\( \S \) 3.1), the homogeneity of the sample (\( \S \) 3.2), and finally, the stellar mass fraction, the mean stellar mass-to-light ratio, and the evolution of the mass-to-light ratios (\( \S \) 3.3). We summarize our results in \( \S \) 4.

2. DATA AND METHOD

2.1. Data

In this paper we reanalyze the data for 15 lenses from the SLACS and seven lenses from the LSD. We neglect two lenses, Q0957+561 and Q2237+030, from the LSD since Q0957+561 is in a cluster and Q2237+030 is a barred spiral galaxy, leaving us with a sample of 22 galaxies with measured velocity dispersions, effective radii, Einstein radii, enclosed masses, and rest-frame B-band magnitudes taken from the original analyses. For convenience we summarize the data in Table 1, particularly since the equivalent table in Treu et al. (2006a, 2006b) contains ordering errors. For consistency we have adjusted all the data to a flat
ACDM cosmological model with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2.2. Method of Analysis

We model the lenses with the two-component mass model for lenses introduced by Keeton (2001), which was also used for early-type galaxies in the Sloan Digital Sky Survey (SDSS) by Padmanabhan et al. (2004). It consists of a Hernquist (1990) model for the luminous galaxy and an NFW profile for the dark matter halo. By using this simple model, we avoid more complicated models based on the simple power law normally used by the LSD/SLACS studies, and we both connect the results to theoretical halo models and avoid models in which the dark matter can be more centrally concentrated than the stars. In essence, we use the mass enclosed by the Einstein radius of the lens to set the virial mass $M_{\text{vir}}$, the stellar velocity dispersion to determine the stellar mass fraction $f_*$, and theoretical halo models to constrain the halo concentration $c$. Finally, by comparing the derived stellar mass to the observed luminosity, we can estimate the rest-frame B-band mass-to-light ratio $M_*/L_*$ and its evolution.

The Hernquist (1990) model used for the luminous lens galaxy is defined by

$$\rho_*(r) = \frac{M_* \, r_1}{2\pi \, (r+r_1)^2}.$$  

where the scale length $r_1 = 0.551 R_*$ is matched to the measured de Vaucouleurs profile effective radius $R_e$ and the stellar mass $M_* = f_* M_{\text{vir}}$ is related to the virial mass by the cold baryon/stellar mass fraction $f_*$. The NFW profile used to model the initial dark matter halo is defined by

$$\rho_{\text{NFW}}(r) = \frac{M_{\text{in}}}{4\pi c^2 (r + c)^2},$$  

where the scale length $r_s$ is related to the virial radius by $c = r_s/r_e$, $f(c) = \ln (1 + c) - c/(1 + c)$, and $M_{\text{in}} = (1 - f_*)M_{\text{vir}}$ is the mass in dark matter. The average concentration is modeled by

$$c = \frac{9}{1 + z} \left( \frac{M_{\text{vir}}}{8.12 \times 10^{12} \, h \, M_\odot} \right)^{-0.14},$$  

and the individual halos have a lognormal dispersion in their concentrations of $\sigma_c = 0.18$ (base 10) around the average (Bullock et al. 2001). These initial models neglect the compression of the dark matter density profile by the more concentrated baryons. We estimated the changes in the dark matter distribution using the adiabatic compression model of Blumenthal et al. (1986). This approximation may exaggerate the compression (Gnedin et al. 2004), so we should regard our compressed and uncompressed results as bounding the possible effects of adiabatic compression. The observations provide two constraints, the mass inside the Einstein radius and the stellar velocity dispersion. For any values of $c$ and $f_*$, we use the projected mass inside the Einstein radius to determine $M_{\text{vir}}$ (which also determines $r_{\text{vir}}$), then use the spherical Jeans equation and a constant orbital isotropy $\beta$ to compute the velocity dispersion expected for the measurement aperture. The effects of seeing were modeled using a Gaussian PSF with the...
observed FWHM of the observations. Given the estimated dispersion $\sigma_{\text{model}}$, the measured dispersion $\sigma_i$, and its uncertainties $e_{\sigma_i}$ for galaxy $i$, we estimate a goodness of fit $\chi^2(\sigma_i) = (\sigma_{\text{model}} - \sigma_i)^2/e_{\sigma_i}^2$. We model the mass-to-light ratios of the stars using the standard power law (e.g., van Dokkum & Franx 1996; Treu 2001; Rusin & Kochanek 2005; Koopmans et al. 2006),

$$\log \left( \frac{M_i}{L_i} \right) = \log \left( \frac{M_0}{L_0} \right) + z \frac{d \log (M/L)}{dz},$$  \hspace{1cm} (4)$$

where $(M/L)_0$ is the value today and $d \log (M/L)/dz$ is the rate at which it changes with redshift $z$. This in turn defines a goodness of fit $\chi^2((M/L)_i)$ with which the model fits the logarithm of the mass-to-light ratio $(M/L)_i$ of galaxy $i$, defined by the ratio of the estimated stellar mass (a model parameter) to the observed luminosity, given its uncertainties

$$e_{L_i} = \Delta \log (M/L)_i = \Delta L_i/\ln (10)L_i.$$  

These two terms define the probability of fitting the velocity dispersion,

$$P(\sigma_i|\xi) = \frac{\exp \left[ -\chi^2(\sigma_i)/2 \right]}{2\pi e_{\sigma_i}},$$

and the mass-to-light ratio,

$$P \left( \frac{M_i}{L_i}|\xi \right) = \frac{\exp \left[ -\chi^2((M/L)_i)/2 \right]}{2\pi e_{L_i}},$$

given the model parameters $f_*, c, (M/L)_0$, and $d \log (M/L)/dz$, which we abbreviate as $\xi$. Combining the two terms, we have the probability of the model fitting the data $D_i$ for galaxy $i$:

$$P_i(D_i|\xi) = P(\sigma_i|\xi) P((M/L)_i|\xi).$$  \hspace{1cm} (5)$$

In addition to the measurement errors listed in Table 1, we should also consider sources of systematic errors. The essence of the method is to compare the mass inside the Einstein ring, $M(<R_e)$, to a virial mass estimate from the velocity dispersion, $\sigma^2 R_e/G$. We can identify five sources of systematic errors. First, while there is little uncertainty in $M_R$, some of the mass may be projected surface density either from a parent group halo to which the lens belongs or from another along the line of sight. The extra density, $\kappa = \Sigma/\Sigma_c$ in dimensionless units, modifies the mass inside the Einstein radius by $\pi \kappa R_e^2 \Sigma_c$, so we can think of its effects as a systematic error in interpreting $\sigma_e = \sigma_e/2$. The full probability distribution of $\kappa$ is skewed to positive values (e.g., Takada & Hamana 2003), but we ignore this problem and assume $\sigma_{\kappa} \approx 0.05$ since the positive tail of the distribution is associated with detectable objects (galaxies and clusters). This systematic error also affects estimates of the mass-to-light ratios. Second, there are $1\%$–$10\%$ uncertainties in the galaxy effective radius measurements which contribute uncertainties of $0.5\%$–$5\%$ to our interpretation of the velocity dispersion. Third, the measured velocity dispersion is a Gaussian fit to the spectrum, which is not identical to the rms velocity appearing in the Jeans equation (e.g., Binney & Tremaine 1987, p. 195). The difference can be estimated from the typical Gaussian-Hermite coefficients $|h_4| \approx 0.02$ (Bender et al. 1994) as a fractional error in $\sigma_e$ of order $\sqrt{6}|h_4| \approx 0.05$ in the velocity dispersion (e.g., van der Marel et al. 2003). Fourth, nonphericity (somewhat to our surprise) leads to negligible systematic errors provided we use the intermediate scale length (the geometric mean of the semimajor and minor axes), at least in the limit of the tensor virial theorem. It leads to large errors if any other scale length is used. Barnabe & Koopmans (2007) have taken the first steps toward removing these two dynamical problems, although they are restricted to oblate two-integral models, which may not be appropriate for massive elliptical galaxies. Finally, calibration errors in the velocity dispersions contribute fractional errors of order 0.03 (see Bernardi et al. 2003a). Combining all these contributions in quadrature, which corresponds to assuming a Gaussian model for each systematic error, we estimate that the typical systematic uncertainty to interpreting the velocity dispersions is approximately $8\%$, with the exact value depending on the uncertainties in the effective radius.

Our statistical methods are chosen so that we can understand the homogeneity of the lens galaxies in either their evolution or their dynamical properties and estimate their average properties in the presence of inhomogeneities. We analyze the results using two Bayesian methods. In the first method we fit the data while simultaneously estimating the systematic errors in the velocity dispersion and the mass-to-light ratio. When combined with the measurement errors, these define new uncertainty estimates for the data which we call the “bad” case errors in comparison to the original uncertainties (the “good” case). These broadened uncertainties can be either representative of true systematic uncertainties, such as the ones we discussed above for the dynamical measurements, or indicative of inhomogeneities in the structure or evolution of the galaxies. In the second method we compare these two cases using the approach outlined in Press (1997) to determine the degree to which the sample is homogeneous or heterogeneous. In this method we assume that there are probabilities $p_s$ and $p_t$ that the galaxies have homogeneous structures or evolutionary histories in the sense that the scatter in the measurements is simply determined by the “good” measurement errors. There are then probabilities $1 - p_s$ and $1 - p_t$ that the galaxies are not a homogeneous group in either their structure or their evolution, where we characterize this by assuming that the uncertainties in the velocity dispersion and the mass-to-light ratio have to be significantly broadened to be the “bad” measurement errors. In essence, we are determining the relative probabilities of the stated measurement errors and our estimate of the true uncertainties from the first method. Both approaches provide uncertainties on the average properties of the sample that account for potential inhomogeneities, although the second method is a better formal approach since it can reject individual objects.

In the first approach we estimate the fractional systematic errors $e_\sigma$ and $e_L$ in the velocity dispersion and luminosity. The $\chi^2$ expressions are modified to use uncertainties of $e_{\sigma'} = (e_{\sigma_e} + e_{\sigma_L}^2)^{1/2}$ and $e_{L'} = (e_{L_{\text{e}}}^2 + e_{L_{\text{e}}}^2)^{1/2}$ for the velocity dispersions and the logarithms of the mass-to-light ratios, respectively. We assume logarithmic priors for $f_*$, $(M/L)_0$, and $d \log (M/L)/dz$, and the theoretical prior defined by equation (3) for the concentration $c_l$. Note that we are forcing all galaxies to have the same concentration, which should have no significant impact given the scales we are studying. The priors for the systematic errors, $P(e_{\sigma}) = 1/(e_{\sigma_e}^2 + e_{\sigma_L}^2)^{1/2}$ and $P(e_{L}) = 1/(e_{L_{\text{e}}}^2 + e_{L_{\text{e}}}^2)^{1/2}$, naturally switch between uniform priors for systematic errors that are small compared to the mean-square measurement errors $(e_{\sigma_e}^2$ and $e_{L_{\text{e}}}^2$), and logarithmic priors for large systematic errors. The resulting probability distribution for the fractional errors is then

$$P(e_{\sigma}, e_L|D) \propto P(e_{\sigma}) P(e_{L}) \int d\xi P(\xi) \prod_i P(D_i|e_{\sigma}, \xi) P(D_i|e_L, \xi),$$  \hspace{1cm} (6)$$
where $P(D|\epsilon_x, \xi)$ and $P(D|\epsilon_L, \xi)$ are the probability distributions modified by the addition of the systematic errors $\epsilon_x$ and $\epsilon_L$. We then use these systematic error estimates to define the uncertainties used for the “bad” case in our second formalism.

The second approach (Press 1997) properly weights all combinatorial possibilities of whether the individual systems are members of a homogeneous sample or not. Let $P_G(\sigma|\xi)$ and $P_G((M/L)|\xi)$ be the probabilities of the data given the parameters for galaxy $i$ if it is a member of a homogeneous group based on the measured, “good” uncertainties, and let $P_B(\sigma|\xi)$ and $P_B((M/L)|\xi)$ be the probabilities that it is not, and the “bad” uncertainties based on the systematic error estimates derived from our first method should be used. The Press (1997) approach provides estimates of the relative likelihoods of describing either the full sample or individual systems by the “good” or “bad” data model. If we want the Bayesian probability distribution for the parameters properly weighted over all possible group membership combinations, we find that

$$P(\xi|D) \propto P(\xi) \int dp_x dp_L \prod_i F_i,$$

where

$$F_i = \left[ p_x P_G(\sigma|\xi) + (1 - p_x) P_B(\sigma|\xi) \right] \times \left[ p_L P_G((M/L)|\xi) + (1 - p_L) P_B((M/L)|\xi) \right]$$

and where $P(\xi)$ sets the prior probability distributions for the parameters. We assume uniform priors for $p_x$ and $p_L$. We obtain the probability distribution for any parameter by marginalizing equation (7) over all other variables and then normalizing the total probability to unity. We can also estimate the probability that the sample is homogeneous in either its structural or evolutionary properties as

$$P(p_x, p_L|D) \propto \int d\xi P(\xi) \Pi_i F_i,$$

and the probability that a particular galaxy is in the dynamically homogeneous class as

$$P(\sigma_i \in \text{homogeneous}|D) = \frac{A_i}{A_i + B_i},$$

where

$$F_i = \left[ p_x P_G(\sigma|\xi) + (1 - p_x) P_B(\sigma|\xi) \right] \times \left[ p_L P_G((M/L)|\xi) + (1 - p_L) P_B((M/L)|\xi) \right]$$

and

$$P(p_x, p_L|D) \propto \int d\xi P(\xi) \Pi_i F_i,$$

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where

$$F_i = \left[ p_x P_G(\sigma|\xi) + (1 - p_x) P_B(\sigma|\xi) \right] \times \left[ p_L P_G((M/L)|\xi) + (1 - p_L) P_B((M/L)|\xi) \right]$$

and

$$P(p_x, p_L|D) \propto \int d\xi P(\xi) \Pi_i F_i,$$

and the probability that a particular galaxy is in the dynamically homogeneous class as

$$P(\sigma_i \in \text{homogeneous}|D) = \frac{A_i}{A_i + B_i},$$
where

\[
\begin{align*}
A_i &= \int d\xi P(\xi) \int dp_\sigma dp_L p_{p_L} P_G(\sigma_i) \\
&\times [p_L P_G((M/L)\xi) + (1 - p_L) P_{B_i}((M/L)\xi)] \Pi_{\neq j} F_j, \\
B_i &= \int d\xi P(\xi) \int dp_\sigma dp_L (1 - p_{\sigma}) P_{B_i}(\sigma_i) \\
&\times [p_L P_G((M/L)\xi) + (1 - p_L) P_{B_i}((M/L)\xi)] \Pi_{\neq j} F_j, \\
\end{align*}
\]

(11)

A similar set of expressions gives the probability that the galaxy is in the set of galaxies with a homogeneous evolutionary history.

3. RESULTS

We divide our discussion of the results into three subsections. First, we present the results for the individual galaxies. Next, we discuss the homogeneity of the structural properties of the galaxies. Finally, we estimate the stellar mass fraction, mass-to-light ratios, and rate of galaxy evolution.

3.1. Properties of Individual Galaxies

Figure 1 shows contours for the goodness of fit of the models to the velocity dispersion, measured for each galaxy as a function of the stellar mass fraction \( f_\ast \) and the concentration \( c \) once we have normalized the mass inside the Einstein radius. For these calculations, we have included our estimates of the systematic errors in the velocity dispersions but used the stated uncertainties in the luminosities. Note that the dispersion measurements cannot determine the halo concentrations, but the goodness of fit contours always pass through the region set by our prior for the concentration. The permitted stellar mass fractions vary widely between objects. Three of the 22 objects, SDSS J0737+321, SDSS J1250+052, and PG 1115+080, appear to require mass distributions that are more centrally concentrated than the stars, in the sense that the best fits for \( f_\ast \) have \( \chi^2 > 2 \). This is also seen in the LSD models for PG 1115+080 (Treu & Koopmans 2002), where the only models consistent with both the lensing constraint and the estimated velocity dispersion are more centrally concentrated than the stars. A fourth lens, SDSS J1627+005, is only marginally consistent with \( f_\ast \leq 1 \). Of the remaining 18 galaxies, 11 are consistent with \( f_\ast = 1 \) (\( \Delta \chi^2 < 1 \)), and seven are not. Four of these 11 galaxies have enormous parameter uncertainties. One problem for many SLACS lenses is that the scales of the velocity dispersion aperture/effective radius differ little from the observed Einstein radius, which limits the leverage for constraining the mass profile.

Figure 2 shows the goodness of fit to the mass-to-light ratio of each galaxy given the best-fit model for the average evolution of
the sample. Most of the galaxies are consistent with this best-fit model for the mass-to-light ratio and its evolution ($\Delta \chi^2 = 1 \sigma$). The mass-to-light ratios of the sample appear to be more uniform than the dynamical properties, probably for the same reasons that there is little scatter in the fundamental plane (see Bernardi et al. 2003b). However, there are three $3 \sigma$ outliers in the sample, SDSS J1420+602, SDSS J1250+052, and H1543+535, all of which have very low mass-to-light ratios compared to the other galaxies. Note that only one of these, SDSS J1250+052, is also an outlier in the dynamical fits. This is not unique to our approach, since our mass-to-light ratio for H1543+535 is comparable to that in Treu & Koopmans (2004). In Figure 6 of Treu et al. (2006a) they also find significantly lower mass-to-light ratios for SDSS J1420+602 and SDSS J1250+052 than they do for the other SLACS members. One possible solution is that the lens masses are significantly misestimated due to contamination from a group or cluster halo, but only H1543+535 has a neighboring bright galaxy, and it is sufficiently distant to only modestly perturb the estimated mass.

3.2. Homogeneity

The broad uncertainties and occasional outliers mean that it is important to have a quantitative approach to determining the homogeneity of the sample and to appropriately weight each object when determining mean properties. This is why we introduced the Bayesian frameworks of $\S$ 2. Figure 3 shows our estimates of the fractional systematic errors from our first analysis method (eq. [6]). The best-fit estimates for the fractional systematic errors in the velocity dispersion and luminosity are $e_\sigma \sim 0.1$ and $e_L \sim 0.18$. The reported measurement errors lie well outside the 99.7% likelihood region. For the dynamical errors, the best-fit systematic errors are quite consistent with our prior estimates based on simple considerations about the dynamical data.

Figure 4 shows that the results for the homogeneity of the sample are very sensitive to the assumed uncertainties. If we simply use the stated measurement errors, then the probability that the sample is homogeneous in its dynamical properties (i.e., that the “good” uncertainty estimates are correct and the scatter is due only to measurement error) is $p_\sigma \leq 24\%$, and the probability that it is homogeneous in mass-to-light ratio evolution is $p_L \leq 14\%$. Many objects have low probabilities of belonging to either a homogeneous dynamical subset (SDSS J1627+0053 with $p_\sigma = 0.005$, SDSS J1250+0523 with $p_\sigma = 0.010$, SDSS J0737+321 with $p_\sigma = 0.010$, PG 1115+080 with $p_\sigma = 0.029$, and SDSS J1420+602

![Figure 2](image-url)
with $p_L = 0.042$) or a homogeneous evolutionary subset (SDSS J1250+0523 with $p_L \approx 0$, H1543+535 with $p_L \approx 0$, SDSS J0912+002 with $p_L = 0.001$, SDSS J1420+602 with $p_L = 0.001$, and MG 1549+305 with $p_L = 0.001$). Not surprisingly, these objects are also outliers in the individual fits from the previous section. If we include our estimates of the systematic errors in interpreting the dynamical measurements, then the probability that the sample is homogeneous in its dynamical properties rises to $p_L \leq 14\%$, but the probability of a homogeneous evolutionary population remains small at $p_L \leq 14\%$. With the inclusion of the systematic error estimates, the objects with the lowest probabilities of belonging to the homogeneous dynamical subset are PG 1115+080 (with $p_L = 0.48$), SDSS J1250+0523 (with $p_L = 0.49$), SDSS J1627–0053 (with $p_L = 0.52$), SDSS J0737+321 (with $p_L = 0.52$), and H1417+526 (with $p_L = 0.55$). These estimates strongly indicate either that the SLACS/LDS lens populations are inhomogeneous or that the measurement errors underestimate the true uncertainties. In a few cases these problematic lenses show some evidence of disks (SDSS J1420+602 and MG 1549+305).

In sum, the SLACS/LDS galaxies are homogeneous in neither their dynamical nor their evolutionary properties if we take the measurement errors at face value. It is likely that most of the problem for the dynamical measurements is that the systematic errors in interpreting velocity dispersions are significant and need to be included in any analysis of the dynamics of lenses. One of these systematic errors, surface density contributions from structures other than the lens galaxy, also produces systematic errors in the mass-to-light ratio, with $\sigma_M = \sigma_L \approx 0.05$, but this is much too small to explain the spread in the mass-to-light ratios. This problem is probably caused by a combination of underestimated uncertainties in the luminosities and true variance in the evolutionary history of early-type galaxies. Rusin & Kochanek (2005) and Treu et al. (2006a) had found earlier that the lens sample was better fit by allowing a range for the mean redshift at which the stars formed than by assuming a single value, and in this analysis a range of formation redshifts would lead to nonzero systematic errors in the mass-to-light ratio.

To make sure that the scatter in the parameters is not model-induced, we also did a calculation for a power-law mass distribution with $\rho \propto r^{-\gamma}$, still using a Hernquist model for the stellar distribution. When we computed the corrected errors, we found that they must be broadened by the same factor as before. Like Treu et al., we found that the best-fit solution is isothermal, $\gamma = 2.00 \pm 0.02$ with the modified error bars, and there is little change for the original error bars. Figure 5 shows the probability distribution for $\gamma$ with the modified error bars. The joint effect constrains $\gamma$ to small ranges, although the individuals’ scatter is larger. This is not
very surprising, since we know from previous studies (see, e.g., Rusin & Kochanek 2005) that sums of Hernquist models with NFW halos that are compatible with lensing constraints have total mass distributions over the relevant scales that are similar to an isothermal distribution.

Fig. 3.—Probability distribution of the fractional systematic errors $e_s$ and $e_t$ in the velocity dispersion and mass-to-light ratio. The contours encompass 68%, 95%, and 99.7% of the probability starting from the maximum likelihood solution indicated by the triangle. The crosses indicate the measurement errors from Treu et al. (2006a, 2006b) and Koopmans et al. (2006), and the rectangles are the modified errors. This figure changes little if we use power-law distributions. [See the electronic edition of the Journal for a color version of this figure.]

3.3. The Stellar Mass Fraction and Mass-to-Light Ratio

We can combine the galaxies to make joint estimates of the stellar mass fraction $f_*$, the mass-to-light ratio $M/L$ at $z = 0$, and its evolution. We considered both Bayesian frameworks, so that either the uncertainties are broadened to make the results consistent with all the lenses (method 1; eq. [6]) or the outliers in the sample are properly down weighted in the analysis (method 2; eq. [7]). The two methods give similar results, so we only present the detailed results from the second Bayesian method. Figure 6 shows the estimated stellar mass fraction $f_*$ for both the individual galaxies and the sample as a whole, and for orbital anisotropies of $\beta = -1/3$, 0, and 1/3, where $\beta = 1 - \sigma_t^2/\sigma_r^2$ is related to the ratio of the tangential $\sigma_t$ and radial $\sigma_r$ velocity dispersions. For isotropic, adiabatically compressed models, we find $f_* = 0.056 \pm 0.011$, and like Koopmans et al. (2006) we find that the isotropy has little effect on the inferred mass distribution. The stellar mass fraction is significantly lower than the global baryon fraction of $0.176^{+0.006}_{-0.019}$ from the Wilkinson Microwave Anisotropy Probe (WMAP) cosmic microwave background anisotropy measurements (Spergel et al. 2007). If we do not include the adiabatic compression of the halo, the stellar mass fraction drops to $0.026 \pm 0.006$, again with little dependence on the isotropy $\beta$. While the uncompressed models have less dark matter in the central regions, the total halo mass is much larger than in the compressed models. To the extent that adiabatic compression occurs, the Blumenthal et al. (1986) model exaggerates its degree (Gnedin et al. 2004); reality is between these two extremes.

We also fit the mass-to-light ratio as $\log (M/L) = \log a + bz$, where $a = (M/L)_0$ is the mass-to-light ratio at $z = 0$ and $b = d \log (M/L)/dz$ is its evolution with redshift. Figure 7 shows the likelihood contours for these two parameters for both compressed and uncompressed models. For the compressed isotropic models, we find $a = (7.2 \pm 0.5) M_\odot/L_\odot$ and $b = -0.72 \pm 0.08$. This agrees with the local value of $a = 7.3 \pm 2.1 M_\odot/L_\odot$ from Gerhard et al. (2001) that was used by Treu et al. (2006a). It also agrees with the Treu et al. (2006a) estimate for the rate of the evolution,
Changing the isotropy over the range $\beta = -1/3, 0, \text{ and } 1/3$ has little effect, while the model without adiabatic compression requires higher normalizations for the mass-to-light ratio ($10^{0.3}$) and slightly slower rates of evolution. Our analysis includes two lenses (PG 1115+080 and H1543+535) that were not used by Treu et al. (2006a), but excluding them from the analysis has little effect on the mass-to-light ratios.

4. DISCUSSION

We reanalyzed the data from the SLACS and LSD surveys of gravitational lenses with velocity dispersion measurements. Our mass distribution consists of a Hernquist model for the luminous galaxy embedded in a theoretically constrained NFW halo model. We investigated the homogeneity of the sample, the stellar mass fraction $f_*$, the local ($z = 0$) stellar mass-to-light ratio $(M_*/L)_0$, and its evolution $d \log (M_*/L)/dz$. As in the earlier study by Koopmans et al. (2006), we found that the effects of orbital anisotropy on both the stellar mass fraction and the mass-to-light ratio are small.

In most cases, a central velocity dispersion measurement provides only a weak constraint on halo structure in the physically interesting region. Typical limits on the mass fraction represented by the stars have logarithmic errors of order 0.5 dex. While this appears to contradict the conclusions of (for example) Koopmans et al. (2006), this is not the case. Koopmans et al. (2006) fit mass models where $\rho \propto r^{-3}$, and find values in the range $1.8 < \gamma < 2.3$. Figure 8 shows the expected range of this slope for our models of SDSS J0037+0942, where we estimated the slope by fitting the $\rho \propto r^{-3}$ power-law model to the projected mass distribution over a radial baseline of $R_e/8$ to $R_e$, which approximates the leverage in using stellar dynamics combined with gravitational lensing to determine halo structure. For this typical lens, the variations in $\gamma$ of $1.6 \leq \gamma \leq 2.06$ are comparable to the system-to-system spread in $\gamma$ observed for the SLACS systems (Koopmans et al. 2006). Thus, the spread in $\gamma$ observed for individual SLACS/LSD lenses is comparable to the range of values found in our halo models, so strong conclusions about halo structure from these systems will depend on averages over the samples rather than the results for individual lenses.

The critical issue for determining the sample average properties is the degree to which the populations are homogeneous. A heterogeneous sample cannot easily be averaged to determine mean properties. We find the probability of homogeneity is very sensitive to the uncertainties in both the velocity dispersion and the luminosity. If we take the measurement errors at face value,
Fig. 7.—Probability distributions for the local mass-to-light ratio \(M_*/L\) and its evolution \(d\log(M_*/L)/dz\) in the adiabatically compressed (top) and uncompressed (bottom) models. The contours show the 68%, 95%, and 99.7% enclosed probability contours for the isotropic models. The estimated evolution rate is marginally inconsistent with the estimate of \(d\log(M_*/L)/dz = -0.50 \pm 0.19\) from Rusin & Kochanek (2005), which is shown by the horizontal band of solid and dashed lines. The three triangles in the top panel show the effect of changing the isotropy on the likelihood peak, with \(\beta = -0.33\), \(\beta = 0\), and \(\beta = 0.33\) as we move from upper left to lower right. The squares with error bars are the results from Treu et al. (2006a) for the same galaxies. [See the electronic edition of the Journal for a color version of this figure.]

There is a low probability of homogeneity in either dynamical structure \((p_x \leq 20\%)\) or evolutionary history \((p_L \leq 15\%)\). Many lenses such as SDSS J1250+052, H1543+535, SDSS J1420+601, SDSS J0912+002, MG 2016+112, and MG 1549+305 have low \((<10\%)\) likelihoods of belonging to a homogeneous sample. The primary problem is probably that there are significant systematic uncertainties that must be included with the measurement errors. Simple considerations show that typical systematic errors in interpreting the velocity dispersions should be large compared to the measurement errors, 8% versus 5%, and adding these estimated systematic uncertainties greatly increases the likelihood of dynamical homogeneity. Sources of systematic error in the mass-to-light ratio are less amenable to simple arguments but should certainly include the dispersion in the average star formation epoch of early-type galaxies found in earlier analyses of galaxy evolution with lenses by Rusin & Kochanek (2005) and Treu et al. (2006a). If we simply analyze the data to determine the most likely systematic errors, we find that we must include fractional systematic errors of approximately 10% in the velocity dispersion estimates and 19% in the mass-to-light ratio estimates in order to make the sample consistent with the hypothesis of homogeneity.

Once we account for the inhomogeneity or systematic errors in the sample, we can evaluate sample averages that properly account for these problems. We find that the halo mass fraction represented by the baryons in stars is \(f_* = 0.056 \pm 0.011\) if we adiabatically compress the dark matter and \(f_* = 0.026 \pm 0.006\) if we do not. These results are comparable to the range of estimates that relied on stellar population models to estimate the stellar mass. For example, Lintott et al. (2006) obtained a stellar mass fraction of 8% by fitting monolithic collapse models to 2000 SDSS galaxies, Hoekstra et al. (2005) found \(f_* = 0.065^{+0.010}_{-0.008}\) using weak lensing, and Mandelbaum et al. (2006) found \(f_* = 0.03^{+0.02}_{-0.01}\) using weak lensing. The results in these studies depend on the assumed initial mass function (IMF); the Hoekstra et al. (2005) estimate drops to \(f_* = 0.035^{+0.009}_{-0.004}\) if the IMF of the stars is changed from a standard Salpeter IMF to a scaled Salpeter IMF. Our results probably bound the stellar mass fraction since the Blumenthal et al. (1986) model we used may overestimate the amount of adiabatic compression (Gnedin et al. 2004). In all our models, the stellar mass fraction is much smaller than the cosmological baryon mass fraction, \(\Omega_b/\Omega_m = 0.176^{+0.006}_{-0.009}\) from WMAP (Spergel et al. 2007), which means that the star formation efficiency \((f_0\Omega_m/\Omega_b)\) of early-type galaxies is only 15%–30%. The remaining baryons must remain as gas distributed on the scale of the halo or its parent (group) halo. This discrepancy appears to be a common problem for any baryon accounting for normal galaxies (e.g., Fukugita 2004) and a significant constraint on star formation efficiency.

Fig. 8.—Range for the three-dimensional density slope exponent \(\gamma\), where \(\rho \propto r^{-\gamma}\), for the typical lens SDSS 30037–0942. We estimated \(\gamma\) by fitting the projected mass distribution as a power law between \(R_p/8\) and \(R_c\). Note that the variation of \(\gamma\) over the physically interesting regime is comparable to the scatter observed by Koopmans et al. (2006) of \(1.8 \leq \gamma \leq 2.3\).
but at least our Bayesian approach carries out these weightings in an objective fashion.

In our basic analysis we cannot distinguish between the adiabatically compressed and uncompressed models. In essence, we can obtain the same mass distribution using either a high stellar mass-to-light ratio and a more extended halo or the reverse. If we impose the locally estimated mass-to-light ratio as a constraint, then the adiabatically compressed model is favored (6 to 1). We can also use mass measurements on much larger scales to distinguish the two models because the total halo mass is larger in the uncompressed model. In particular, we can calculate the weak lensing $\Delta \Sigma$ and compare it to the measurement by Gavazzi et al. (2007; also see Mandelbaum et al. 2006) for an overlapping sample of SLACS lenses, where they found that $\Delta \Sigma = 100 \pm 30 h M_\odot$ pc$^{-2}$ on scales of $94 h^{-1}$ kpc. With this constraint the adiabatically compressed models are again strongly favored (by 1000 to 1). In general, any third constraint that is dominated by the contribution from one mass component will break the degeneracy and lead to constraints on the degree of adiabatic compression or an additional structural variable such as the inner slope of the dark matter density distribution.

The sample of lenses available for such analyses will continue to grow and can include lenses with time-delay measurements (which constrain the halo structure by measuring the surface density near the lensed images; Kochanek 2002), as well as those with velocity dispersions. With larger samples it should be possible to explore additional correlations such as the scaling of the stellar mass fraction and mass-to-light ratios with halo mass and the dependence of the evolution rate on halo mass. In the SAURON project, Cappellari et al. (2006) investigated the mass-to-light ($I$ band) ratios of elliptical and lenticular galaxies, and they found that the ratios increase with the velocity dispersions of the systems:

$$M/L = (3.80 \pm 0.14)(\sigma_v/200 \text{ km s}^{-1})^{0.84 \pm 0.07}.$$

Although the luminosity band is different from what we use here, it might imply that the mass-to-light ratios for the early-type galaxies are not uniform everywhere. In the Mandelbaum et al. (2006) and Padmanabhan et al. (2004) analyses of early-type galaxies in the SDSS, the changes in the mass-to-light ratio with halo mass are due to an increasing dark matter mass fraction rather than changes in the stellar populations, but their results depend on population synthesis models to correctly estimate the stellar masses. In a larger sample of lenses, this could be tested directly.

We would like to thank L. Koopmans, L. Moustakas, E. Rozo, and T. Treu for their comments and R. Mandelbaum for discussions on weak lensing. We also thank the referee for constructive comments.

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