DARK MATTER MASS FRACTION IN LENS GALAXIES: NEW ESTIMATES FROM MICROLENSING

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\textbf{ABSTRACT}

We present a joint estimate of the stellar/dark matter mass fraction in lens galaxies and the average size of the accretion disk of lensed quasars based on microlensing measurements of 27 quasar image pairs seen through 19 lens galaxies. The Bayesian estimate for the fraction of the surface mass density in the form of stars is $\alpha = 0.21 \pm 0.14$ near the Einstein radius of the lenses ($\sim 1$--$2$ effective radii). The estimate for the average accretion disk size is $R_{1/2} = 7.9^{+3.8}_{-2.6} \sqrt{M/0.3 M_\odot}$ light days. The fraction of mass in stars at these radii is significantly larger than previous estimates from microlensing studies assuming quasars were point-like. The corresponding local dark matter fraction of 79\% is in good agreement with other estimates based on strong lensing or kinematics. The size of the accretion disk inferred in the present study is slightly larger than previous estimates.

\textit{Key words:} gravitational lensing: micro – quasars: emission lines

1. INTRODUCTION

The amount and distribution of dark matter relative to stars is a crucial probe of early-type galaxy structure. In particular, changes in the dark matter fraction with radius provide important information about the mechanisms of galaxy formation and the interaction of dark and baryonic matter during the initial collapse (including processes like baryonic cooling, settling, star formation, and feedback) and subsequent mergers (see Diemand & Moore 2011 for a review).

However, measuring this dark matter fraction is difficult. Existing estimates use X-ray observations, stellar dynamics, or gravitational lensing, and each of these methods has its own advantages and difficulties. X-ray observations of the hot gas in massive galaxies can provide an estimate of the total mass under the assumption of hydrostatic equilibrium (see Buote & Humphrey 2012). This method is very robust and simple, with its main uncertainties coming from the robustness of the hydrostatic equilibrium hypothesis, the possibility of nonthermal contributions to the pressure, and contamination from emission by larger-scale group/cluster halo gas. Stellar dynamics can also be used to estimate the structure of the gravitational potential (see, for example, Courteau et al. 2014). In this case, the structure of the orbits (anisotropy) is the primary source of uncertainty. With both X-ray and stellar dynamics it is difficult to extend the measurements to large radii.

Gravitational lensing is also a very powerful probe of dark matter because it provides direct measurements of the total mass of the system (within a certain radius) regardless of whether it is dark or baryonic. On large scales, weak lensing can be used to estimate the mass distribution in the outer parts of halos. Such studies have shown that the mass profiles at those radii are consistent with the Navarro et al. (1997; hereafter NFW) or Einasto (1965) profiles predicted by simulations (e.g., Mandelbaum et al. 2008). The inner regions of galaxies are more complex, as baryons influence the mass profile and can make the halos significantly steeper (Blumenthal et al. 1986; Gnedin et al. 2004). In these inner regions, strong lensing can be used to robustly estimate the total galaxy mass within the Einstein Radius of the lens (typically one to two effective radii). Indeed, this estimate of the total projected mass inside the Einstein radius of the lens galaxy is very robust and depends very weakly on the specific lens model (i.e., on the specific radial profile or the angular structure of the lens) and this can be used to statistically constrain the structure of galaxies (Rusin & Kochanek 2005). The radial mass distribution can be constrained if additional or extended images exist (e.g., Sonnenfeld et al. 2012), or by combining lensing with stellar dynamics (e.g., Romanowsky & Kochanek 1999; Koopmans et al. 2006). However, dividing the measured mass between dark matter and stars is more difficult, as it requires a model of the stellar mass. Photometry, in combination with stellar population synthesis (which can provide an estimate for the stellar $M/L$ ratio), can be used to estimate the stellar mass distribution (see, for example, Jiang & Kochanek 2007; Auger et al. 2009; Tortora et al. 2010; Leier et al. 2011; Oguri et al. 2014). Nevertheless, in this procedure, there is always great uncertainty due to the IMF of the stars, particularly given recent arguments in favor of “bottom heavy” and variable IMFs (van Dokkum & Conroy 2010, 2011; Conroy & van Dokkum 2012). Examples of lensing studies are Rusin & Kochanek (2005), Koopmans et al. (2006), Auger et al. (2010), Leier et al. (2011), and Oguri et al. (2014). These studies generally find that the integrated dark matter fraction inside the Einstein radius is roughly 0.3–0.7. Estimates of the local value at the Einstein radius are more model dependent.

Microlensing of the images of gravitationally lensed quasars provides a direct means of measuring the dark matter fraction at the location of the lensed images. Microlensing is caused by the granularities in the mass distribution created by stars and their remnants, which induce time-dependent changes in the flux of the lensed quasar images (see the review by Wambsganss 2006). At any instant, they produce flux ratio anomalies that cannot be accounted for by the smooth macro model of the lens. Particularly when the stars are only a small fraction of
the surface mass density, microlensing is very sensitive to the relative fractions of stars and dark matter near the images (e.g., Schechter & Wambsganss 2004). We can therefore estimate relative fractions of stars and dark matter near the images (e.g., the surface mass density, microlensing is very sensitive to the fraction of mass in microlenses. Here, we carry out a joint analysis of both. In Section 2, we describe the statistical analysis of the data based on microlensing simulations using magnification maps. In Section 3, we compare the results with previous studies and discuss the possible implications.

2. STATISTICAL ANALYSIS AND RESULTS

We use the microlensing magnification estimates for 27 quasar image pairs in 19 lens systems from MED09. In order to have the largest possible sample, but with a similar range of observed rest wavelengths, we include all of the objects from MED09 with magnifications measured in the wavelength range between Lyα (1216 Å) and Mg ii (2798 Å). With this choice, the average rest wavelength is \( \lambda = 1736 \pm 373 \) Å, but we still keep 27 out of 29 image pairs from 19 out of 20 lensed quasars. Only the system RXS J1131–1231 is excluded, as it was observed in [O iii] at a much larger wavelength of \( \sim 5000 \) Å. These microlensing magnification estimates are calculated after subtracting the emission line flux ratios, which are little affected by microlensing (see, e.g., Guerras et al. 2013), from the continuum flux ratios, and are therefore virtually free from extinction, substructure, and macro model effects (as these affect the line and continuum flux ratios equally). Our strategy is to compare the observed microlensing magnification for a given image pair \( \Delta m_{\text{obs}}^i \) with a statistical sample of simulated values for that measurement as a function of the source size \( r_s \) and the fraction of surface mass density in stars \( \alpha \). This will allow us to calculate the likelihood of the parameters \( r_s, \alpha \) given the observations \( L(r_s, \alpha|\Delta m_{\text{obs}}^i) \). The procedure is repeated for each of the 27 image pairs. We calculate magnification maps for each image using a grid with 11 values for the fraction of the surface mass density in stars, \( \alpha \), logarithmically distributed between 0.025 and 0.8 as \( \alpha_j = 0.025 \times 2^{j/2} \) with \( j = 0, \ldots, 10 \). The 517 magnification maps were created using the Inverse Polygon Mapping algorithm described by Mediavilla et al. (2006, 2011a).

We used equal mass microlenses of 1 \( M_\odot \). All of the linear sizes can be scaled for a different microlens mass as \( \sqrt{M/M_\odot} \). The maps have a size of 2000 × 2000 pixels with a pixel size of 0.5 light-days. The maps therefore span 1000 lt-days. The individual sizes of maps and pixels in (more natural) units of Einstein radii for microlenses of 1 \( M_\odot \) are given in Table 1. On average, the maps span approximately 50 Einstein radii with a pixel scale of roughly 0.025 Einstein radii.

The source size \( r_s \) is taken into account by modelling the source brightness profile as a Gaussian, \( I(r) \propto \exp(-r^2/2r_s^2) \). Mortonson et al. (2005) show that the specific shape of the radial profile is not important for microlensing studies because the results are essentially controlled by the half-light radius rather than the detailed profile. The Gaussian size \( r_s \) is related to the half-light radius by \( r_{1/2} = 1.18r_s \). To account for the source size, we convolve the magnification maps with Gaussians of 16 different sizes over a logarithmic grid, \( \ln(r_s/\text{lt-days}) = 0.3 \times k \) with \( k = 0, \ldots, 15 \), which spans \( r_s \sim 1 \) to \( r_s \sim 90 \) light-days. From the maps for a pair of images of a given lensed quasar with a fraction of stars \( \alpha \) and convolved to size \( r_s \), we can calculate the likelihood of the parameters given the observed microlensing magnifications \( \Delta m_{\text{obs}}^i \) as

\[
L(r_s, \alpha|\Delta m_{\text{obs}}^i) = P(\Delta m_{\text{obs}}^i|r_s, \alpha) \propto \sum e^{-\chi^2/2},
\]

where

\[
\chi^2 = \frac{1}{\sigma^2} \sum (\Delta m_{\text{obs}}^i - \Delta m_{\text{sim}}^i)^2
\]

is obtained for each of the 27 image pairs.
for each of the 27 pairs in our sample. As we are using single
image at 10^4 positions and summing over all possible
combinations. This procedure is repeated for the 176 possible
pairs, producing a two-dimensional (2D) likelihood function
for image pair i. The process is repeated
for each lens and found that the results are
consistent with the estimates of the parameters. We also recomputed the results
using different priors to
uncertainties to

\[ \chi^2 = \frac{(\Delta m - \Delta m_i^{\text{obs}})^2}{\sigma^2} \]  

(2)

and \( \sigma \) is a characteristic value for the error in the observed
microlensing magnification (which we have set to 0.15 mag).
For each image pair, the summation in Equation (1) is performed
over 10^8 trials by sampling the magnification map of
each image at 10^4 positions and summing over all possible
combinations. This procedure is repeated for the 176 possible
values of the \( (r_s, \alpha) \) pairs, producing a two-dimensional (2D)
likelihood function for image pair i. The process is repeated
for each of the 27 pairs in our sample. As we are using single
epoch microlensing, the results for individual pairs/objects have
large uncertainties.

Since there is little signal in the individual pair likelihoods,
we combine the 27 likelihood distributions to produce a joint
likelihood function

\[ L(r_s, \alpha) \propto \prod_{i=1}^{27} L(r_s, \alpha | \Delta m_i^{\text{obs}}). \]  

(3)

The results of this procedure are shown in Figure 1. The expected
covariance between size and stellar mass fraction found
by MED09 can be clearly seen, but we find a well-defined
maximum in the likelihood distribution. The maximum like-
lihood estimate for the (average) mass fraction in stars is
\( \alpha = 0.2 \pm 0.1 \) (at 68% confidence level) and for the accretion
disk size it is \( r_s = 8.1^{+4.1}_{-2.6} \) light days or, equivalently, \( R_{1/2} = 9.6^{+7.2}_{-3.9} \) light days (for microlenses of 0.3 \( M_\odot \) and at a rest wave-
length of roughly 1736 Å). This value for the size of the accretion
disk is roughly 50%–100% larger than previously reported values
but within the range of uncertainties (see Morgan et al. 2008,
2012; Blackburne et al. 2011; Mediable et al. 2011b; Muñoz et al. 2011; Jiménez-Vicente et al. 2012, 2014; Motta et al. 2012;
Mosquera et al. 2013).

Figure 1 also shows the posterior probability for the two
parameters in a Bayesian estimate with logarithmic priors on
the accretion disk size and the stellar mass fraction. In this case,
we have \( P(r_s, \alpha) \propto P(r_s)P(\alpha) \prod_{i=1}^{27} L(r_s, \alpha | \Delta m_i^{\text{obs}}) \) with
\( P(r_s) \propto 1/r_s \) and \( P(\alpha) \propto 1/\alpha \). From these posterior probability
distributions, we find Bayesian estimates of \( \alpha = 0.21 \pm 0.14 \) at
68% confidence, and \( r_s = 6.7^{+3.3}_{-2.2} \) light days for microlenses
of 0.3 \( M_\odot \), or \( R_{1/2} = 7.9^{+3.8}_{-2.6} \) light days, slightly smaller
than the maximum likelihood estimates. If we increase the
uncertainties to \( \sigma = 0.2 \) mag, we find no significant changes in the
estimates of the parameters. We also recomputed the results
by sequentially dropping each lens and found that the results are
not dominated by any single system.

### 3. DISCUSSION AND CONCLUSIONS

With our joint analysis of stellar mass fraction and source
size, we find a larger stellar mass fraction than earlier statistical
studies. In Figure 2, we compare our determination of the stellar

| Object          | Pair | \( \Delta m \) | \( R_E/R_{eff} \) | Map Size in \( \eta_0 \) | Pixel Size in \( \eta_0 \) |
|-----------------|------|--------------|-----------------|-----------------|-----------------|
| HE0047–1756     | B–A  | −0.19        | 1.63            | 44.61           | 0.02            |
| HE0435–1223     | B–A  | −0.24        | 1.60            | 47.32           | 0.024           |
| C–A            | −0.30 |              |                 |                  |                 |
| D–A            | 0.09  |              |                 |                  |                 |
| HE0512–3329     | B–A  | −0.40        |                 | 79.08           | 0.039           |
| SDSS0808+2006   | B–A  | −0.47        | 3.30            | 54.97           | 0.027           |
| SBS0909+532     | B–A  | −0.60        | 1.02            | 77.88           | 0.039           |
| SBS0924+0219    | B–A  | 0.00         | 2.93            | 44.09           | 0.022           |
| FBQ0951+2635    | B–A  | −0.69        | 0.72            | 35.61           | 0.018           |
| QSO0957+561     | B–A  | −0.30        | 1.29            | 32.93           | 0.022           |
| SDSS1001+5027   | B–A  | 0.23         |                 | 40.76           | 0.020           |
| SDSS11004+4112  | B–A  | 0.00         |                 | 59.11           | 0.030           |
| C–A            | 0.45  |              |                 |                  |                 |
| Q1017–20        | B–A  | −0.26        | 1.46            | 60.69           | 0.030           |
| HE1104–1805     | B–A  | 0.60         | 2.19            | 58.74           | 0.029           |
| PG1115+0800     | A2–A1| −0.65        | 2.48            | 38.46           | 0.019           |
| SDSS1206+4332   | A–B  | −0.56        |                 | 68.12           | 0.034           |
| SDSS1535+1138   | A–B  | 0.00         |                 | 38.03           | 0.019           |
| HE1413+117      | B–A  | 0.00         |                 | 61.16           | 0.034           |
| C–A            | −0.25 |              |                 |                  |                 |
| D–A            | −0.75 |              |                 |                  |                 |
| BJ1422+231      | A–B  | 0.16         | 2.29            | 51.18           | 0.026           |
| C–B            | 0.02  |              |                 |                  |                 |
| D–B            | −0.08 |              |                 |                  |                 |
| SBS1520+530     | B–A  | −0.39        | 0.96            | 60.15           | 0.030           |
| WFJ20334723     | B–C  | −0.50        | 1.56            | 58.81           | 0.029           |
| A2–A1          | 0.00  |              |                 |                  |                 |

Notes. Microlensing Einstein radii \( \eta_0 \) used in Columns 5 and 6 correspond to microlenses of
\( M = 1 M_\odot \).

- From Oguri et al. (2014).
- From Sluse et al. (2012).
- From Fadely et al. (2010).
- From Lehár et al. (2000).
surface density fraction to a simple theoretical model and to the best fit of a sample of lens galaxies by Oguri et al. (2014). The simple theoretical model is the early-type galaxy equivalent of a maximal disk model for spirals. We follow the rotation curve of a de Vaucouleurs component for the stars outward in radius until it reaches its maximum and then simply extend it as a flat rotation curve to become a singular isothermal sphere (SIS) at large radius (see details in the Appendix). The ratio of the surface mass density of the de Vaucouleurs component to the total surface mass density is shown as a dashed curve in Figure 2. We also show as a gray band the best fit for the stellar fraction in the form of stars determined by Oguri et al. (2014) in a study of a large sample of lens galaxies using strong lensing and photometry, as well as the best model using a Hernquist component for the stars and an NFW halo for the dark matter with and without adiabatic contraction, also from Oguri et al. (2014). We have used the average and dispersion estimates for the Einstein and effective radii available for 13 of the objects in our sample from Oguri et al. (2014), Sluse et al. (2012), Fadely et al. (2010), and Lehár et al. (2000; see Table 1) as an estimate of $R_E/R_{\text{eff}}$ in Figure 2. The average value and dispersion of the sample is $R_E/R_{\text{eff}} = 1.8 \pm 0.8$. This also averages over the different radii of the lensed images. The agreement of our estimates with the expectations of the simple theoretical model and with estimates from other studies (Oguri et al. 2014) is quite good. For comparison, the estimate of Pooley et al. (2012; using the Einstein and effective radii estimates for 10 out of 14 of their objects from Schechter et al. 2014) seems somewhat lower than expected at those radii. The range of stellar mass fractions from MED09 for source sizes in the range 0.3–15.6 light days is also shown in Figure 2. In this case, the discrepancy between our estimate and their reported value of $\alpha = 0.05$ is completely due to the effect of the source size. Although accretion disk sizes are known to be smaller in X-rays, recent estimates are in the range of 0.1–1 light-days, depending on the mass of the black hole (see Mosquera et al. 2013), and these finite sizes will increase the stellar surface densities implied by the X-ray data. Another possible origin for this discrepancy is that Pooley et al. (2012) use the macro model as an unmicrolensed baseline for their analysis. It is well known that simple macro models are good at reproducing the positions of images, but have difficulty reproducing the flux ratios of images due to a range of effects beyond microlensing. Recently, Schechter et al. (2014) found that the fundamental plane stellar mass densities have to be scaled up by a factor 1.23 in order to be compatible with microlensing in X-rays in a sample of lenses with a large overlap with that analyzed by Pooley et al. (2012). It is unclear how this need for more mass in stars at the position of the images found by Pooley et al. (2012) can be reconciled with the apparently low estimate of mass in stars at those radii by Pooley et al. (2012). Our estimate of the stellar mass fraction agrees better with the results of microlensing studies of individual lenses (Keeton et al. 2006; Kochanek et al. 2006; Morgan et al. 2008, 2012; Chartas et al. 2009; Pooley et al. 2009; Dai et al. 2010) that reported values in the range 8%–25%, and with the estimates
from strong lensing studies (see for example Jiang & Kochanek 2007; Gavazzi et al. 2007; Treu 2010; Auger et al. 2010; Treu et al. 2010; Leier et al. 2011; Oguri et al. 2014) which produced stellar mass fractions in the range 30%–70% integrated inside the Einstein radius of the lenses.

The estimated size of the accretion disk in this work is slightly larger than the results found by other authors but still compatible with them (see Morgan et al. 2008; Blackburne et al. 2011; Mediavilla et al. 2011b; Muñoz et al. 2011; Jiménez-Vicente et al. 2012, 2014; Motta et al. 2012; Mosquera et al. 2013). Those studies find values roughly in the range of four to five light-days. Thus, our present estimate for the size of the accretion disk maintains the discrepancy with the simple thin disk model (Shakura & Sunyaev 1973) that predicts accretion disks of sizes roughly two to three times smaller. Spectroscopy (preferably at several epochs) for a larger sample of lens systems would allow us to expand the sample and to extend its conclusions. A larger sample could also be divided into statistically significant suitable subsamples to examine the dependence of the stellar mass fractions in the range 30%–70% integrated inside the present work shown in Figure 2. We are also grateful to the anonymous referee for useful suggestions that improved the presentation of this work. This research was supported by the Spanish Ministerio de Educación y Ciencia with grants AYA2011-24728, AYA2010-21741-C03-01, and AYA2010-21741-C03-02. J.J.V. is also supported by the Junta de Andalucía through the FQM-108 project. J.A.M. is also supported by the Generalitat Valenciana with grant PROMETEOII/2014/060. C.S.K. is supported by NSF grant AST-1009756.

APPENDIX

A SIMPLE THEORETICAL MODEL FOR THE LOCAL STELLAR MASS FRACTION IN LENS GALAXIES

Here, we describe the simple theoretical model shown as a dashed curve in Figure 2. In this model, the stars are distributed in the differential version of their results for comparison with the (local) fraction of mass in form of stars, which is represented as a dashed line in Figure 2, is the ratio of the stellar to total mass surface densities, \( \alpha(x) = \Sigma_s(x)/\Sigma_t(x) \). Note that \( \Sigma \propto v_{\text{max}}^2 \propto \Sigma_0 \) so that \( \alpha(x) \) is independent of the value of \( \Sigma_0 \).

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