MICROLENSING-BASED ESTIMATE OF THE MASS FRACTION IN COMPACT OBJECTS IN LENS GALAXIES

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ABSTRACT

We estimate the fraction of mass that is composed of compact objects in gravitational lens galaxies. This study is based on microlensing measurements (obtained from the literature) of a sample of 29 quasar image pairs seen through 20 lens galaxies. We determine the baseline for no microlensing magnification between two images from the ratios of emission line fluxes. Relative to this baseline, the ratio between the continua of the two images gives the difference in microlensing magnification. The histogram of observed microlensing events peaks close to no magnification and is concentrated below 0.6 mag, although two events of high magnification, Δm ≈ 1.5, are also present. We study the likelihood of the microlensing measurements using frequency distributions obtained from simulated microlensing magnification maps for different values of the fraction of mass in compact objects, α. The concentration of microlensing measurements close to Δm ≈ 0 can be explained only by simulations corresponding to very low values of α (10% or less). A maximum likelihood test yields α ≈ 0.05_{-0.03}^{+0.09} (90% confidence interval) for a quasar continuum source of intrinsic size r_s ≈ 2.6 × 10^{-15} cm. This estimate is valid in the 0.1–10 M⊙ range of microlens masses. We study the dependence of the estimate of α with r_s, and find that α ≤ 0.1 for r_s ≲ 1.3 × 10^{16} cm. High values of α are possible only for source sizes much larger than commonly expected (r_s ≫ 2.6 × 10^{16} cm). Regarding the current controversy about Milky Way/LMC and M31 microlensing studies, our work supports the hypothesis of a very low content in MACHOS (Massive Compact Halo Objects). In fact, according to our study, quasar microlensing probably arises from the normal star populations of lens galaxies and there is no statistical evidence for MACHOS in the dark halos.

Key words: dark matter – galaxies: halos – gravitational lensing

1. INTRODUCTION

The composition of matter in the halos of galaxies is a central problem in astrophysics. During the last 10 years, several observational projects have used gravitational microlensing (Paczynski 1986) to probe the properties of the halos of the Milky Way (MACHO, Alcock et al. 2000; EROS, Tisserand et al. 2007) and M31 (POINT-AGAPE, Calchi Novati et al. 2005; MEGA, de Jong et al. 2006). These experiments are based on the detection of magnification in the light curve of a source induced by an isolated point-like (or binary) object passing near the observer’s line of sight. From the successful detection of a number of microlensing events these collaborations have estimated the fraction of the halo mass that is composed of lensing objects, α. However, the reported results disagree. For the Milky Way’s halo the measurements of the MACHO collaboration (Alcock et al. 2000) correspond to a halo fraction of 0.08 < α < 0.50 while EROS (Tisserand et al. 2007) obtains α < 0.08. On the other hand, re-analysis of publicly available MACHO light curves (Belokurov et al. 2004) leads to results similar to those reported by EROS (however, see also the counter-report by Griest & Thomas 2005). For M31 the AGAPE (Calchi Novati et al. 2005) collaboration finds a halo fraction in the range 0.2 < α < 0.9, while MEGA (de Jong et al. 2006) finds a limit of α < 0.3.

The method applied to the Milky Way and M31 can be extended to the extragalactic domain by observing the microlensing induced by compact objects in the lens galaxy halo in images of multiply imaged quasars (quasar microlensing; Chang & Refsdal 1979, see also the review by Wambsganss 2006). Interpreting the light curves of QSO 2237+0305, Webster et al. (1991) suggest that the monitoring of microlensing variability can provide a measure of the optical depth in compact objects and in the smooth mass distribution. Lewis & Irwin (1996) proposed a statistical approach to the determination of the mass density in compact objects based on the comparison between the observed and simulated magnification probability distributions. Microlensing can also be measured from a single-epoch snapshot of the anomalous flux ratios induced by this effect between the images of a lensed quasar (Witt et al. 1995; see also Schechter & Wambsganss 2002). Schechter & Wambsganss (2004) explore the practical application of this idea by using a sample of 11 systems with measured flux anomalies. Other quasar microlensing studies of interest for the present study are aimed at the determination of accretion disk sizes (e.g., the studies based in relatively large samples by Poindexter et al. 2007, Morgan et al. 2007 and references therein).

In practice, the study of extragalactic microlensing meets significant obstacles, in particular (e.g., Kochanek 2004) larger timescales for microlensing variability and lack of a baseline for no magnification needed to detect and to quantify microlensing (see, however, the time variability based studies of several individual systems in Morgan et al. 2008 and references therein). In addition, microlensing by an isolated object is not a valid approximation. Microlensing at high optical depth should be modeled (e.g., by simulating magnification maps; see Schneider et al. 1992).
We avoid these obstacles by setting the baseline of no microlensing magnification using the narrow emission lines (NELs) in the spectra of lensed quasar images (Schechter & Wambsganss 2004 follow a similar approach but using theoretical models to define the baseline). It is generally expected that the regions where NELs originate are very large (compared with the continuum source) and are not affected by microlensing (this assumption can also be adopted, to some extent, for low ionization broad emission lines; Kaspi et al. 2000; Abajas et al. 2002). If we define the baseline from emission lines measured in the same wavelength regions as the continua affected by microlensing, we can also remove the extinction and isolate the microlensing effects.

“Intrinsic” flux ratios between the images in the absence of microlensing can be determined from the observation of the “intrinsic” magnifications between the images in the same wavelength as the continua affected by microlensing. The microlensing magnifications in the continuum and in the line emission can be determined from the observation of the “intrinsic” magnifications between the images in the same wavelength as the continua affected by microlensing.

### Table 1

| Object       | Image | Pair | \((\Delta m)^a\) | \((\Delta m)_{\text{cont/lines}}\) \((\text{cont/lines})^b\) | Lya | [Si iv]/[O iv] | C iv | [C ii] | [Mg ii] | [O iii] |
|--------------|-------|------|------------------|------------------------------------------------------------|-----|--------------|------|--------|--------|--------|
| HE 0047−1756 | B−A   | −0.19| 1.17/1.36        | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| HE 0435−1223 | B−A   | −0.24| ...              | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| HE 0512−3329 | B−A   | −0.40| 0.16            | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| SDSS 0806+2006 | B−A   | −0.47| 0.20            | ...                                                         | 0.06/0.33 | 0.06/0.72 | ...  | ...    | ...    | ...    |
| SBS 0909+532 | B−A   | −0.60| 0.15            | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| SDSS J0924+0219 | B−A   | 0.00 | ...              | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| FBQ 0951+2635 | B−A   | −0.69| 0.35            | ...                                                         | 0.08/1.12 | 0.13/0.46 | ...  | ...    | ...    | ...    |
| QSO 0957+561 | B−A   | −0.30| −0.30/0.00      | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| SDSS J1001+5027 | B−A   | 0.23 | 0.04            | ...                                                         | 0.63/0.35 | 0.38/0.19 | ...  | ...    | ...    | ...    |
| SDSS J1004+4112 | B−A   | 0.00 | 0.50/0.50       | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| C−A         | 0.45  | 0.64/0.19     | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| QSO 1017−207 | B−A   | −0.26| 0.11            | ...                                                         | −2.21/−2.08 | −2.24/−2.06 | −2.24/−1.41 | −2.15/−1.76 | ...  | ...    | ...    | ...    |
| HE 1104−1805 | B−A   | 0.60 | 0.03            | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| PG 1115+090 | A2−A1 | −0.65| −0.65/0.0        | ...                                                         | 1.75/1.12 | 1.68/1.12 | ...  | ...    | ...    | ...    |
| RXS J1131−1231 | A−B   | 1.39 | ...              | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| C−B         | 1.58  | ...          | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| SDSS J1206+4332 | A−B   | −0.56| 0.21            | ...                                                         | 0.32/1.08 | 0.54/0.89 | ...  | ...    | ...    | ...    |
| SDSS J1353+1138 | A−B   | 0.00 | ...              | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| HE 1413+117 | B−A   | 0.00 | 0.04            | ...                                                         | 0.23/0.19 | 0.20/0.23 | ...  | ...    | ...    | ...    |
| C−A         | −0.25| 0.10          | ...                                                         | −0.03/0.27 | −0.07/0.27 | ...  | ...    | ...    | ...    |
| D−A         | −0.75| 0.08          | ...                                                         | 0.2/−1.07 | 0.22/−0.85 | ...  | ...    | ...    | ...    |
| B J1422+231 | A−B   | 0.16 | 0.27/0.11       | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| C−B         | 0.02  | 0.75/0.77     | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| D−B         | −0.08 | 3.92/4.00    | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |
| SBS 1520+530 | B−A   | −0.39| 0.07            | ...                                                         | −0.04/0.27 | 0.08/0.54 | ...  | ...    | ...    | ...    |
| WFI 2033−4723 | B−C   | −0.50| ...              | ...                                                         | −0.09/0.41 | ...        | ...  | ...    | ...    | ...    |
| A2−A1       | 0.00  | 0.32/0.32    | ...                                                         | ... | ...         | ...  | ...    | ...    | ...    |

Notes.

a Average microlensing magnification, \((\Delta m) = \langle \Delta m_{\text{cont}} - \Delta m_{\text{line}} \rangle \).

b Magnitude differences between images in the continuum and in the line emission, respectively (when a global value for an spectral region including several lines is given).

c Magnitude differences between images in the continuum and in the line emission, respectively (when an individual value for one or more lines is available).

d Wisotzki et al. (2004; flux ratio given by the authors; continuum flux ratio estimated from Figure 3).

e Wisotzki et al. (2003; microlensing magnifications taken from Table 3).

f Wucknitz et al. (2003; microlensing magnification estimated from Figure 3).

g Inada et al. (2006; flux ratios computed from electronically digitized spectra).

h Mediavilla et al. (2005; microlensing magnification estimated from Figure 7).

i Eigenbrod et al. (2006; see the text).

j Schechter et al. (1998; flux ratios computed from electronically digitized spectra).

k Goicoechea et al. (2005; line flux ratio given by the authors; continuum flux ratio estimated from Figure 1).

l Oguri et al. (2005; flux ratios computed from electronically digitized spectra).

m Gómez-Álvarez et al. (2006; flux ratios estimated from Figures 3 and 4).

n Surdej et al. (1997; flux ratios computed from electronically available spectra).

o Wisotzki et al. (1993; flux ratio given by the authors; continuum flux ratios estimated from Figure 3).

p Popović & Chartas (2005; line flux ratio given by the authors; continuum flux ratio estimated from Figure 9).

q Sluse et al. (2007; flux ratios taken from Table 5).

r Oguri et al. (2005; flux ratios computed from electronically digitized spectra).
s Inada et al. (2006; see the text).

t Popović & Chartas (2005; flux ratios computed from electronically available spectra).
u Impey et al. (1996; flux ratios taken from Table 3).
v Chavushyan et al. (1997; flux ratios computed from electronically digitized spectra).
w Morgan et al. (2004; flux ratios estimated from Figure 9).
also be large enough to average out the effects of microlensing (see Kochanek 2004 and references therein). However, the extinction at mid-infrared and radio wavelengths is lower than the extinction at the wavelengths in which microlensing is usually detected and measured (optical, near-infrared, and X-ray). Consequently, the difference between the mid-infrared (radio) and the optical (X-ray or near-infrared) continuum fluxes will include not only the effects of microlensing but also the effects of extinction. In addition, note that the availability of data at optical wavelengths is considerably greater than at other wavelengths.

Thus, we will use the NEL and continuum flux ratios among the different images of a lensed QSO to estimate the difference of microlensing magnification between the images at a given epoch with certain restrictions that we detail in the following paragraphs.

The flux (in magnitudes) of an emission line observed at wavelength $\lambda$ of image $i$ of a multiply imaged quasar is equal to the flux of the source, $m_i^\text{lin}(\lambda)$, magnified by the lens galaxy (with a $\Phi_i$ magnification factor; $\mu_i = 2.5 \log \Phi_i$) and corrected by the extinction of this image caused by the lens galaxy, $A_i\left(\frac{\lambda}{1+z_s}\right)$ (see, e.g., Muñoz et al. 2004),

$$m_i^\text{lin}(\lambda) = m_0^\text{lin}\left(\frac{\lambda}{1+z_s}\right) + \mu_i + A_i\left(\frac{\lambda}{1+z_l}\right),$$

(1)

where $z_s$ and $z_l$ are the redshifts of the source and the lens, respectively.

In the case of the continuum emission, we must also take into account the intrinsic variability of the source combined with the delay in the arrival of the signal, which is different for each image, $\Delta t_i$, and the microlensing magnification, which depends on wavelength and time (with a $\phi_i\left[\frac{\lambda}{1+z_s},t\right]$ magnification factor; $\Delta \mu_i = -2.5 \log \phi_i$),

$$m_i^\text{con}(\lambda,t) = m_0^\text{con}\left(\frac{\lambda}{1+z_s},t-\Delta t_i\right) + \mu_i + A_i\left(\frac{\lambda}{1+z_l}\right) + \Delta \mu_i\left(\frac{\lambda}{1+z_l},t\right).$$

(2)

Thus, the difference between continuum and line fluxes cancels the terms corresponding to intrinsic magnification and

| Object        | Image Pair | $\Delta m_{\text{lines}}$ | $\Delta m_{\text{mid-IR}}$ |
|--------------|------------|--------------------------|---------------------------|
| SDSS J1004+4112a | B−A | 0.50 | 0.30 |
|               | C−A | 0.19 | 0.50 |
| HE 1104−1805b  | B−A | 1.12 | 1.13±0.06 |
|               | A2−A1 | 0.0 | 0.08±0.06 |
| HE 1413+117d   | B−A | 0.21±0.02 | 0.19±0.07 |
|               | C−A | 0.27±0.00 | 0.36±0.07 |
|               | D−A | 0.96±0.11 | 0.99±0.06 |
| B J1422+231c   | A−B | 0.11 | 0.18±0.05 |
|               | C−B | 0.77 | 0.61±0.06 |

Notes.

a Mid-IR data from Ross et al. (2009).
b Mid-IR data from Poinder et al. (2007).
c Mid-IR data from Chiab et al. (2005).
d Mid-IR data from MacLeod et al. (2009).

If we consider a pair of images, 1 and 2, the continuum ratio relative to the zero point defined by the emission line ratio can be written (in magnitudes) as

$$\Delta m(\lambda,t) = (m_1-m_2)^\text{con} - (m_1-m_2)^\text{lin} = \Delta \mu_1\left(\frac{\lambda}{1+z_1},t\right) - \Delta \mu_2\left(\frac{\lambda}{1+z_2},t\right).$$

(3)

If we consider a pair of images, 1 and 2, the continuum ratio relative to the zero point defined by the emission line ratio can be written (in magnitudes) as

$$\Delta m(\lambda,t) = (m_1-m_2)^\text{con} - (m_1-m_2)^\text{lin} = \Delta \mu_1\left(\frac{\lambda}{1+z_1},t\right) - \Delta \mu_2\left(\frac{\lambda}{1+z_2},t\right).$$

(4)

We have referred the equations for the magnification of both images to an arbitrary time, $t$ (note that microlensing-induced variability between a pair of images is uncorrelated).

The first term of Equation (4) is the relative microlensing magnification between images 1 and 2. The significance of the second term, $\Delta m_{\text{con}}$, which represents the source variability, can be estimated by comparing the intrinsic quasar variability on timescales typical of the time delay between images in gravitational lens systems with the expected distribution of microlensing magnifications. As we shall discuss in Section 4, the intrinsic source variability is not significant for our computations.

In summary, with the proposed method similar information as in the Milky Way MACHO experiments is obtained but with a single-epoch measurement. The objective of this study is to apply this method to published data of quasar microlensing. In Section 2, we collect the data from the literature and fit models to the systems of multiply imaged quasars to derive suitable values of the projected matter density at the image locations. Using these values, probabilistic models for microlensing magnifications are derived in Section 3.1 for a range of fractions of mass in compact objects. Sections 3.2 and 3.3 are devoted to estimate this fraction. Finally, in Section 4 we present and discuss the main conclusions.
2. OBSERVED MICROLENSING MAGNIFICATIONS AND MACRO-LENS MODELS

We collected the data, $\Delta m$ (see Equation (4)), examining all the optical spectroscopy found in the literature (see Table 1). In most cases, the microlensing magnification or the scaling of the emission line ratio with respect to the continuum ratio are directly provided by the authors or can be estimated from a figure. For SDSS 0806+2006, FBQ 0951+2635, SDSS J1001+5027, QSO 1017−207, SDSS J1206+4332, HE 1413+117, and SBS 1520+530 we used the electronically available or digitized spectra of the images to estimate the microlensing magnification following the steps described in Mediavilla et al. (2005). In Table 1, we include (when available) the flux ratios for each line and its corresponding continuum. Specific details of the procedure followed to obtain the data are also given.

For some of the image pairs (≈30% of the sample) there are mid-IR flux ratios available. Except for one system, SDSS J1004+4112 (where image C is probably affected by extinction, Gómez-Álvarez et al. 2006), they are in very good agreement with the emission-line flux ratios (see Table 2). The average difference between mid-IR and emission line flux ratios is only 0.11 mag (0.07 mag if SDSS J1004+4112 is removed). In fact, the agreement is unexpectedly good taking into account the possible influence of extinction and source variability. In any case, this comparison supports the consistency of the basic hypothesis (that the emission line fluxes are not affected by microlensing) and the reliability of the data.

Figure 1 shows the frequency of observed microlensing magnifications, $f_{\text{obs}}(\Delta m)$. This histogram exhibits two significant characteristics: the relatively high number of events with low or no microlensing magnification and the concentration (≈80%) of the microlensing events below $|\Delta m| = 0.6$. Any model attempting to describe microlensing magnification should account for these features. At a lower level of significance, the presence of two events of high magnification, $\Delta m \sim 1.5$, should also be noted. The data presented in Table 1 come from many different bibliographic sources with the subsequent lack of information.

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5 There are also several X-ray events in the literature that have been explained in terms of microlensing (e.g., Pooley et al. 2007 and references therein). These events probably arise from a tiny inner region, as compared with the optical continuum emitting region, and deserve an analogous but separate study when a sufficiently large sample of X-ray microlensing measurements become available.

Figure 2. Example of magnification maps for the case $\kappa = \gamma = 0.45$. From top to bottom and from left to right, maps correspond to $\alpha = 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.50, 1.00$. 
The models have been computed with the “lensmodel” code by No. 2, 2009. PROBING WITH MICROLENSING THE HALOS OF LENS GALAXIES 1455.

In Table 4, we show \( n_{k_1,k_2} \) (\( k_1 < k_2 \)), the frequency distribution of image pairs that occur at combined projected matter densities \( k_1, k_2 \). The distribution peaks at bin \( (k_1 = 0.45, k_2 = 0.55) \). In many of the image pairs in Table 3 the images are roughly located at similar distances from the lens galaxy center, \( r_1 \sim r_2 \). In an SIS model the convergence for each of the lensed images is given by \( k_1 = 1/2(1+x) \) and \( k_2 = 1/2(1-x) \), where \( x \) is the position of the source in units of the Einstein radius. The image configuration \( r_1 \sim r_2 \) is obtained when \( x \gtrsim 0 \); therefore, the expected values for the convergence are \( k_1 \lesssim 0.5 \) and \( k_2 \gtrsim 0.5 \). This is in agreement with Table 4 and in fact this simple reasoning could have been used to estimate, from a statistical point of view, the peak of the distribution of convergence values, \( n_{k_1,k_2} \), in our sample.

Observational uncertainties in the flux ratios, differential extinction in the lens galaxy and more complicated mass distributions for modeling the lens galaxy could have an important impact on the estimates of \( k \) and \( y \). Therefore, the values for \( k \) and \( y \) in Table 3 computed for an SIS+\( y \gamma \) model should be taken individually only as compatible values with high uncertainties. However, we will assume that the distribution of values in its entirety can be considered as statistically representative for the sample of observed image pairs. Fortunately, the uncertainty in the macro-lens models does not play a crucial role in the conclusions of our study.
3. STATISTICAL ANALYSIS OF THE OBSERVED MICROLENSING MAGNIFICATIONS

To analyze the microlensing magnification data, we need to consider that each $\Delta m$ measurement results from the flux ratio of two images seen through different locations at the lens galaxy. The microlensing magnification probability of a given image, $f_{\kappa_1,\kappa_2,\gamma}(m_1)$, depends on the projected matter density in compact objects, $\kappa_1$, the total projected mass density, $\kappa_1$, and the shear, $\gamma_1$. Thus, the probability distribution of the difference in microlensing magnification of a pair of images, $\Delta m = m_1 - m_2$, is given by the integral

$$f_{\kappa_1,\kappa_2,\kappa_1,\gamma_1,\gamma_2}(\Delta m) = \int f_{\kappa_1,\kappa_2,\gamma_1}(m_1) f_{\kappa_2,\gamma_2}(m_2) (m_1 - \Delta m)dm_1.$$  

To simplify the analysis we will suppose that the fraction of matter in compact objects, $\alpha = \kappa_1/\kappa$, is the same everywhere. The probability distribution of the difference in microlensing magnification of a pair of images can then be written as

$$f_{\alpha,\kappa,\gamma}(\Delta m) = \int f_{\kappa_1,\kappa_2,\gamma_1}(m_1) f_{\kappa_2}(m_2) (m_1 - \Delta m)dm_1.$$  

From this expression we can evaluate the probability of obtaining a microlensing measurement $\Delta m_1$ from a pair of images, $f'_{\alpha,\kappa,\gamma}(\Delta m_1)$. Then, to estimate $\alpha$ using all the available information we maximize the likelihood function corresponding to the $N$ measurements collected in Table 1,

$$\log L(\alpha) = \sum_{i=1}^{N} \log f'_{\alpha,\kappa,\gamma}(\Delta m_i).$$  

3.1. Probability Distributions of the Difference in Microlensing Magnifications for Image Pairs, $f_{\alpha,\kappa,\gamma}(m)$

We first compute the microlensing magnification probability distributions for one image, $f_{\alpha,\kappa,\gamma}(m)$. The first step is to simulate microlensing magnification maps for the different values of $\kappa$ and $\gamma$ in Table 3. We consider several values for the fraction of mass in compact objects $^5$: $\alpha = 1, 0.5, 0.3, 0.25, 0.2, 0.15, 0.10, 0.05, 0.03,$ and $0.01$. The histogram of each magnification map then provides a frequency distribution model of microlensing magnifications.

We obtain square maps 24 Einstein radii on a side with a spatial resolution of 0.012 Einstein radii per pixel. To compute the magnification maps we use the inverse polygon mapping method described in Mediavilla et al. (2006). An example of the maps is shown in Figure 2. The microlensing magnification at a given pixel is then obtained as the ratio of the magnification in the pixel to the average magnification. Histograms of these

5 This sequence of microlensing maps parameterized by $\alpha = \kappa_1/\kappa$ assumes that the overall mass distribution (compact objects and smooth mass distribution) is close to isothermal. However, in many studies (e.g., Dai et al. 2009) the lens galaxy is simulated with a constant mass-to-light ($M/L$) ratio model representing the galaxy stellar content (typically a de Vaucouleurs profile) embedded in a smooth halo of dark matter with no compact objects (a NFW halo, for instance; Navarro et al. 1996). In this case, the sequence of models is parameterized by $f_{M/L}$, the fraction of mass in the stellar component relative to a constant $M/L$ ratio model with no halo (that is, the model with $f_{M/L} = 1$). Although the meanings of $\alpha$ and $f_{M/L}$ are different, the results of both procedures can be compared obtaining from each $f_{M/L}$ model values of $\alpha$ and $\kappa_1$.

normalized maps give the relative frequency of microlensing magnifications for a pixel-size source (see some examples in Figure 3). These distributions are in agreement with the results obtained with a different method by Lewis & Irwin (1995).

To model the unresolved quasar source we consider a Gaussian with $r_s = 2.6 \times 10^{15}$ cm (1 ld; Shalyapin et al. 2002; Kochanek 2004). The convolution of this Gaussian with the “pixel” maps gives the magnification maps for the quasar. For a system with redshifts $z_1 \sim 0.5$ and $z_2 \sim 2$ for the lens and the source respectively, the Einstein radius for a compact object of mass $M$ is $\eta_0 \sim 5.2 \times 10^{16} \sqrt{M/M_{\odot}}$ cm. Thus, for $M = 1 M_{\odot}$, $\eta_0 \sim 5.2 \times 10^{16}$ cm, and the size of a pixel is $6.2 \times 10^{14}$ cm.

Finally, the histograms of the convolved maps give the frequency distributions of microlensing magnifications, $f_{\alpha,\kappa,\gamma}(m)$, which show differences with respect to the results obtained for a pixel-size source at the high magnification wing (the same effect that can be observed in Lewis & Irwin 1995). From the cross-correlation of pairs of these individual probability functions $f_{\alpha_1,\kappa_1,\gamma_1}(m_1)$, and $f_{\alpha_2,\kappa_2,\gamma_2}(m_2)$ (see Equation (6)) we obtain the probability function of the difference in microlensing magnification between two images, $f_{\alpha_1,\alpha_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m = m_1 - m_2)$. In Figures 4–6 the $f_{\alpha_1,\alpha_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m)$ distributions corresponding to the 29 image pairs of Table 3 are plotted.

3.2. Maximum Likelihood Estimate of the Fraction of Mass in Compact Objects, $\alpha$: Confidence Intervals

In Figure 7, we present $\log L(\alpha)$ (see Equation (7)). Using the $\log L(\alpha \pm n\sigma_\alpha) \sim \log L_{\text{max}} - n^2/2$ criterion we derive $\alpha(\log L_{\text{max}} = 0.10^{+0.04}_{-0.03}$ (90% confidence interval).

The maximum likelihood method can be affected by errors in the microlensing measurements, $\sigma_{\Delta m}$. From Equation (7) we
Figure 4. Probability models, $f_{\alpha_1,\alpha_2,k_1,k_2,\gamma_1,\gamma_2}(\Delta m = m_1 - m_2)$, corresponding to each image pair in the sample for different values of the fraction of mass in compact objects, $\alpha$ (see the text). $\mu_1$ and $\mu_2$ are the magnifications of the images considered in each pair. The vertical dashed line corresponds to the microlensing measurement value.

obtain

$$\Delta \log L(\alpha) = \sum_{i=1}^{N} \frac{1}{f_{\alpha_1,\alpha_2,k_1,k_2,\gamma_1,\gamma_2}(\Delta m_i)} \frac{\partial f_{\alpha_1,\alpha_2,k_1,k_2,\gamma_1,\gamma_2}(\Delta m_i)}{\partial \Delta m_i} \sigma_{\Delta m_i}. \tag{8}$$

According to this last expression, microlensing measurement errors do not significantly affect the likelihood of flat probability distributions (typical of large values of $\alpha$). On the contrary, the likelihood functions corresponding to low values of $\alpha$ (associated with sharply peaked probability distributions) can be strongly modified by the microlensing measurement errors. Note, moreover, that these changes tend to penalize the low $\alpha$ hypothesis.

To show the impact of $\sigma_{\Delta m}$ on the maximum likelihood estimate of $\alpha$, in Figure 7 we also present $\log L(\alpha)$ (see Equation (7)) with error bars, $\pm \Delta \log L(\alpha)$, estimated considering that each $\Delta m_i$ is a normally distributed variable with $\sigma_{\Delta m} = 0.20$ (a realistic estimate). Using the $\log L(\alpha \pm \sigma_{\alpha}) \sim \log L_{\text{max}} - n^2/2$ criterion and taking into account the error bars of $\log L(\alpha)$, we derive $\alpha(\log L_{\text{max}}) = 0.05^{+0.09}_{-0.03}$ (90% confidence interval).

3.3. Influence of the Continuum Source Size, Influence of the Microlenses Mass

Increasing the size parameter of the Gaussian representing the continuum source, $r_s$, affects the previous results by smoothing the magnification patterns and, consequently, the probability distributions. To study the dependence of the estimate of $\alpha$ on the source size we have computed probability and likelihood functions for several values of this parameter, $r_s = 0.62 \times 10^{15}, 2.6 \times 10^{15}, 8 \times 10^{15}$, and $26 \times 10^{15}$ cm. To correct $r_s$ from projection effects we have taken into account that the intrinsic and projected source areas are related by a $\cos i$
Figure 5. Probability models, $f_{\alpha_1,\alpha_2,\kappa_1,\kappa_2,\gamma_1,\gamma_2}(\Delta m = m_1 - m_2)$, corresponding to each image pair in the sample for different values of the fraction of mass in compact objects, $\alpha$ (see the text). $\mu_1$ and $\mu_2$ are the magnifications of the images considered in each pair. The vertical dashed line corresponds to the microlensing measurement value.

factor; that is $r_e \sim \sqrt{\cos i} r_{\text{rs}}$. Assuming that the (disk) sources are randomly oriented in space (the probability of finding a disk with inclination, $i$, proportional to $\sin i$) and averaging on the inclination, we obtain $r_{\text{rs}} \sim 1.5 r_e$. In Figure 8, we present the likelihood functions corresponding to sources of several deprojected size parameters, $r_{\text{rs}}$. In Figure 9, we plot the maximum likelihood estimate of $\alpha$ versus $r_{\text{rs}}$. Error bars correspond to 90% confidence intervals. According to this figure, low values of $\alpha$ are expected for continuum source sizes, $r_{\text{rs}}$, of the order of $10^{16}$ cm or less. Observing microlensing variability for nine gravitationally lensed quasars Morgan et al. (2007) measure the accretion disk size. The average value of the nine half-light radius determinations is $\langle r_{1/2} \rangle = 6 \times 10^{15}$ cm. For this value we found (see Figure 9) $\alpha = 0.05 \pm 0.09$. Morgan et al. (2007) report a scaling between the accretion disk size and the black hole mass. In the range of black hole masses considered by Morgan et al. (2007) the maximum is $M_{\text{BH}} = 2.37 \times 10^9 M_\odot$, which, using the scaling derived by these authors, corresponds to $r_{1/2} \approx 2.4 \times 10^{16}$ cm. For this size we obtain (see Figure 9) $\alpha \approx 0.10$. Values $M_{\text{BH}} \geq 10^{10} M_\odot (r_{1/2} \geq 3.4 \times 10^{16}$ cm) should be considered to obtain $\alpha \geq 0.20$. On the other hand, Pooley et al. (2007) comparing X-ray and optical microlensing in a sample of 10 lensed quasars inferred $r_{1/2} \sim 1.3 \times 10^{16}$ cm. For this size we obtain (see Figure 9) $\alpha = 0.10 \pm 0.05$. Thus, according to these recent size estimates based on the observations of two relatively large samples of gravitational lenses, high values of $\alpha$ are possible only if the continuum source size is substantially larger than expected.

Owing to the scaling of the Einstein radius with mass, $\eta_0 \propto \sqrt{M}$, a change in the mass of microlenses can be
alternatively seen as a change in the spatial scaling of the magnification pattern that leaves invariant the projected mass density, $\kappa$. Thus, multiplying the mass of the microlenses by a factor $C$ (and leaving unaltered the continuum size) is equivalent to multiplying the size of the continuum source by a factor $1/\sqrt{C}$ (leaving unaltered the masses of microlenses). Then the computed models corresponding to sources of sizes $r_s = 0.62 \times 10^{15}$, $2.6 \times 10^{15}$, and $8 \times 10^{15}$ cm (with $1 \, M_\odot$ microlenses) are equivalent to models corresponding to microlens masses of 17, 1, and $0.1 \, M_\odot$ (with $r_s = 2.6 \times 10^{15}$ cm). This result implies that the probability models do not differ significantly if we change the mass of microlenses between 17 and $0.1 \, M_\odot$.

Thus, microlensing statistics are insensitive to changes of mass in the expected range of stellar masses.

4. DISCUSSION AND CONCLUSIONS

In the previous sections, we have extended to the extragalactic domain the local (Milky Way, LMC, and M31) use of microlensing to probe the properties of the galaxy halos. Although our primary aim was to explore the practical application of the proposed method, we found that the data available in the literature can be consistently interpreted only under the hypothesis of a very low mass fraction in microlenses; at 90% confidence: $\alpha(\log L_{\text{max}}) = 0.05^{+0.09}_{-0.03}$ (maximum likelihood estimate) for a
quasar continuum source of intrinsic size $r_s = 2.6 \times 10^{15}$ cm. This result arises directly from the shape of the histogram of microlensing magnifications, with a maximum of events close to no magnification and stands for a wide variety of microlensing models statistically representative of the considered image pairs. There is a dependence of the estimate of $\alpha$ on the source size but high values of the mass fraction ($\alpha > 0.2$) are possible only for unexpectedly large source sizes ($r_s > 4 \times 10^{16}$ cm). The low mass fraction is in good agreement with the results of EROS (Tisserand et al. 2007) for the Milky Way, with the estimate of OGLE for the LMC (Wyrzykowski et al. 2009), and with the limit established by MEGA (de Jong et al. 2006) for M31. The agreement is also good with the few microlensing-based estimates available for individual objects. In RXJ 1131$-$1231, Dai et al. (2009) found $\alpha \sim 0.1$. In PG 1115$+$080, Morgan et al. (2008) obtained values in the range $0.08 \sim 0.15$. For the same system, Pooley et al. (2009) found $\alpha \sim 0.1$ for a source of size $r_s = 1.3 \times 10^{16}$ cm.

On the other hand, our estimate of the fraction of mass in microlenses, $\alpha (\log L_{\text{max}}) = 0.05^{+0.09}_{-0.03}$, approximates the expectations for the fraction of visible matter. Jiang & Kochanek (2007), for instance, comparing the mass inside the Einstein ring in 22 gravitational lens galaxies with the mass needed to produce the observed velocity dispersion, inferred average stellar mass fractions of 0.026 $\pm$ 0.006 (neglecting adiabatic compression) and 0.056 $\pm$ 0.011 (including adiabatic compression). As discussed in Jiang & Kochanek (2007) these values are also in agreement with other estimates of the stellar mass fraction that relied on stellar population models: $\sim 0.08$ (Lintott et al. 2006), $0.065^{+0.010}_{-0.008}$ (Hoekstra et al. 2005), and $0.03^{+0.02}_{-0.01}$ (Mandelbaum et al. 2006). Thus, we can conclude that microlensing is probably caused by stars in the lens galaxy, and that there is no statistical evidence for MACHOS in the halos of the 20 galaxies of the sample we considered.

How robust are these results? There are several sources of uncertainty to consider. First, we neglected in Equation (4) the term arising from source variability, $\Delta m_{\text{con}}^{\text{src}}$. From a group of 17 gravitational lenses with photometric monitoring available in the literature we estimate an average gradient of variability of 0.1 mag year$^{-1}$. Taking into account that the average delay between images is about three months (a conservative estimate; note that the group of lens systems used includes many doubles, some of them with very large time delays) we can expect an amplitude related to intrinsic source variability of $\Delta m_{\text{con}}^{\text{src}} \sim 0.03$, which, according to the histogram of magnifications (Figure 1), is not significant. Moreover, if we assume that the probability of $\Delta m_{\text{con}}^{\text{src}}$ is normally distributed, the global effect of source variability is to broaden the histogram of microlensing magnifications, diminishing the peak and enhancing the wing. In other words, source variability leads to an underestimate of $\alpha$. Thus, the mass fraction should be even lower if significant source variability were hidden in the data. In the same way, other sources of error in the data, such as the difficulty in separating line and continuum or in removing from the narrow emission lines the high ionization broad emission lines that could be...
partially affected by microlensing, probably tend to induce additional magnitude differences, $\Delta m$, between the images and, hence, to an overestimate of $\alpha$. On the contrary, cross-contamination between the spectra of a pair of images masks the impact of microlensing and may affect our results. Although most of the bibliographic sources of microlensing measurements analyze this problem concluding that the spatial resolution was sufficient to extract the spectra without contamination, it is clear that high signal-to-noise ratio (S/N) data obtained in subarcsecond seeing conditions will help to control this important issue.

Another point to address is the treatment of some of the quads, where only a subset of the images are used. Are we systematically excluding faint images that might be highly demagnified by microlensing? Let us examine the four incomplete quads in our sample. The fold lens SDSS J1004+4112 has two close images A and B. A is probably a saddle-point image and shows the most anomalous flux (Ota et al. 2006). In contrast, the optical/X-ray flux ratios of C and D are almost the same. Thus, there is no reason to suppose that the image without a useful spectrum (D) has higher microlensing probability than the others. PG 1115+080 is another fold quad. $A_1$ and $A_2$ are the two images closest to the critical curve and have a (moderately) anomalous flux ratio and optical variability (Pooley et al. 2007). The two images without available spectra (C and D) show only a small optical variability and are not particularly prone to microlensing. The case of SDSS 0924+0219 is more problematic. There are two sets of data for this object, one by Eigenbrod et al. (2006) based on observations of the low ionization lines [Mg ii] and [C iii], which, after two epochs of observation, reveals no difference between the line and continuum flux ratios of components A and B. The other set of data (Keeton et al. 2006) is based on Ly$\alpha$ observations (a high ionization emission line supposed to come from a smaller region than the low ionization emission lines) and microlensing is detected not only in the continuum but also in the emission lines. This implies that the baseline for no microlensing magnification cannot be defined and, consequently, we could not consider Keeton et al. (2006) results. Anyway, we have repeated (as a test) the entire maximum likelihood estimate procedure to derive $\alpha$ but now using for SDSS 0924+0219 the microlensing measurements by Keeton et al. (2006). The results are almost identical: $\alpha = 0.05_{-0.03}^{+0.10}$.

The size of the sample also limits the statistical interpretation. An improvement in the S/N of the histogram of microlensing magnifications is very important to ascertain the statistical significance of the low frequency of events at large magnification (only two events of high magnification are detected), which can impose severe constraints on the microlensing models. Another reason to increase the size of the sample is the possibility to define subsamples at different galactocentric distances where different ratios of visible to dark matter are expected. In the same way, it would be possible to define subsamples according to the type of lens galaxy or other interesting properties of lens systems.

In any case, the impact of the main result of our study—absence of MACHOS in the 10–0.1 $M_\odot$ mass range in the halos of lens galaxies—and its future prospects, points to the need to improve the statistical analysis in two ways: increasing the number, quality, and homogeneity of the microlensing magnification measurements from new observations, and reducing the uncertainties in the macro-lens models.

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