A ROBUST DETERMINATION OF THE SIZE OF QUASAR ACCRETION DISKS USING GRAVITATIONAL MICROLENSING

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ABSTRACT

Using microlensing measurements for a sample of 27 image pairs of 19 lensed quasars we determine a maximum likelihood estimate for the accretion disk size of an average quasar of \( r_\text{d} = 4.0^{+2.4}_{-1.1} \) lt-day at rest frame (\( \lambda = 1736 \) Å) for microlenses with a mean mass of \( \langle M \rangle = 0.3 \, M_\odot \). This value, in good agreement with previous results from smaller samples, is roughly a factor of five greater than the predictions of the standard thin disk model. The individual size estimates for the 19 quasars in our sample are also in excellent agreement with the results of the joint maximum likelihood analysis.

Key words: accretion, accretion disks – gravitational lensing: micro – quasars: general

1. INTRODUCTION

The thin disk (Shakura & Sunyaev 1973) is the standard model for describing the inner regions of quasars. This model predicts typical sizes for the accretion disks of luminous quasars of \( \sim 10^{15} \) cm (\( \sim 0.4 \) lt-day) in the (observer frame) optical bands. However, recent measurements based on quasar microlensing are challenging this prediction. Based on a combined optical and X-ray study of microlensing in 10 quadruply lensed quasars, Pooley et al. (2007) found that the source of optical light is larger than expected from basic thin accretion disk models by factors of 3–30. Studying microlensing variability observed for 11 gravitationally lensed quasars, Morgan et al. (2010) also found that the microlensing estimates of the disk size are larger (by a factor \( \sim 4 \)) than would be expected from thin disk theory. Other monitoring-based studies focused on individual objects such as QSO2237+0305 (Kochanek 2004; Anguita et al. 2008; Eigenbrod et al. 2008; Mosquera et al. 2009; Agol et al. 2009; Poindexter & Kochanek 2010), PG1115+080 (Morgan et al. 2008), RXJ1131−1231 (Dai et al. 2010), HE1104−1805 (Poindexter et al. 2008), or HE0435−1223 (Blackburne et al. 2011a) generally support these conclusions.

From single-epoch optical/IR and X-ray measurements, Blackburne et al. (2011b) used the wavelength dependence of microlensing (chromaticity) to study the structure of accretion disks in 12 four-image lensed quasars, finding disk sizes larger than predicted by nearly an order of magnitude. More detailed studies of individual objects based in microlensing chromaticity (Eigenbrod et al. 2008; Poindexter et al. 2008; Mosquera et al. 2011; Mediavilla et al. 2011b; Muñoz et al. 2011) also found that the size estimated from microlensing is substantially larger than the values predicted by the thin disk theory (by factors of about 10 in HE0435−1223, 5 in SBS0909+532, and 4 in HE1104−1805). Upper limits on the sizes of MG0414+0534 and SDSSJ0924+0219 have also been set by Bate et al. (2008) and Floyd et al. (2009), respectively.

Here, we will generalize these results by extending the study to the sample of 20 lensed quasars of Mediavilla et al. (2009, hereafter MED09). Our data consist of microlensing amplitude measurements for 29 image pairs from 20 lensed quasars based on a comparison between the flux ratios in the continuum and an adjacent emission line. The emission line flux ratio provides an unmicrolensed baseline that also removes the effects of extinction (see, e.g., Falco et al. 1999; Muñoz et al. 2004) and lens models in the determination of the magnification anomalies. As noted in previous works (Kochanek 2004; Eigenbrod et al. 2008; Blackburne et al. 2011b), studies favoring the selection of objects with noticeable magnification anomalies (or epochs with high microlensing activity) may lead to a bias toward smaller quasar size determinations. The fact that one object does not show microlensing magnification anomalies may be because it is either too big or it lies in a region without significant magnification fluctuations. Thus, non-detection of microlensing also puts constraints on the size of the sources and should be taken into account. The MED09 sample is also unaffected by this bias (indeed the histogram of estimated microlensing magnifications in this sample peaks at \( \Delta \mu = 0 \)). However, the data from MED09 do not include, for most image pairs, enough measurements at different wavelengths to address chromaticity. For this reason we will start discussing the impact of chromaticity on the determination of microlensing based sizes (Section 2) to show that size estimates are dominated by microlensing amplitude and are relatively independent of chromaticity. In Section 3, we will use the microlensing data from MED09 to calculate a maximum likelihood estimate of the accretion disk size. The estimate will be for the typical size of the accretion disk of an average quasar rather than that of any particular source. We also make individual size estimates for the 19 objects using a complementary Bayesian approach, finding excellent agreement with the likelihood analysis. The main conclusions are presented in Section 4.

2. SIZE DETERMINATION FROM SINGLE-WAVELENGTH MICROLENSING MEASUREMENTS

We will base our analysis on the microlensing measurements inferred by MED09 from optical spectroscopy available in the literature (29 quasar image pairs seen through 20 lens
The microlensing magnification between two images, 1 and 2, is calculated as \( \Delta m = (m_2 - m_1)_{\text{micro}} = (m_2 - m_1)_{\text{cont}} - (m_2 - m_1)_{\text{line}} \), where \( (m_2 - m_1)_{\text{line}} \) is the flux ratio in an emission line and \( (m_2 - m_1)_{\text{cont}} \) is the flux ratio of the continuum adjacent to the emission line. With this method, the microlensing magnification is isolated from extinction and from the mean lensing magnification, as these affect the line and the adjacent continuum equally. The consistency of this procedure has been confirmed with mid-IR data (MED09). The histogram of observed microlensing magnifications in MED09 showed that 93\% of the quasar image pairs have microlensing \( |\Delta m| \leq 0.8 \, \text{mag} \). In this section, we are going to use this statistical constraint to estimate quasar accretion disk sizes from single-wavelength microlensing measurements.

We will apply a statistical approach similar to that used by Mediavilla et al. (2011b) to a representative lens system. Therefore, we take for the lens a standard SIS with values \( \kappa_1 = \gamma_1 = 0.45 \) and \( \kappa_2 = \gamma_2 = 0.55 \) for the convergence and shear at the positions of the two images. These values are typical of the lenses in the MED09 (cf. their Table 4). For the redshifts of the lens and source we have taken the values \( z_l = 0.57 \) and \( z_s = 1.76 \), which are the average values for the sample.

Using these parameters for the macro lens, we generate microlensing magnifications maps at the positions of images 1 and 2 using the inverse polygon mapping algorithm described in Mediavilla et al. (2006, 2011a). The calculated maps are \( 2000 \times 2000 \) pixels in size, with a pixel size of 0.5 lt-day, or equivalently \( 1.295 \times 10^{15} \) cm. In the image plane, the covered area is the source plane area increased by factors of \( \lambda R/\lambda B \) and the chromaticity \( (\Delta m)_{\text{obs}} \), where \( \alpha \) is the wavelength-dependent parameter (related to the half-light radius as \( R_{1/2} = 1.18 r_s \)). The wavelength dependence of the disk size is parameterized by a power law with exponent \( p \) such that \( r_s(\lambda) \propto \lambda^p \). We smooth each of the two magnification maps with Gaussians scaled to two wavelengths, \( \lambda_B \) and \( \lambda_R \), representing characteristic blue and red wavelengths. We choose \( \lambda_B/\lambda_R = 2.3 \), the ratio between Ly\( \alpha \) and Mg\( ii \), which is roughly the wavelength range covered by observations in the optical band.

We calculate the probability of observing microlensing magnifications \( \Delta m = \mu_2 - \mu_1 \) (where \( \mu_1 \) and \( \mu_2 \) are the magnifications at the positions of images 1 and 2, respectively) at wavelengths \( \lambda_B \) and \( \lambda_R \), namely, \( \Delta m_B \) and \( \Delta m_R \). For every pair of values \( (\Delta m_B, \Delta m_R) \), the probability is calculated for a 2D grid in the source size at \( \lambda_B \) (i.e., \( r_s(\lambda_B) \)) and in the exponent \( p \). We use a natural logarithmic grid in \( r_s \) such that \( \ln r_s^i = 0.3 \times i \) for \( i = 0, \ldots, 11 \) (\( r_s^i \) in lt-day) and a linear grid in \( p \) such that \( p^i = 0.25 \times i \) for \( i = 0, \ldots, 13 \). We restrict ourselves to the case \( |\Delta m_B| > |\Delta m_R| \), as we assume that the size of the source increases with wavelength, and therefore the largest magnifications are expected for the smallest (i.e., bluest) sources.\(^8\)

The probability of observing \( \Delta m_B^{\text{obs}} \) and \( \Delta m_R^{\text{obs}} \) in a model with parameters \( r_s^i \) and \( p^i \) is given by

\[
\chi^2 = \frac{(\Delta m_B - \Delta m_B^{\text{obs}})^2}{\sigma_{\Delta m_B}^2} + \frac{(\Delta m_R - \Delta m_R^{\text{obs}})^2}{\sigma_{\Delta m_R}^2},
\]

where \( N_{ij} \) is the number of trials with \( \Delta m_B \) and \( \Delta m_R \) for the case with parameters \( r_s^i \) and \( p^i \), and \( \sigma_{\Delta m_B} \) and \( \sigma_{\Delta m_R} \) are the uncertainties in the observed microlensing magnifications, for which we have taken a typical value of \( \sigma_{\Delta m_B} = \sigma_{\Delta m_R} = 0.05 \, \text{mag} \).

The calculations are performed for a grid of \( \Delta m_B \), \( \Delta m_R \) with \( \Delta m_B = 0.2 \times k \) for \( k = -4, \ldots, 4 \) and \( \Delta m_R = 0.2 \times m \) for \( m = 0, \ldots, k \) (so we always have \(|\Delta m| < |k|\) and \(|\Delta m_B| > |\Delta m_R|\) for \( \alpha = 0.05 \) and \( \alpha = 0.1 \). This range of values for the strength of microlensing covers the vast majority of observed cases as shown in the histogram of observed microlensing strengths in the sample of MED09 (their Figure 1). Thus, the probability distribution \( p_{r_s, p} (\Delta m_B^{\text{obs}}, \Delta m_R^{\text{obs}}) \) is calculated for 

\[
14 \times 12 \times 29 \times 2 = 9744 \text{ cases for each one of those cases (i.e., for every quadruplet (p, r_s, \Delta m_B^{\text{obs}}, \Delta m_R^{\text{obs}})), the probability is calculated using} 10^4 \text{ trials. Since each trial draws an independent magnification from two different maps, this does not exhaust the possible number of independent trials.}

The results for the case \( \alpha = 0.05 \) are shown in Figure 1 for \( \Delta m_B > 0 \). We have shown only the right side of the full figure, as the cases with \( \Delta m_B < 0 \) are roughly similar to those with the same value of \( |\Delta m_B| \) so that the scenario is fairly symmetric with respect to \( \Delta m_B = 0 \). For the case of \( \alpha = 0.1 \) the results are very similar but the peaks in the probability distributions are displaced toward slightly higher values of \( r_s \).

With the exception of the cases in which \( \Delta m_B = \Delta m_R \), the distributions show a clear covariance in the sense that larger sizes imply lower values of the exponent \( p \). We also see that larger values of \( \Delta m_B \) favor smaller values for the source size \( r_s \).

The most important result from this figure is that the probability distribution with respect to the size \( r_s \) is dominated by the strength of microlensing \( \Delta m_B \) with very little dependence on the amount of chromaticity. Conversely, the value of the chromaticity \( \Delta m_R - \Delta m_B \) is the main factor in determining the exponent \( p \). Indeed, the most probable values of \( r_s \) (values within 1\( \sigma \) around the maximum of the distributions in Figure 1) remain roughly constant along each column in Figure 1 as we move through the different rows. This fact is illustrated in Figure 2, where the marginalized (over \( p \)) probability distributions for different values of \( \Delta m_R \) are shown for the case of \( \Delta m_B = 0.6 \). The figure shows clearly that the most probable size is fairly independent of \( \Delta m_B \) (unless \( \Delta m_B = \Delta m_R \)) Thus, even if we lack information on chromaticity, we can still obtain valuable information on the sizes of the sources from measurements of microlensing at a single wavelength. Another interesting and robust result from Figure 1 is that, unless there is no detected microlensing \( (\Delta m_B = 0) \), the maxima of the distributions are all located in a fairly restricted range in \( r_s \). Therefore, microlensing magnifications in the range \( 0 \leq (\Delta m_B) \leq 0.8 \) will provide sizes in a rather restricted range between \( \sim 1(\Delta m/\Delta m_{\odot}) \) and \( \sim 16(\Delta m/\Delta m_{\odot}) \) lt-day irrespective of chromaticity, with larger magnifications favoring smaller sizes.

3. DISCUSSION

Based on the results of the previous section, it is possible to constrain the size of the sources from measurements of

\[ \chi^2 = \frac{(\Delta m_B - \Delta m_B^{\text{obs}})^2}{\sigma_{\Delta m_B}^2} + \frac{(\Delta m_R - \Delta m_R^{\text{obs}})^2}{\sigma_{\Delta m_R}^2}. \]

\(^8\) Inversions are possible but rare (see Poindexter et al. 2008).
Figure 1. Grid of two-dimensional probability distributions \( p_{\mu,\nu}(\Delta m_{\text{obs}}^B, \Delta m_{\text{obs}}^R) \) for the 15 cases with \( \Delta m_B > 0 \) and \( \alpha = 0.05 \). Each column corresponds to the distribution for a given value of \( \Delta m_B \) indicated at the top of the column. Each row corresponds to the distribution for a given value of \( \Delta m_R \) indicated at the right. For each distribution the abscissae represent \( p \) from 0.0 to 3.25 and the ordinates represent \( \ln r_s \) from 0.0 to 3.3 (\( r_s \) in lt-day). The contour levels are drawn at intervals of 0.25\( \sigma \) (the contour at \( n\sigma \) is drawn at \( \exp(-n^2\sigma^2/2) \) from the peak of the distribution). The contour at 1\( \sigma \) is thicker than the rest.

The microlensing strength at a single wavelength, even if we have no information on the amount of chromaticity present. As noted above (see also Kochanek 2004; Eigenbrod et al. 2008; Blackburne et al. 2011b), each single microlensing measurement is affected by a degeneracy between the range of possible magnifications and source size effects. Statistics of large samples of lensed quasars (like MED09) can be used to minimize this uncertainty. In particular, we use a maximum likelihood method to estimate an average size from the product of the individual likelihood functions for each image pair. This method includes the cases with little or no microlensing that by themselves would give rise only to lower limits on the size on an equal footing with those showing significant microlensing.

The microlensing magnifications in this sample have been calculated using the continuum-to-line-flux ratios of different lines for different objects. As size is related to wavelength, we should ideally use objects with magnifications obtained from lines at similar wavelengths. On the other hand, to have good statistics, we should also try to keep the sample as large as possible. With these restrictions in mind, we have chosen a compromise in which we used all objects with magnifications measured in the wavelength range between Ly\( \alpha \) (1216 Å) and Mg \( \text{\footnotesize{II}} \) (2798 Å). With this choice, the average rest wavelength is
in the relatively narrow range of $(\lambda) = 1736 \pm 373$ Å, while we still keep 27 image pairs from 19 lensed quasars. The dispersion introduced by the effect of wavelength in the size estimate will be taken into account later. We then use the measured microlensing magnifications in these 27 pairs as observed $\Delta m_B$ (where $B$ now stands for the average wavelength $(\lambda) = 1736$ Å).

We computed magnification maps for each one of the images of the 27 pairs individually taking the $\alpha$ and $\gamma$ values from MED09 (except for SBS0909+532, for which we take the values in Mediavilla et al. 2011a). We again consider only $\alpha = 0.05$ and $\alpha = 0.1$. The calculated maps are $2000 \times 2000$ pixels in size, with a pixel size of 0.5 lt-day. We have used the same logarithmic grid in $r_s$ from Section 2, as well as a linear grid $r_s^i = 1.0 + 2.0 \times i$ lt-day for $i = 0, \ldots, 24$. Using the magnification maps, the probability of observing a microlensing magnification $\Delta m_{\text{obs}}$ in image pair $j$ for a model with parameter $r_s^i$ is given by

$$p_{r_s^i} (\Delta m_{\text{obs}}) \propto \int N_i e^{-\chi^2/2} d\Delta m,$$

where

$$\chi^2 = \frac{(\Delta m - \Delta m_{\text{obs}})^2}{\sigma^2_{\Delta m_{\text{obs}}}}.$$  

We can calculate a likelihood function for $r_s$ as

$$L (r_s^i) \propto \prod_j p_{r_s^i} (\Delta m_{\text{obs}}^j),$$

where $j$ runs over the 27 image pairs considered.

The results of this procedure for $\alpha = 0.05$ and $\alpha = 0.1$ are shown in Figure 3. The maximum likelihood occurs for $\ln r_s = 2.0^{+0.3}_{-0.8}$ and $\ln r_s = 2.3^{+0.4}_{-0.8}$ (ls in lt-day) for $\alpha = 0.05$ and $\alpha = 0.1$, respectively. Taking into account that $r_s \propto \langle M \rangle^{1/2}$ where $\langle M \rangle$ is the mean mass of the microlenses, our results for the mean size of the accretion disks of quasars are $r_s = 7.4^{+3.6}_{-0.8} (\langle M \rangle/M_\odot)^{1/2}$ lt-day for $\alpha = 0.05$ and $r_s = 10^{+5.0}_{-5.0} (\langle M \rangle/M_\odot)^{1/2}$ for $\alpha = 0.1$. When scaled for a mean microlens mass of $\langle M \rangle = 0.3 M_\odot$, representative of the stellar
In Figure 4, we compare our estimates with previous results. Estimates from the present work are indicated with filled symbols and estimates from previous works with open symbols. We have taken black-hole masses from Table 1 in Mosquera & Kochanek (2011), which they take from Peng et al. (2006), Greene et al. (2010), and Assef et al. (2011). The thin line corresponds to the theoretical prediction for the thin disk model at 1736 Å (with $L/L_E = 1$ and $\eta = 0.1$). The thick line corresponds to the empirical fit by Morgan et al. (2010) scaled to $(\lambda) = 1736$ Å using $p = 4/3$.

Our estimates are in good agreement with previous results (Blackburne et al. 2011b; Mediavilla et al. 2011a; Mosquera et al. 2011; Muñoz et al. 2011; Morgan et al. 2010; Floyd et al. 2009; Anguita et al. 2008; Poindexter et al. 2008; Eigenbrod et al. 2008; Bate et al. 2008, and Kochanek 2004) and show a discrepancy with respect to the predictions of the thin disk model of approximately a factor of five.

4. CONCLUSIONS

We performed a statistical analysis to estimate the average size of the accretion disks of lensed quasars from the large sample (MED09) of microlensing magnification measurements. We find that most information on the size of the accretion disk is contained in the amplitude of the microlensing magnification and fairly independent of the amount of chromaticity.

From a statistical analysis using measured microlensing magnification strengths from 27 image pairs from 19 lensed quasars in the sample of MED09 we measured the average size of the accretion disk of lensed quasars at a rest wavelength of $(\lambda) = 1736$ Å. For a typical mean mass in the stellar population of the lens of $(M) = 0.3 M_\odot$, and taking into account the intrinsic dispersion in $\lambda$, we find $r_s = 4.0^{+2.1}_{-3.1}$ and $r_s = 5.5^{+3.1}_{-3.7}$ lt-day for $\alpha = 0.05$ and $\alpha = 0.1$, respectively. These estimates are in agreement with other studies (Blackburne et al. 2011b; Mediavilla et al. 2011a; Mosquera et al. 2011; Muñoz et al. 2011; Morgan et al. 2010; Floyd et al. 2009; Anguita et al. 2008; Poindexter et al. 2008; Eigenbrod et al. 2008; Bate et al. 2008; Kochanek 2004) and we again find that disks are larger than predicted by the thin disk theory. We have also estimated the sizes of the 19 individual objects in the sample to find that they are in very good statistical agreement with the result from the maximum likelihood analysis.

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