A microlensing study of the accretion disc in the quasar MG 0414+0534

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ABSTRACT

Observations of gravitational microlensing in multiply imaged quasars currently provide the only direct probe of quasar emission region structure on submicroarcsecond scales. The analyses of microlensing variability are observationally expensive, requiring long-term monitoring of lensed systems. Here, we demonstrate a technique for constraining the size of the quasar continuum emission region as a function of wavelength using single-epoch multiband imaging. We have obtained images of the lensed quasar MG 0414+0534 in five wavelength bands using the Magellan 6.5-m Baade telescope at Las Campanas Observatory, Chile. These data, in combination with two existing epochs of Hubble Space Telescope data, are used to model the size of the continuum emission region $\sigma$ as a power law in wavelength, $\sigma \propto \lambda^v$. We place an upper limit on the Gaussian width of the $r'$-band emission region of 1.80 $\times$ 10$^{16}$ h$^{-1/2}$ \((M/M_{\odot})^{1/2}\) cm, and constrain the power-law index to 0.77 $\leq v \leq$ 2.67 (95 per cent confidence range). These results can be used to constrain models of quasar accretion discs. As an example, we find that the accretion disc in MG 0414+0534 is statistically consistent with a Shakura–Sunyaev thin-disc model.

Key words: accretion, accretion discs – gravitational lensing – quasars: individual: MG 0414+0534.

1 INTRODUCTION

Models of quasar accretion are currently poorly constrained by observations (Blaes 2007). Accretion discs are much too small for direct imaging, and so other observational methods are required to probe their structure. Gravitational microlensing of multiply imaged quasars is one such technique, uniquely able to probe accretion disc structure on scales $\sim$10$^{16}$ cm.

The quasar central engine is thought to consist of an accretion disc surrounding a supermassive black hole. It is a general feature of accretion disc models (e.g. Shakura & Sunyaev 1973; Hubeny & Hubeny 1997) that longer wavelength radiation is emitted from larger regions in the disc. Accretion discs are thus a perfect target for gravitational microlensing analyses, as the amplitude of fluctuations produced by gravitational microlensing depends strongly on the size of the emission region in the source. In particular, microlensing models predict larger fluctuations at shorter wavelengths (e.g. Rauch & Blandford 1991; Jaroszyński, Wambsganss & Paczyński 1992; Agol & Krolik 1999; Yonehara et al. 1999).

Considerable effort has been invested in microlensing analyses to constrain the sizes of quasar emission regions (e.g. Wambsganss, Paczyński & Schneider 1990b; Rauch & Blandford 1991; Witt, Mao & Schechter 1995; Wyithe et al. 2000b; Wyith, O‘Dowd & Webster 2005; Morgan et al. 2006; Chartas et al. 2008). Recent efforts have focused on observations in (typically) two wavelength bands, in an effort to better constrain models of quasar accretion. These analyses frequently make use of the method presented in Kochanek (2004).

Pooley et al. (2007) analysed 10 quadruply imaged quasars (including MG 0414+0534, the quasar studied in this paper), and argued qualitatively that optical emission regions must be larger than expected from basic thin-disc models by the factors of $\sim$3–30. This result was supported by Morgan et al. (2007), in which accretion disc sizes were determined for 10 lensed quasars, and Morgan et al. (2008), which focused on X-ray and optical monitoring of PG 1115+080. Anguita et al. (2008) used \( g' \) - and $r'$-band monitoring of Q2237+0305 to obtain a spectral slope consistent with the standard thin-disc models. Poindexter, Morgan & Kochanek (2008) also found an accretion disc scale and slope consistent with standard thin-disc models, using 13 years of photometric data of the two-image lens HE 1104-1805.

The quantitative analyses discussed above rely upon monitoring of microlensing-induced brightness fluctuations over an extended time period. Constraints on the size of the emission region in the source are obtained by producing a large number of simulated microlensing light curves and searching for fits to the observational data. These constraints are therefore dependent on the transverse...
velocity, which can be estimated from the light curve (Wyithe, Webster & Turner 2000a; Kochanek 2004). In Bate, Webster & Wyithe (2007, hereafter BWW07) we demonstrated an alternative technique for placing constraints on the size of quasar emission regions using single observations of lensed quasars displaying a flux ratio anomaly.

Several gravitationally lensed quasars are observed to contain a pair of images straddling a critical curve. Basic lensing theory predicts that these images should have the same magnification. However in several cases, one image is observed to be significantly demagnified relative to the other (Chang & Refsdal 1979; Blandford & Narayan 1986; Witt et al. 1995). It has been argued that microlensing by a combination of smooth and clumpy matter in the lensing galaxy is the most likely explanation for this discrepancy (Schechter & Wambsganss 2002).

By exploring microlensing simulations with varying source size and smooth matter content in the lens, we have previously obtained a 95 per cent upper limit on the size of the $I$-band emission region in the anomalous lensed quasar MG 0414+0534 of $2.62 \times 10^{16} h^{-1/2} (M/M_\odot)^{1/2} \text{ cm}$ (BWW07). As with all lengths measured from microlensing simulations, this size is normalized to the Einstein Radius, which is scaled by the square root of the microlens mass $M$.

In this paper, we extend our analysis across multiple filters. Images of MG 0414+0534 in the $r'$, $i'$, $z'$, $J$ and $H$ filters were obtained on 2007 November 3, using the Magellan 6.5-m Baade telescope. We also make use of Wide-Field Planetary Camera 2 (WFPC2) F675W and F814W filters, taken on 1994 November 8 (Falco, Lehár & Shapiro 1997). These data allow us to obtain emission region size constraints in each filter or, equivalently, a power-law fit to the radius of the continuum emission region in the quasar as a function of the emitted wavelength.

The observations are described in Section 2. In Section 3, we summarize our simulation method, with particular emphasis on how it varies from that presented in BWW07. In Section 4, we present the resulting power-law fit to accretion disc radius as a function of the emitted wavelength, and discuss our conclusions.

Throughout this paper, we use a cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2 OBSERVATIONS

We observed MG 0414+0534 using the Magellan 6.5-m Baade telescope on 2007 November 3, in $\lesssim 0.5$ arcsec seeing. Observations were made using the Inamori Magellan Areal Camera and Spectrograph (IMACS) (in f/2 mode) $r'$, $i'$ and $z'$ filters and the Persson's Auxiliary Nasmyth Infrared Camera (PANIC) $J$ and $H$ filters. Integration times were approximately 5 min per filter. Images are provided in Fig. 1.

We fit Gaussians to each quasar image. We began by assuming a round, Gaussian point spread function, and then allow the ellipticity to vary as a free parameter. The $H$-band image best shows

Figure 1. Magellan IMACS and PANIC imaging of MG 0414+0534, taken on 2007 November 3. The anomalous flux ratio $F_{b/a}$ increases as we move bluewards.
The apparent magnitudes of the four lensed images and the lensing galaxy observed on 2007 November 3 are provided in Table 1. Flux ratios in each filter between the two images of interest, $F_{\text{obs}} = A_2/A_1$, are provided in Table 2. This table contains flux ratios from the observations presented in this paper, as well as two sets of $HST$ observations, obtained from the CfA-Arizona Space Telescope Lens survey (CASTLES) Survey web page http://cfa-www.harvard.edu/castles/). The 1994 November 8 observations were taken with the IMACS and PANIC instruments on the Magellan 6.5-m Baade telescope. The 1997 August 14 observations were taken with the NICMOS instrument on $HST$ (obtained from the CfA-Arizona Space Telescope Lens survey (CASTLES) Survey web page http://cfa-www.harvard.edu/castles/). The 1994 November 8 observations were taken with the WFPC2 instrument on $HST$ (Falco et al. 1997).

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The observational data provide us with flux ratio as a function of wavelength, \( F(\lambda) \), at three separate epochs. Microlensing simulations, detailed below, offer the link between source size and flux ratio, \( F(\sigma) \).

We conducted our microlensing simulations using an inverse ray-shooting technique (e.g. Kayser, Refsdal & Stabell 1986; Wambsganss, Paczyński & Katz 1990a). The key parameters for such simulations are the convergence \( \kappa_{\text{tot}} \) and the shear \( \gamma \) of the lens at the image positions. We used the MG 0414+0534 lens model of Witt et al. (1995), provided in Table 3. The convergence of the lens can be split into two components—a compact stellar component \( \kappa_s \) and a continuously distributed component \( \kappa_{\text{d}} \). We allowed the smooth matter percentage \( s = \kappa_{\text{d}}/\kappa_{\text{tot}} \) in the lens to vary between 0 and 99 per cent, in 10 per cent increments.

The microlenses were drawn from a Salpeter mass function \( dN/dM \propto M^{-2.35} \) with \( M_{\text{max}}/M_{\text{min}} = 50 \). Physical sizes are therefore scaled by the average Einstein Radius projected on to the source plane \( \eta_0 \), which is \( \sim 3.75 \times 10^5 h_0^{-1/2} ((M)/M_\odot)^{1/2} \) cm for MG 0414+0534. Magnification maps were generated covering an area of \( 24\eta_0 \times 24\eta_0 \), with a resolution of \( 2048 \times 2048 \) pixel. 20 maps were generated for each image and for each smooth matter percentage.

We then randomly selected source positions in each of the A1 and A2 magnification maps. At each source position, we calculated the magnifications of 40 Gaussian sources of increasing characteristic width \( \sigma \). The characteristic width of the sources varied from 0.05\( \eta_0 \) to 2.00\( \eta_0 \) in increments of 0.05\( \eta_0 \). Dividing A1 magnifications by A2 magnifications allowed us to build up a library of 25 500 curves of magnification ratio (equivalently, flux ratio) as a function of source width, \( F(\sigma) \).

We allowed the width of the innermost (\( \sigma' \)-band) emission region \( \sigma_0 \) to vary between 0.05\( \eta_0 \) and 2.00\( \eta_0 \) and the power-law index \( \nu \) to vary between 0 and 15. These values were found to cover the interesting areas of parameter space in coarse simulations. For each combination of \( \sigma_0 \) and \( \nu \), we calculated emission region widths \( \sigma_s \) at the central wavelength of each filter, \( \lambda_s \) (see Table 2), using equation (1). The value of \( \lambda_0 \) was taken to be 6231 Å, the central wavelength of the \( \nu' \) filter.

By comparing \( \sigma_s(\lambda_s) \) with each of our library of \( F(\sigma) \) curves (interpolating linearly in \( \sigma \)), we obtained 25 500 values of \( F_\text{sim}(\sigma_0) \) for each combination of \( \sigma_0 \) and \( \nu \) at each epoch. These were then compared with \( F_\text{obs}(\lambda_s) \), to obtain \( \chi^2 \) values, which were converted to likelihoods using

\[
L_i(F_{\text{obs}}|\sigma_0, \nu, \eta_0) = \exp \left( -\frac{\chi^2_i}{2} \right).
\]

A final likelihood was obtained for each combination of \( \sigma_0 \) and \( \nu \) at each epoch by summing over the individual likelihoods for each of the 25 500 simulated flux ratio curves,

\[
L(F_{\text{obs}}|\sigma_0, \nu, \eta_0) = \sum_{i=1}^{25500} L_i(F_{\text{obs}}|\sigma_0, \nu, \eta_0).
\]

We convert these likelihoods to an a posteriori differential probability distribution using Bayes’ theorem:

\[
\frac{d^3P}{d\sigma_0 d\nu ds} \propto L(F_{\text{obs}}|\sigma_0, \nu, \eta_0) \frac{dP_{\text{prior}}}{d\sigma_0} \frac{dP_{\text{prior}}}{d\nu} \frac{dP_{\text{prior}}}{ds}.
\]

We assume constant Bayesian priors for inner width \( \sigma_0 \), power-law index \( \nu \) and smooth matter percentage \( s \).

Marginalizing over smooth matter percentage, we obtain probability distributions for \( \sigma_0 \) and \( \nu \) at each epoch,

\[
\frac{d^2P}{d\sigma_0 d\nu} = \int \frac{d^3P}{d\sigma_0 d\nu ds} ds.
\]

The individual probability distributions are provided in Fig. 3. The left-hand panel shows the Magellan IMACS and PANIC distribution, the middle panel shows the HST NICMOS distribution and the right-hand panel shows the HST WFPC2 distribution.

The probability distributions at each of the three epochs were then combined to obtain a final distribution for \( \sigma_0 \) and \( \nu \), which is shown in Fig. 4 (top panel).

### 4 RESULTS

Fig. 4 (top panel) shows contours through the probability distribution for the Gaussian width of the innermost (\( \sigma' \)-band) emission region \( \sigma_0 \) and power-law index \( \nu \). By marginalizing over the power-law index \( \nu \), we obtain a 95 per cent upper limit on the width of the \( \sigma' \)-band emission region in MG 0414+0534 of 0.48\( \eta_0 \).

**Table 3.** Lensing parameters.

| Image | \( \kappa_{\text{tot}} \) | \( \gamma \) | \( \mu_{\text{tot}} \) |
|-------|----------------|----------|---------------|
| \( A_1 \) | 0.472 | 0.488 | 24.2 |
| \( A_2 \) | 0.485 | 0.550 | -26.8 |

Lensing parameters for images \( A_1 \) and \( A_2 \) in MG 0414+0534 (Witt et al. 1995).

![Figure 3](https://academic.oup.com/mnras/article-abstract/391/4/1955/1747700)

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width $\sigma_0 = 0.16\eta_0$. This size can be combined with $v = 4/3$, and is marked as a cross in Fig. 4 (top panel).

There has been some disagreement between previous microlensing analyses regarding the size of optical emission regions in lensed quasars. Pooley et al. (2007) and Morgan et al. (2008) both found that quasar optical emission regions are larger than predicted by Eddington-limited thin-disc models. Conversely, Anguita et al. (2008) and Poindexter et al. (2008) found disc sizes consistent with thin-disc models.

Poindexter et al. (2008) noted that the solution to this discrepancy might be a slightly shallower temperature profile than predicted for a Shakura–Sunyaev thin disc. Our results are consistent with this suggestion. We note, however, that the only previous analysis of MG 0414+0534 (Pooley et al. 2007) found that it was one of only two lensed quasars in a sample of 10 for which a Shakura–Sunyaev disc was just large enough to explain both the observed X-ray and optical flux ratios.

Poindexter et al. (2008) also fit a power law in wavelength to accretion disc radius for the lensed quasar HE 1104-1805. They obtained a power-law index of $v = 1.64^{+0.56}_{-0.46}$ (68 per cent confidence). At the 68 per cent confidence level, the power-law index obtained here is $v = 1.48^{+0.60}_{-0.44}$. These results are indistinguishable at the 1σ level. This is particularly interesting as the methods used in the two analyses differ significantly. Poindexter et al. (2008) compared 13 years of monitoring data in 11 wavebands to the simulated microlensing light curves. We take advantage of the fact that two images straddling a critical curve each behave differently when microlensed, allowing us to obtain similar results with only three epochs of imaging in 10 overlapping wavebands.

5 CONCLUSIONS

In conclusion, we have demonstrated a technique for using near-contemporaneous multi-band imaging of anomalous lensed quasars to constrain the radius of the quasar continuum emission region as a function of emitted wavelength. The application of this technique to MG 0414+0534 yielded an upper limit on the width of the $r'$-band emission region of $1.80 \times 10^{-16} h^{-1/2}_\eta (M/M_\odot)^{1/2}$ cm and a power-law index range of $0.77 \leq v \leq 2.67$, both with 95 per cent confidence. These results are consistent with a Shakura–Sunyaev accretion disc model.

The greatest strength of our method is its observational efficiency. Previous analyses have relied upon multi-epoch monitoring, with the tightest size constraints typically obtained during the fortuitous observation of high-magnification events. The method demonstrated here requires only as much time as is necessary to obtain sufficient signal-to-noise ratio of the lensed images in each filter. However, it is only useful if the lensed quasar is displaying an anomalous flux ratio. We have assumed that this anomalous flux ratio is produced solely by microlensing, although we cannot rule out differential extinction due to dust in the lensing galaxy as an alternative explanation.

We have obtained observations of additional systems with anomalous flux ratios, the analysis of which is forthcoming.

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