A DOUBLED DOUBLE HOTSPOT IN J0816+5003 AND THE LOGARITHMIC SLOPE OF THE LENSING POTENTIAL

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ABSTRACT

We present an analysis of observations of the doubly-lensed double hotspot in the giant radio galaxy J0816+5003 from MERLIN, MDM, WIYN, WHT, UKIRT and the VLA. The images of the two hotspot components span a factor of two in radius on one side of the lensing galaxy at impact parameters of less than 500 pc. Hence we measure the slope of the lensing potential over a large range in radius, made possible by significant improvement in the accuracy of registration of the radio and optical frame and higher resolution imaging data than previously available. We also infer the lens and source redshifts to be 0.332 and \( z \geq 1 \) respectively. Purely on the basis of lens modelling, and independently of stellar velocity dispersion measurements, we find the potential to be very close to isothermal.

Subject headings: gravitational lensing: strong radio continuum: galaxies: galaxies: quasars: individual (J0816+5003)

1. INTRODUCTION

In contrast to multiply-imaged, compact flat-spectrum sources, strongly-lensed extended, steep spectrum sources occupy a distinctly inferior position in the gravitational lens pantheon. Yet, in a paper that marks the beginning of the modern era in gravitational lensing, Press & Gunn (1973) argued that radio lobes were the most promising targets in searching for lensing. Indeed, examples in their figure 6 resemble the lens which is the study of this paper, but since that paper was written, lensed lobes have proven more difficult to interpret.

Chief among the difficulties is the continuing poor registration between the radio and optical reference frames (Deutsch 1999). Radio lobes tend not to have optical emission that allows their position to be determined with respect to any lensing galaxy that might be identified. As lobes are extended and polarized, they offer more potential constraints than multiply imaged point sources, but modelling such emission requires substantial machinery (Kochanek, Blandford, Lawrence & Narayan 1989; Ellithorpe et al. 1996; Dye & Warren 2005; Vegetti & Koopmans 2009). For the most part, lensed lobes have been passed over in favor of their compact flat-spectrum cousins.

We describe in this paper Merlin and VLA observations of the doubly-lensed double radio hotspot J0816+5003 (a.k.a. 6C0812+501) discovered both by Lehár et al. (2001), using a clever automated strategy for finding extended radio emission which is gravitationally lensed, and independently by the Oxford group searching for high redshift radio galaxies. The techniques for high redshift radio galaxy searches include filtering on the basis of steep radio spectra and small angular size (e.g. Blundell et al. 1998; Jarvis et al. 2001; Jarvis et al. 2001) in the course filtering radio source surveys to optimize searches for high redshift radio galaxies. J0816+5003 is an example of a candidate included in the initial search but subsequently excluded by the filtering criteria.

The lens we study in this paper is the hotspot complex within the northern lobe of the giant radio galaxy J0816+5003, which has an angular extent of over an arcminute and is pictured in figure 1 of Lehár et al. (2001). Both the associated radio core, a half arcminute away to the south west, and its optical counterpart are identified, allowing accurate registration of the lensed hotspot and the lensing galaxy. In addition we find, with higher resolution radio imaging than was available to Lehár et al. (2001), that the hotspot has two components both of which are doubly imaged. Finally, the lensed images are asymmetrically located with respect to the lensing galaxy, permitting determination of the radial profile of the lensing potential. In particular, the images of the two sources span a factor of two in radius on one side of the galaxy at impact parameters of less than 500 pc.

This, together with accurate radio and optical astrometric registration as well as higher resolution radio images than were available to Lehár et al. (2001), enables us to make a pure-lensing measurement of the slope of the potential of the total mass of the lensing galaxy on the scales probed, including the dark matter. By combining lensing and dynamical analyses, the SLACS team have investigated this and other properties (e.g. Bolton et al. 2007; Gavazzi et al. 2007; Bolton et al. 2008; Barnabè et al. 2009). The slope of the potential figures prominently both in measurements of the Hubble constant and in discussions of the mass profiles of elliptical galaxies (Chen, Kochanek, & Hewitt 1995; Bernstein & Fischer 1994; Romanowsky & Kochanek 1999; Williams & Saha 2000; Witt et al. 2000; Cohn et al. 2001). There are very few examples where one can measure the slopes in this way — some exceptions

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include MG 1654+134, MG 1654+134 (Kochanek 1995), 0957+561 (Grogan & Narayan 1996), MG 2016+112, B1152+199 (Rusin et al. 2002), but cf. B1933+503 (Colín et al. 2001) and especially PG 1115+080 (Chen, Kochanek, & Hewitt 1995). Some newly found lenses by the SLACS team have also yielded constraints on the slope, albeit in most cases by a comparison of stellar velocity dispersions and Einstein ring radii (Koopmans et al. 2006).

With regard to measurement of $H_0$, a very small fraction of systems are suitable for measurement of time delays but as mentioned above, only a small fraction of systems are suitable for measurement of the slope of the potential. Since the overlap of these two sets is slim, it remains important to glean as much as possible about the slopes of galaxies potentials and extrapolate from the former to the latter (Kochanek & Schechter 2004). The currently accepted value of $H_0$ is reconcilable with inferred values from the 10 firm time-delay measurements in gravitational lenses only if dark matter halos are eliminated and a constant mass-to-light ratio used.

2. OBSERVATIONS

2.1. VLA imaging

J 0816+5003 was observed for 2 minutes on 1996 Dec 06 in the A-configuration of the Very Large Array (hereafter VLA) at 5 GHz under program code AR365 originally as part of an Oxford survey for high redshift radio galaxies. The data were reduced using standard procedures in the AIPS software package. The primary flux calibrator was 3C 286 and the phase calibrator was 0804+499. The image showing its lensed northern hotspot structure is shown in Figure 1.

2.2. Merlin imaging

To obtain higher resolution radio imaging than in Figure 1, J 0816+5003 was observed with six antennas of the Multi-Element Linked Radio INterferometer (hereafter MERLIN) at 1.7 GHz on 1997 Jun 27 for 10.58 hrs, during which observations of a nearby phase calibrator, B0803+514, were interleaved. Again, the data were reduced using standard procedures within AIPS including standard polarimetric calibration made possible by the extensive parallactic angle coverage of the phase calibrator throughout the 10+ hour observation.

Figures 2 and 3 show contours of the total intensity MERLIN data in different ways as described in the figure captions, with the highest resolution image having a point spread function with FWHM of $0.08'' \times 0.08''$.

2.3. Optical and near-IR imaging

In order to establish the nature of any galaxy associated with 6C 0816+5003, this source was observed for 5 minutes in $R$-band on 1997 Jan 9 on the William Herschel Telescope (hereafter WHT) using the Aux Port Camera, and was flat-fielded and reduced using standard procedures. A greyscale of this image is presented in Figure 1.

Near-infra red K-band observations of J 0816+5003 were made using the UFTI instrument for 27 minutes on the United Kingdom Infra-Red Telescope (hereafter UKIRT) on 2002 Jan 13. Unfortunately conditions were not photometric, but approximate flux density boot strapping was made via a short (9-minute) service observation on 2002 Mar 11. For each of these observations, following standard practice, each successive 60-sec exposure was jittered from the previous position and a flat-field was created by combining all frames from a particular observation using a median filter. All data reduction was performed in IRAF and followed Willott et al. (2003).
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Fig. 2.— MERLIN image at 1.7 GHz of part of the lensed north hotspot in J0816+5903 showing the southern two components of the three depicted in Fig. 1. This image was made using the IMAGR routine of the AIPS software package with a Briggs’ robustness parameter of $-3$ and super-resolved with a restoring beam of $0.08'' \times 0.08''$. The lowest contour is $0.3$ mJy/beam and adjacent contours differ by a factor of $\sqrt{2}$. The beam is $0.08'' \times 0.08''$.

Fig. 3.— MERLIN image at 1.7 GHz of the same part of the north hotspot shown in Fig. 2 but with the image compressed in the East-West direction by a factor of four. The lowest contour is $0.3$ mJy/beam and adjacent contours differ by a factor of $\sqrt{2}$. The beam is $0.08'' \times 0.08''$.

2.4. Redshifts of lens and lensed galaxy

The ISIS spectrograph on the WHT was used on 2002 Feb 5 using the red and blue arms of the ISIS spectrograph (with R158R and B300B gratings respectively), in order to find the redshifts of the background source, namely the radio galaxy, and the lensing galaxy. The spectra were reduced using standard IRAF procedures. The redshift of the lensing galaxy is inferred to be $0.332$, on the basis of an observed 4000Å break and the Ca H and K absorption lines (at 3968 and 3933 Å respectively) shortward of this. At this redshift, $1''$ is $4.738$ kpc assuming $H_0 = 71$ km s$^{-1}$, $\Omega_0 = 1$ and $\Lambda_0 = 0.73$. The background source, being a radio galaxy, belongs to a relatively homogeneous category of sources with respect to its host galaxy. This is displayed most apparently by the tightness of the radio galaxy K-z relation [Lilly & Longair 1984]. Indeed, with work on the radio galaxy K-z Hubble relation [Jarvis et al. 2001; Willott et al. 2003] we are able to make a crude estimate of the redshift of the radio source. A magnitude of $K \sim 17.8$ from the UKIRT observations implies a redshift of $z \gtrsim 1.0$, which is also consistent with its broad-band optical colours. We can also gain more information from the optical WHT spectrum, where the presence of a relatively bright continuum but the absence of any of the bright forbidden narrow-emission lines, implies that the radio galaxy probably lies within the redshift desert at $1.2 < z < 1.7$ (i.e. [OII] 3727 has been redshifted out of, and Ly$-\alpha$ has
yet to enter, the optical passband). While the $K$-band magnitude indicates that the radio galaxy is probably at $z \gtrsim 1$, the WHT spectrum tentatively indicates that $z \sim 1$. Thus, we can be certain that the radio galaxy is at a much greater distance than the lens.

The WIYN and MDM scales were both determined from fits which assumed that the scale was the same in both directions. The scale factor in both cases was determined to better than 1 part in $10^4$. The positional rms between the WIYN and MDM objects was 0.34 pixels which at a scale of 0.1406189′′/pix is roughly 0.05′′. Thirty six stars were used in the WIYN fit. The error in the galaxy position was taken to be 0.05 pixel (as judged from the scatter in the different position measurements) that translates into a 0.007′′ error in the lens position (in each direction). The Right Ascensions and Declinations of the lensing galaxy and of the radio galaxy core and their relative separation were measured using an average of three differences obtained from DAOFIND, IMEXAM and VISTA and are reproduced in Table II.

The positions of the pair (E and W) of doubled (N1 and N2) hotspot components are listed in the first four rows of Table II and were determined using JMFIT within AIPS on the image shown in Fig. 4. The positional uncertainty along each axis is 4 milli-arcsec for the unresolved N2-E, N2-W and N1-W components, and because of being slightly resolved that for the N1-W component is 10 milli-arcsec. The east and north offsets are measured with respect to the position of the radio nucleus of the radio galaxy (which is at 08 16 37.40774 +50 03 38.9782) which locks the radio and optical frames together because of the coincidence of the radio nucleus with the centre of the optical host galaxy. The positional uncertainty of the lensing galaxy is good to 0.007′′ and dominated by the 0.5′′ seeing of the WIYN image. The flux densities at 1.7 GHz of the compact lensed components are also measured using JM-FIT and are for the brightest compact features, excluding surrounding smooth extended emission.

By applying a correction to the Right Ascension and Declination of the radio galaxy to align it with the radio core, and applying this exact same correction to the former RA and Dec exact relative offsets between the lensed images and lens were then input to the model.
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<table>
<thead>
<tr>
<th>component</th>
<th>RA J2000</th>
<th>Dec J2000</th>
<th>east offset arcsec</th>
<th>north offset arcsec</th>
<th>flux density mJy</th>
</tr>
</thead>
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<tr>
<td>N2-E</td>
<td>08 16 38.82360</td>
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<td>13.5881</td>
<td>29.1493</td>
<td>1.12 ± 0.11</td>
</tr>
<tr>
<td>N2-W</td>
<td>08 16 38.81384</td>
<td>+50 04 08.2098</td>
<td>13.4944</td>
<td>29.2316</td>
<td>0.93 ± 0.11</td>
</tr>
<tr>
<td>N1-E</td>
<td>08 16 38.86700</td>
<td>+50 04 06.4285</td>
<td>14.0046</td>
<td>27.4503</td>
<td>4.01 ± 0.12</td>
</tr>
<tr>
<td>N1-W</td>
<td>08 16 38.82578</td>
<td>+50 04 06.2481</td>
<td>13.6090</td>
<td>27.2699</td>
<td>5.74 ± 0.12</td>
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<tr>
<td>lens</td>
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<td>+50 04 07.7950</td>
<td>13.6412</td>
<td>28.8530</td>
<td></td>
</tr>
</tbody>
</table>

Table 1

**Fitted positions and flux densities of radio components.**

![Fig. 5.](http://redfive.rutgers.edu/~keeton/gravlens/index.html)

**Fig. 5.** — Upper panel: the source plane showing as blue crosses the positions of the intrinsic double hotspot feature. Lower panel: image plane.

4.1. General Approach

Gravitational lenses can be modelled in terms of a dimensionless two-dimensional potential $\phi$ that is a function only of position on the sky. Dimensionful quantities – distances and masses – can then be derived from redshift measurements and specification of the Hubble constant.

While there is in principle a great deal of information to be extracted from multiple images of extended sources, this quickly leads into dividing the source into pixels, each of which is taken as a free parameter (Dye & Warren 2005; Vegetti & Koopmans 2009). Radio hotspots are particular challenging because there is relatively little symmetry to be exploited (Laing 1989; Black et al. 1992; Hardcastle et al. 1997; Leahy et al. 1997). Moreover image infidelities may be present in the details of the brightness structure. For example, while the resolution of the MERLIN image is approaching that ideally needed for this system, the six antennas of the MERLIN array undersample much of the extended structure seen in the VLA image, whose resolution is insufficient to reveal the underlying structure. Resolution of this awaits the emerging generation of radio telescopes especially the e-MERLIN and EVLA. For the present we limit ourselves to modelling the positions and fluxes of the compact components of the hotspots.

Reasonable and robust first-order results can be obtained using only point sources. We use the excellent public domain program `lensmodel` written and graciously made available by Chuck Keeton (Keeton 2001). Our sources are clearly extended, but we try to take out the tangential stretching, seen clearly in the MERLIN image shown in Figure 2, by squashing by a factor of four in the East-West direction. The resulting image can be seen in Figure 3. Obtaining accurate radio positions of the double images of each pair were made easier by the fact that one of the knots shows no signal in Stokes $Q$ at the resolution of the MERLIN data, so the position for the other pair was measured from a Stokes $Q$ image. To measure the other pair, the Stokes $Q$ image was subtracted from a polarised intensity map $\sqrt{Q^2 + U^2}$. This approach overcame the problem that the image shown in Figure 2 does not completely resolve the two blobs in N2. [N.B., the rotation measure in the lensing galaxy implied by the polarisation angle variation with frequency is only 20 rad/m$^2$, modest by normal galaxy standards (Leahy et al. 1986).]

4.2. Details of the model

We chose to model the two dimensional projected gravitational potential with the function

$$\phi = b \left[ \frac{\theta_x^2 + \theta_y^2}{(1 - \epsilon)^2} \right]^{\alpha/2}$$

(1)
where $\theta'_e$ and $\theta'_p$ are angular position on the sky and $\epsilon$ is the ellipticity of the equipotentials. In the limit of zero ellipticity, the radius of the Einstein ring, $r_E$ can be obtained from the parameter $b$ with $r_E = b^{1/2-\alpha}$. Potentials due to circularly symmetric isothermal galaxies (i.e. with $\alpha = 1$) with external tides yield similar results but with slightly inferior fits to the data. For the small ellipticities considered here there is no advantage to using elliptical isodensity contours, which in the limit of small $\epsilon$ are a factor of 3 flatter than the equipotentials.

![Figure 6](image_url)

**Fig. 6.** — Plot of $\chi^2$ as a function of $\alpha$, the power-law slope of the potential.

The results of stepping through $\alpha$ and allowing all the other 11 parameters vary are shown in Figure 6. Our best fit is for $\alpha = 1.031$, with an uncertainty, as judged from the change in $\chi^2$, of 0.002. The best fitting model parameters are given in Table 2. Note, in particular, that the best fitting position for the lens differs from our measured position by less than 0.003".

5. SLOPE OF LENSING POTENTIAL

The use of a particular gravitational lens system in deducing $H_0$ is only as good as our knowledge of the lensing potential. The galaxy responsible for lensing the hotspot in J0816+5003 has a power-law which is remarkably close to isothermal.

In addition, it is unlikely that the lensing potential is much shallower than isothermal because there is no hint of evidence for any odd (e.g. ‘third’) image (Winn et al. 2003; Rusin & Ma 2001). The flux density ratio of the peak of the brighter northern (N2-E) blob on the MERLIN image to 3x the rms noise on this image exceeds 10. Kochanek (1995), similarly, finds that in MG1654+134 that $0.9 < \alpha < 1.1$. Rusin et al. (2002) find in B1152+199 that $0.95 < \alpha < 1.21$ and Treu & Koopmans (2002) find in MG2016+112 that $\alpha = 1.0 \pm 0.1 \pm 0.1$. However, seemingly inconsistently with this emerging general picture, Chen, Kochanek, & Hewitt (1993) claim that the mass profile of the lensing galaxy in MG1131+0456 to be incompatible with $\alpha = 1$. In addition, for PG1115+080 Romanowsky & Kochanek (1999) report that no viable lens model can yet be ruled out.

6. FUTURE WORK AND CONCLUSIONS

Sensitive radio images at resolution better than a few 10s of milli-arcsec would considerably broaden the scope of a lensing model to be fitted, and this is within the capability of current technology. The key observational limitation however, remains the registration of the optical frame with respect to the radio frame and widespread efforts to improve this situation generally should remain a priority.

We conclude by remarking that our pure-lensing measurement of slope of the potential of the lensing galaxy in this system as being very close to isothermal is a measurement of the total mass on the scales probed, including the dark matter. However, it sheds no light on the “bulge-halo conspiracy” that separately the dark and light matter do not appear to be isothermal — the light matter being steeper than isothermal, the dark matter being shallower (Treu 2007, Bolton et al. 2007, 2008, Gavazzi et al. 2005, Barnabè et al. 2009) — but collectively they appear isothermal over an increasing range in redshift as the system we have studied in this paper illustrates.

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REFERENCES

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[...continued]
### Table 2

Lens parameters for the best fitting model. The position angle for the long axis of the equipotentials is measured E from N. In the limit of zero ellipticity the radius of the Einstein ring, in arcseconds, is given by

\[ r = \frac{b}{1/(2 - \alpha)}. \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
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<tr>
<td>lens strength ( b )</td>
<td>0.906</td>
</tr>
<tr>
<td>ellipticity ( \epsilon )</td>
<td>0.061</td>
</tr>
<tr>
<td>P.A.</td>
<td>57°</td>
</tr>
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<td>lens offset (RA)</td>
<td>13.6389''</td>
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<tr>
<td>lens offset (Dec)</td>
<td>28.8536''</td>
</tr>
<tr>
<td>slope ( \alpha )</td>
<td>1.031</td>
</tr>
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</table>


