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

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Received 2009 December 22; accepted 2010 August 15; published 2010 October 21

ABSTRACT

We present an analysis of observations of the doubly lensed double hot spot in the giant radio galaxy J0816+5003 from MERLIN, MDM, WIYN, WHT, UKIRT, and the VLA. The images of the two hot spot components span a factor of 2 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 ~1, respectively. Purely on the basis of lens modeling, and independently of stellar velocity dispersion measurements, we find the potential to be very close to isothermal.

Key words: gravitational lensing: strong – quasars: individual (J0816+5003) – radio continuum: galaxies

Online-only material: color figures

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 modeling such emission requires substantial machinery (Kochanek et al. 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 hot spot J0816+5003 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. 2001a, 2001b) in the course of 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 hot spot 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 southwest, and its optical counterpart are identified, allowing accurate registration of the lensed hot spot and the lensing galaxy. In addition we find, with higher resolution radio imaging than was available to Lehár et al. (2001), that the hot spot 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 2 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 et al. 1995; Bernstein & Fischer 1999; 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 include MG 1654+134 (Kochanek 1995), 0957+561 (Grogin & Narayan 1996a, 1996b; Fischer et al. 1997), MG 2016+112 (Treu & Koopmans 2002), B1152+199 (Rusin et al. 2002), but cf. B1933+503 (Cohn et al. 2001) and especially PG 1115+080 (Chen et al. 1995; Romanowsky & Kochanek 1999). 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
Figure 1. VLA contours of the north hot spot structure of J0816+5003 at 5 GHz. It has a beam of 0.55″ × 0.36″ at a P.A. of 82.39°. The lowest contour is at 0.4 mJy beam⁻¹ and adjacent contours differ by a factor of √2. The gray scale is an R-band image from the WHT. The convention for naming follows that instigated by Lehár et al. (2001). (A color version of this figure is available in the online journal.)

of these two sets is slim, it remains important to glean as much as possible about the slopes of galaxy 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

J0816+5003 was observed for 2 minutes on 1996 December 6 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 hot spot structure is shown in Figure 1.

2.2. MERLIN Imaging

To obtain higher resolution radio imaging than in Figure 1, J0816+5003 was observed with six antennas of the Multi-Element Linked Radio INterferometer (hereafter MERLIN) at 1.7 GHz on 1997 June 27 for 10.58 hr, 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′′ × 0.08′′.

Figure 2. MERLIN image at 1.7 GHz of part of the lensed north hot spot in J0816+5003 showing the southern two components of the three depicted in Figure 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′′ × 0.08′′. The lowest contour is 0.3 mJy beam⁻¹ and adjacent contours differ by a factor of √2. The beam is 0.08′′ × 0.08′′.

2.3. Optical and Near-IR Imaging

In order to establish the nature of any galaxy associated with J0816+5003, this source was observed for 5 minutes in $R$ band on 1997 January 9 on the William Herschel Telescope (hereafter WHT) using the Aux Port Camera, and was flat fielded and reduced using standard procedures. A gray scale of this image is presented in Figure 1.

Near-infrared $K$-band observations of J0816+5003 were made using the UFTI instrument for 27 minutes on the United Kingdom Infra-Red Telescope (hereafter UKIRT) on 2002 January 13. Unfortunately conditions were not photometric, but approximate flux density boot strapping was made via a short (9 minute) service observation on 2002 March 11. For each of these observations, following standard practice, each successive 60 s 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).

2.4. Redshifts of Lens and Lensed Galaxy

The ISIS spectrograph on the WHT was used on 2002 February 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 4000 Å break and the Ca H and K absorption lines (at 3968 and 3933 Å, respectively) shortward of this (Figure 4). 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. 2001a; 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 broadband optical colors. 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., [O ii] 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.

3. OPTICAL ASTROMETRY

To deduce accurately the slope of the potential of the lensing galaxy requires secure relative astrometry between the images and the lenses. In the case of PG 1115+080, a difference in the image positions of several parts in a thousand makes a difference between a best-fit power-law slope of $\alpha = -1$ rather than $\alpha = 0$ (Schechter 2000), which relates to the surface mass density profile with radius $r$ as $\Sigma(r) \propto r^{\alpha-2}$. In the case of J0816+5003, the lensed images are only detectable in the radio waveband and the lensing galaxies are not visible in the radio. Thus, making deductions about the slope of the power law of the galaxy lensing its hot spot depends on how well the radio and the optical/near-IR frames can be tied together. The derivation of astrometric solutions using an image from a telescope with reimaging optics or with a prime focus corrector (such as the WHT, UKIRT, or Keck) and with a reference from the USNO catalog would not be sufficiently successful, due to off-axis distortions.

A $17'' \times 17''$ R-band image of this field was observed with the Michigan-Dartmouth-MIT 1.3 m telescope (hereafter MDM 1.3 m) by Jules Halpern on 2002 February 22. The astrometry of this image was fitted with John Thorstensen’s automated astrometric program$^5$ which matched 156 bright stars over this field from the USNO catalog$^6$ and put the astrometric solution into the fits headers. This astrometric solution was transferred to a 4096 × 2048 pixel $K$-band image obtained from the WIYN with 0'0.5 seeing on 2002 March 14.

\footnote{5 http://mdm.kpno.noao.edu/Manuals/automatch.html}

\footnote{6 http://ftp.nofs.navy.mil/projects/pmm/}

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{figure3}
\caption{MERLIN image at 1.7 GHz of the same part of the north hot spot shown in Figure 2, but with the image compressed in the east–west direction by a factor of 4. The lowest contour is 0.3 mJy beam$^{-1}$ and adjacent contours differ by a factor of $\sqrt{2}$. The beam is 0'.08 × 0'.08.}
\end{figure}

\begin{figure}[ht]
\centering
\includegraphics[width=0.8\textwidth]{figure4}
\caption{Spectrum from the ISIS spectrograph on the WHT, observed on 2002 February 05. The redshift of the lens galaxy is inferred to be 0.332, on the basis of the H and K absorption lines shortward of the 4000 Å break. (A color version of this figure is available in the online journal.)}
\end{figure}
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 $0\prime.1406189$ pixel$^{-1}$ is roughly $0\prime.05$. Thirty-six stars were used in the WIYN fit. The error in the galaxy position was taken to be 0.05 pixels (as judged from the scatter in the different position measurements) that translates into a $0\prime.007$ 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 1.

The positions of the pair (E and W) of doubled (N1 and N2) hot spot components are listed in the first four rows of Table 1 and were determined using JMFIT within AIPS on the image shown in Figure 3. The positional uncertainty along each axis is 4 mas 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 mas. 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 center of the optical host galaxy. The positional uncertainty of the lensing galaxy is good to $0\prime.007$ and dominated by the $0\prime.5$ seeing of the WIYN image. The flux densities at 1.7 GHz of the compact lensed components are also measured using JMFIT 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 R.A. and decl., exact relative offsets between the lensed images and lens were then input to the model.

4. DIMENSIONLESS MODEL FITTING

The most northerly feature of the hot spot complex (N3) shown in Figure 1 is likely to be distorted (tangentially sheared) by the presence of the lensing galaxy; it exhibits no multiple compact components in the MERLIN data. Thus, as is often the case, the hot spot in this giant radio galaxy has multiple intrinsic (unlensed) components (Laing 1989). However, its impact parameter from the galaxy means that it is not multiply imaged (see Figure 5).

4.1. General Approach

Gravitational lenses can be modeled 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 hot spots are particularly 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, as a free parameter (Dye & Warren 2005; Vegetti & Koopmans 2016; Rusin & Ma 2001). The flux density ratio of the peak of the brightest

\[ \chi^2 \]

is the

\[ \theta' \]

and \( \theta^2 \) 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, in arcseconds, is given by \( r_E = b^{1/2 - \alpha} \).

4.2. Details of the Model

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

\[ \phi = b \left( \theta_2^2 + \frac{\theta_1^2}{(1 - \epsilon)^2} \right)^{\alpha/2} \]

where \( \theta'_1 \) and \( \theta'_2 \) 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.

The results of stepping through \( \alpha \) and allowing all the other 11 parameters to 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 hot spot 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 brightest northern (N2-E) blob on the MERLIN image to \( 3 \times \) the rms noise on the same image is greater than 10.

Kochanek (1995), similarly, finds in MG1654+134 that \( 0.9 < \alpha < 1.1 \). Rusin et al. (2002) find in B 1152+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 et al. (1995) claim that the mass profile of the lensing galaxy in MG1131+0456 is 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 tens of milliarcsecond would considerably broaden the scope of a

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**Figure 6.** Plot of \( \chi^2 \) as a function of \( \alpha \), the power-law slope of the potential. (A color version of this figure is available in the online journal.)

| Parameter | Value |
|-----------|-------|
| Lens strength \( b \) | 0.906 |
| Ellipticity \( \epsilon \) | 0.061 |
| P.A. | 57 |
| Lens offset (R.A.) | 13.6389 |
| Lens offset (decl.) | 28.8536 |
| Slope \( \alpha \) | 1.031 |

**Notes.** 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 \( r_E = b^{1/2 - \alpha} \).
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 the 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. 2007; 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.

P.L.S. and K.M.B. thank the Institute for Advanced Study at Princeton for hospitality. K.M.B. thanks the Royal Society for a University Research Fellowship. P.L.S. thanks the NSF for grants AST-0206010 and AST-0607601. We are very grateful to John Thorstensen for his excellent astrometric software and graciously enabling us to get a 15 minute image from the MDM 1.3 m telescope and to Jules Halpern for providing the image. We thank the staff of the MDM and WYIN observatories. MERLIN is a UK national facility operated by the University of Manchester on behalf of STFC. The UK Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the STFC. The WHT is operated on the island of La Palma by the Isaac Newton Group in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias. The VLA is a facility of the NRAO operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation. This research has made use of the NASA/IPAC Extragalactic Database, which is operated by the Jet Propulsion Laboratory, Caltech, under contract with the National Aeronautics and Space Administration. We thank the referee for a careful reading of the manuscript.

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