J0316+4328: a Probable “Asymmetric Double” Lens

E. R. Boyce1*, S. T. Myers2, I. W. A. Browne1, W. J. Stroman2,3 and N. J. Jackson1

1 University of Manchester, Jodrell Bank Observatory, Macclesfield, Cheshire SK11 9DL
2 National Radio Astronomy Observatory, PO Box O, Socorro, NM 87801, United States
3 Iowa State University, Department of Physics and Astronomy, 12 Physics Hall, Ames, IA 50011, United States

ABSTRACT
We report a probable gravitational lens J0316+4328, one of 19 candidate asymmetric double lenses (2 images at a high flux density ratio) from CLASS. Observations with the Very Large Array (VLA), MERLIN and the Very Long Baseline Array (VLBA) imply that J0316+4328 is a lens with high confidence. It has 2 images separated by 0.′′40, with 6 GHz flux densities of 62 mJy and 3.2 mJy. The flux density ratio of ∼19 (constant over the frequency range 6-22 GHz) is the largest for any 2 image gravitational lens. High resolution optical imaging and deeper VLBI maps should confirm the lensing interpretation and provide inputs to detailed lens models. The unique configuration will give strong constraints on the lens galaxy’s mass profile.

Key words: gravitational lensing – cosmology:miscellaneous.

1 INTRODUCTION
Galaxy-scale gravitational lenses are valuable tools for the study of galactic structure. The locations and brightnesses of the images provide constraints on the overall lens galaxy profile, while remaining anomalies and time variations in the brightnesses due to micro-lensing probe substructure on scales from dark matter clumps (Mao & Schneider 1995; Dalal & Kochanek 2002) and satellite galaxies (McKean et al. 2007) to stars (Schechter & Wambsganss 2002). Lens images are sensitive to the surface densities at the locations where they form, generally at galactocentric radii of a few kpc for bright lens images. Measuring the overall lens galaxy profile over a range of scales requires more information, which can be provided by stellar velocity dispersions at radii < 1 kpc (Koopmans et al. 2006) or weak lensing at radii of tens of kpc (Gavazzi et al. 2007). Lenses with central images measure the density profile on many scales using strong lensing alone, giving strong constraints at radii of ∼100 pc, including any contribution from a central super-massive black hole (Winn et al. 2004).

For lensed quasars, the best measurement of the lens galaxy profile can be done if the quasar is radio-loud. The size of the emitting region is larger in the radio than in optical or X-ray (Koopmans & de Bruyঁe 2006), making the image brightnesses less susceptible to microlensing, while central images are strongly affected by dust absorption and confusion in the optical regime but not in the radio frequency range 5-40 GHz (Winn et al. 2004). The largest sample of radio-loud lenses has been provided by CLASS (Myers et al. 2003), which found 22 instances of a bright radio source lensed by a foreground galaxy.

A crucial step in CLASS was the rejection of double sources with a flux density ratio > 10 : 1 (Myers et al. 2003) after the initial 8.4 GHz VLA snapshot. This was done for two reasons; for statistical completeness of the lens sample it was necessary to be sure that all secondary components could be detected reliably and it also significantly reduced the amount of follow-up observations required. A secondary compact component of similar brightness to the primary is likely to be a lensed image, while a secondary component much fainter than the primary is most likely to be weak structure belonging to the primary source. This strategy necessarily excluded “asymmetric doubles”: 2 image lenses with a high flux density ratio. Such lenses are of interest because they are most likely to host observable central images (Mao et al. 2001; Bowman et al. 2004), while even the absence of a central image gives the strongest constraints in an asymmetric double (Rusin & Ma 2001; Boyce et al. 2006; Zhang et al. 2007). Though the recognition of weak secondaries with ratios > 10 : 1 in CLASS may not have been 100% reliable, many are detectable. We have, therefore, conducted a program to identify such lenses by following up promising candidates which were initially rejected only on the basis of a high flux density ratio.

2 SURVEY AND OBSERVATIONS
We selected 18 candidates which were fitted by multiple compact components in the initial CLASS VLA snapshots, and for which the second brightest component was 10 – 30...
frequencies, relative to the primary compact source. e.g. J0008+6837 had 2 compact radio components, the fainter of these had a steeper
radio spectrum between 5 and 8.5 GHz. Most of our candidates were typical radio sources with a flat-spectrum, compact core and
a steeper spectrum, often extended, lobe or knot in a jet. Only J0316+3350, J0935+0719 and J0958+2948 could be considered lens
candidates from the VLA observations.

| Source          | R.A. (J2000) | Dec.  | Observing Time (mins.) | Notes                      |
|-----------------|-------------|------|------------------------|----------------------------|
| J0008+6837      | 00 08 33.5  | 68 37 22 | 14                      | - Rejected: 2nd component steeper |
| J0152+3350      | 01 52 34.6  | 33 50 33 | 6                       | 8 - Rejected: 2nd component steeper |
| J0316+3350      | 03 16 50.9  | 43 28 19 | 11                      | 12 17 Possible Lens from VLA observations |
| J0644+5955      | 06 44 04.7  | 59 55 21 | 6                       | 7 - Rejected: 2nd and 3rd components extended, steeper |
| J0812+3441      | 08 12 03.0  | 40 41 08 | 18                      | 18 - Rejected: 2nd and 3rd components extended, steeper |
| J0852+5922      | 08 52 30.0  | 59 22 50 | 18                      | 19 - Rejected: 2nd component steeper |
| J0903+4651      | 09 03 04.0  | 46 51 04 | 4                       | 5 45 Rejected: 2nd component extended |
| J0935+1079      | 09 35 01.1  | 07 19 19 | 12                      | 14 23 Possible Lens from VLA observations |
| J0938+3934      | 09 38 39.2  | 39 34 20 | 18                      | 18 - Rejected: 2nd component extended, steeper |
| J0958+2948      | 09 58 58.9  | 29 48 04 | 12                      | 13 21 Possible Lens from VLA observations |
| J1131+5146      | 11 31 16.5  | 51 46 34 | 18                      | 19 - Rejected: 2nd component extended, steeper |
| J1252+1910      | 12 52 27.8  | 19 10 38 | 18                      | 19 - Rejected: 2nd component extended, steeper |
| J1253+6304      | 12 53 17.5  | 63 04 36 | 18                      | 18 24 Rejected: 2nd component flattened, 3rd component extended |
| J1343+2844      | 13 43 00.2  | 28 44 07 | 6                       | 6 - Rejected: 2nd component extended, steeper |
| J1540+1447      | 15 40 49.5  | 14 47 46 | 4                       | 5 28 Rejected: 2nd component extended, steeper |
| J1641+5115      | 16 41 55.7  | 51 15 47 | 9                       | 10 - Rejected: 2nd component extended, steeper |
| J2139+1027      | 21 39 42.6  | 10 27 43 | 7                       | 7 14 Rejected: 2nd component extended, steeper |
| J2353+3231      | 23 53 20.9  | 32 31 44 | 14                      | 14 - Rejected: 2nd component extended, steeper |

Table 1. Summary of VLA observations. Flatter and steeper refer to the spectral indices of weaker components over the observed
frequencies, relative to the primary compact source. e.g. J0008+6837 had 2 compact radio components, the fainter of these had a steeper
radio spectrum between 5 and 8.5 GHz. Most of our candidates were typical radio sources with a flat-spectrum, compact core and
a steeper spectrum, often extended, lobe or knot in a jet. Only J0316+3350, J0935+0719 and J0958+2948 could be considered lens
candidates from the VLA observations.

The maps of J0316+4328 with the VLA and MERLIN are presented as Figures 1 and 2 while fits to the components
are presented in Table 2. We also mapped the system in Stokes Q, U and V, using the MERLIN data, and
detected no polarised emission at an rms of 0.13 mJy/beam.
Table 2. Gaussian fits to the components of J0316+4328, giving positions relative to component A in the 22 GHz VLA map, integrated flux densities and sizes (deconvolved major axes). Components C and D were clearly resolved in the 6.0 GHz MERLIN map (see Figure 3), so in this case 2 gaussians were fitted. The flux density is the total flux density of the 2 components, the size is their separation. B is unresolved in each map, while A is marginally resolved with MERLIN. The off-source rms values were 0.13, 0.09 and 0.09 mJy/beam and the beam sizes were 0.051 × 0.045, 0.020 × 0.018 and 0.011 × 0.007 in the 6.0, 8.5 and 22.5 GHz maps, respectively.

| Component | R.A. | Dec. | 6.0 GHz MERLIN Size (mJy) | 8.5 GHz VLA Size (mJy) | 22.5 GHz VLA Size (mJy) |
|-----------|------|------|--------------------------|------------------------|-------------------------|
| A         | 0".00| 0".00| 0".051                   | 0".06                  | 0".05                   | 0".26                  |
| B         | 0".11| -0".38| 0".017                  | 0".05                  | 0".05                   | 0".36                  |
| C         | 0".32| 0".18| 0".09                   | 0".17                  | 0".15                   | 2".09                  |
| D         | -0".76| -0".12| 0".07                   | 0".21                  | 3".25                   | 1".21                  |

Figure 2. 22.5 GHz VLA A array map of J0316+4328. Components A and image B are both compact, with a flux density ratio of 19.6 ± 1.3. With higher resolution, components C and D are clearly extended. The off-source rms is 0.09 mJy/beam and the beam is 0″11 × 0″07 at a position angle of 25°. The coordinates are offset from 03 16 50.93 +43 28 19.3, the greyscale is in mJy/beam, and the contours increase in factors of 2 from 0.3 mJy/beam.

Figure 3. 6.0 GHz MERLIN map of J0316+4328. Component B is compact, component A is marginally extended (major axis 0″051 at a position angle of 54°). The flux density ratio of components A and B is 19.2 ± 0.8, taking the total flux density of A. Components C and D are resolved by MERLIN. The off-source rms is 0.13 mJy/beam and the beam is 0″051 × 0″045 at a position angle of 61°. The coordinates are offset from 03 16 50.93 +43 28 19.3, the greyscale is in mJy/beam, and the contours increase in factors of 2 from 0.4 mJy/beam.

J0316+4328 has 2 compact components (A and B) with flux density ratios of 19.6 ± 1.3, 17.0 ± 0.6, 19.2 ± 0.8 at 6.0 GHz, 8.5 GHz and 22 GHz, respectively. Errors are 1-σ values taken from the map rms. The 2 steeper spectrum components (C and D) either side of A and B are extended with the VLA and clearly resolved by MERLIN. These are probably lobes situated either side of the radio source’s core which lie too far from the lensing galaxy to be multiply imaged.

We observed J0316+4328 with the Very Long Baseline Array (VLBA) at 8.4 GHz on 2006 July 16. The observation was made at an observing rate of 256 Mb/s and included 113 minutes on J0316+4328. Self-calibration was used to derive the phase solutions, and it was not possible to fit good solutions on the longest baselines, so the Mauna Kea, St. Croix and Hancock antennas were omitted. Components A and B (Figures 4 and 5) were found to have reduced flux densities compared to those in the VLA maps (Table 3), presumably due to resolving out extended emission. No emission was detected at the locations of components C and D; they were completely resolved out by the VLBA. Component A has 84% of its flux density in a central point source A1 and the remainder in jet components A2 and A3. Component B has a single point source sub-component B1, with a flux density ratio relative to A1 of 23.7 ± 1.5, matching the 6 GHz and 22 GHz ratios at the 2-σ level.

Some simple lens models which fit the bright images place the central image only ~ 20 mas from image B. While these models are severely underconstrained (due to the dearth of information on the lens galaxy), it is plausible that the VLA and MERLIN maps would blend image B with the central image, meaning that only the VLBA maps constrain the central image. No source was seen between images A and B, with a 5-σ limit of 0.33 mJy, although interpreting a non-detection over many resolution elements is not straightforward, see Zhang et al. (2007).
Table 3. Gaussian fits to the components of J0316+4328 in the VLBA maps, giving positions relative to A1, integrated flux densities and sizes (deconvolved major axes). The blank field rms values were (0.08, 0.065) mJy/beam in the A and B fields, respectively. The beam size was $2.8 \times 2.5$ mas.

| R.A. (mas) | Dec. (mas) | Size (mas) | $S$ (mJy) |
|-----------|-----------|------------|--------|
| A1        | 0.0       | 0.0        | 1.3    | 23.7   |
| A2        | 5.4       | 4.9        | 2.2    | 1.6    |
| A3        | 34.1      | 25.9       | 4.5    | 3.0    |
| B1        | 120.4     | -379.9     | 0.0    | 1.0    |

![Figure 4](image-url)  
Figure 4. 8.4 GHz VLBA map of the A component in J0316+4328, omitting the Mauna Kea, Hancock and St. Croix antennas. At VLBI scales component A splits into an unresolved core A1 and jet components A2 and A3 at distances of 7 and 43 mas and position angles of $48^\circ$ and $53^\circ$, respectively. This matches the 51 mas size and $54^\circ$ position angle of component A in the 6.0 GHz MERLIN map (Figure 3). The off-source rms is 0.08 mJy/beam and the beam is $2.8 \times 2.5$ mas at a position angle of $16^\circ$. The co-ordinates are offset from component A1, the greyscale is in mJy/beam, and the contours increase in factors of 2 from 0.4 mJy/beam.

![Figure 5](image-url)  
Figure 5. 8.4 GHz VLBA map of the B component in J0316+4328, omitting the Mauna Kea, Hancock and St. Croix antennas. It appears as a single compact point source B1, with a flux density ratio relative to A1 of $23.7 \pm 1.5$. The off-source rms is 0.065 mJy/beam and the beam is $2.8 \times 2.5$ mas at a position angle of $16^\circ$. The co-ordinates are offset from the brightest component A1 (shown in Figure 4), the greyscale is in mJy/beam, and the contours increase in factors of 2 from 0.2 mJy/beam.

3 DISCUSSION

Although we lack high-resolution optical data, we are very confident that J0316+4328 is a gravitational lens. Components A and B are very likely to be lensed images of the same quasar, as they are compact at resolutions from $0.2$ to $0.05$ and exhibit the same flux density ratio over a factor of 3.5 in frequency (Figure 4). At 3 mas resolution substructure is seen only in the brighter, more magnified image. All but one of the CLASS candidates with multiple compact components in VLBA maps were confirmed as lenses (Browne et al. 2003). The exception, B0827+525, had significantly different spectra for the 2 components and is likely to be a binary quasar (Koopmans et al. 2000).

We plan to obtain a VLBI map with rms $\sim 0.02$ mJy, which would definitively confirm the lensing interpretation by detecting parity-reversed substructure in image B matching that in image A. If B is a lensed image 19 times fainter than A, it should include sub-components B2 and B3 with flux densities of 0.08 and 0.16 mJy, and separations from B1 of 1.7 and 10 mas. This map would also improve the flux density measurement of B1 (which currently limits the precision of the VLBI flux density ratio), and might even detect a central image.

We are also pursuing high resolution optical images with the William Herschel telescope and spectroscopic observations with the Lick telescope. The USNO B1 catalog shows an optical object with R=19.1 and B=20.3 at 03 16 50.8693 +43 28 19.880, an offset of $-0.69$ in right ascension and $+0.55$ in declination from image A in the MERLIN map. The USNO catalog has astrometric accuracy of $0.2$ (Monet et al. 2003) and this object has errors of $0.38$ in right ascension and $0.10$ in declination, while the MERLIN map has astrometric accuracy and positional error both better than $0.05$. The optical and radio positions are consistent at the 2-$\sigma$ level, but it is not possible to identify the USNO object as a lensed image, the lens galaxy, or a blend of both. High resolution optical images should confirm the lensing interpretation, and allow detailed lens modelling.

For isothermal profiles with moderate ellipticity or...
shear, the lensing cross-section for asymmetric doubles (magnification ratio \(10 - 20\)) is \(\sim 20\%\) that of quads and symmetric doubles (magnification ratio \(1 - 10\)) combined. With 21 quad or symmetric double lenses in CLASS, 4-5 asymmetric doubles would be expected. 3 such systems have been found, counting the confirmed lens B1030+074 and the 2 strong candidates J0316+4328 and J0935+0719.

Our lens modelling must accommodate the extended, steep-spectrum components C and D. Their radio spectra are different from each other as well as from A and B (Figure 6), and their separation is 1″12 as opposed to 0″40 for images A and B, so C and D are unlikely to be a pair of lens images. Their orientation either side of image A, and the fact that substructure in A points towards the brighter component C, argues that they are diffuse lobes lying either side of the source’s core, in a typical double radio source configuration. With the lens image separation of 0″40 arguing for a relatively less massive lens galaxy with a small lensing cross-section, it should be possible to find models where the source’s lobes lie outside the multiply-imaged region of the source plane, while the core lies just within it. The configuration actually resembles that of the first lens system B0957+561 (Walsh, Carawell, & Weymann 1977; Roberts, Greenfield, & Burke 1977).

Our modelling will give strong constraints on the lens galaxy’s density profile. For near isothermal models which are a good approximation to most lens galaxies (Rusin et al. 2003; Koopmans et al. 2006), images A and B form at radii differing by a factor of 15-20 and constrain the density profile over this large range of galactocentric radius. The constraints will be particularly strong if substructure is detected in each image, as in the case of B1152+199 (Rusin et al. 2002). Also, central images become brighter as image B becomes fainter, relative to image A. Compared to quad or symmetric double lenses, J0316+4328 is more likely to show a central image in sensitive VLBI maps, and even an upper limit on the central image flux density will be a more stringent model constraint.

### 4 CONCLUSION

We have detected a probable gravitational lens with 2 bright images at a considerably higher flux density ratio than any previously known double lens. Improved VLBI and high-resolution optical observations are underway. This highly asymmetric lens should give unusually stringent constraints on the density profile of the lens galaxy.

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