

# CLASS B0445+123: a new two-image gravitational lens system

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## ABSTRACT

A new two-image gravitational lens system has been discovered as a result of the Cosmic Lens All-Sky Survey. Radio observations with the Very Large Array (VLA), the MultiElement Radio Linked Interferometer Network and the Very Long Baseline Array at increasingly higher resolutions all show two components with a flux density ratio of  $\sim 7 : 1$  and a separation of 1.34 arcsec. Both components are compact and have the same spectral index. Follow-up observations made with the VLA at 8.4 GHz show evidence of a feature to the south-east of the brighter component and a corresponding extension of the weaker component to the north-west. Optical observations with the William Herschel Telescope show  $\sim 1.7$ -arcsec extended emission aligned in approximately the same direction as the separation between the radio components with an *R*-band magnitude of  $21.8 \pm 0.4$ .

**Key words:** gravitational lensing – galaxies: individual: B0445+123.

## 1 INTRODUCTION

The Cosmic Lens All-Sky Survey (CLASS), conducted in four phases between 1994 and 1999, has mapped a total of 16 503 radio sources with the aim of detecting gravitationally lensed, flat-spectrum, compact objects. The sources for the first two phases were selected from the 87GB (Gregory & Condon 1991) catalogue while those in the later CLASS-3 and CLASS-4 samples were chosen from the updated GB6 (Gregory et al. 1996) survey when it became available. Spectral selection was performed by comparing the 5-GHz 87GB (or GB6) flux with that from the 1.4-GHz NVSS catalogue (Condon et al. 1998); sources with a spectral index,  $\alpha$ , of  $\leq -0.5$  between 1.4 and 5 GHz (where  $S \propto \nu^\alpha$ ) and total flux densities  $\geq 30$  mJy at 5 GHz were then included in the list of targets for CLASS. The initial selection of the CLASS samples is described in greater detail in Myers et al. (2002) and radio maps and catalogues covering the entire CLASS sample are available at <http://www.jb.man.ac.uk/research/gravlens/>.

Each object in the survey was first mapped at a resolution of 0.2 arcsec with the Very Large Array (VLA) at a frequency of 8.4 GHz. The images were then systematically examined for signs of structure. Potential lens candidates are those sources displaying multiple compact components within 15 arcsec of each other. They were selected from the CLASS sample according to specific criteria; the full width at half maximum (FWHM) of at least two of the components must be  $\leq 170$  milliarcsec (mas) when observed with the VLA at 200-mas resolution, the separation of the components must be  $\geq 300$  mas, all components observed must have similar surface brightnesses, the sum of the 8.4-GHz flux densities must be  $\geq 20$  mJy and the flux density ratio between the two brightest components must be  $\leq 10 : 1$ .

In order to distinguish between physically extended objects (e.g. core-jet systems) and those displaying gravitational lensing effects, sources displaying multiple compact components in the VLA images were mapped at a frequency of 5 GHz and a resolution of 50 mas using the MultiElement Radio Linked Interferometer Network (MERLIN). Sources showing components with significantly different surface brightnesses at this stage of the survey were rejected from the search.

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**Table 1.** Radio and optical observations of B0445+123.

Date (yyyymmdd)	Telescope	Frequency/band	Time on source	Resolution/seeing (arcsec)
19950903	VLA	8.4 GHz	30 s	0.2
19990702	VLA	15 GHz	3 h	0.1
19990903	VLA	8.4 GHz	3 h	0.2
20000309	MERLIN	5 GHz	1 h	0.05
20010321	VLBA	5 GHz	1 h	0.002
20020203	WHT	R band	4 × 600 s	1.0
20011117	Keck	Spectrum	1 h (blue), 1 h (red)	

**Table 2.** The two components of B0445+123. All flux densities are given in mJy and are accurate to  $\approx 5$  per cent. V95 indicates the original VLA observation made in 1995, while V99 indicates the follow-up observations made with the VLA in 1999. The dates of each observation are given in Table 1.

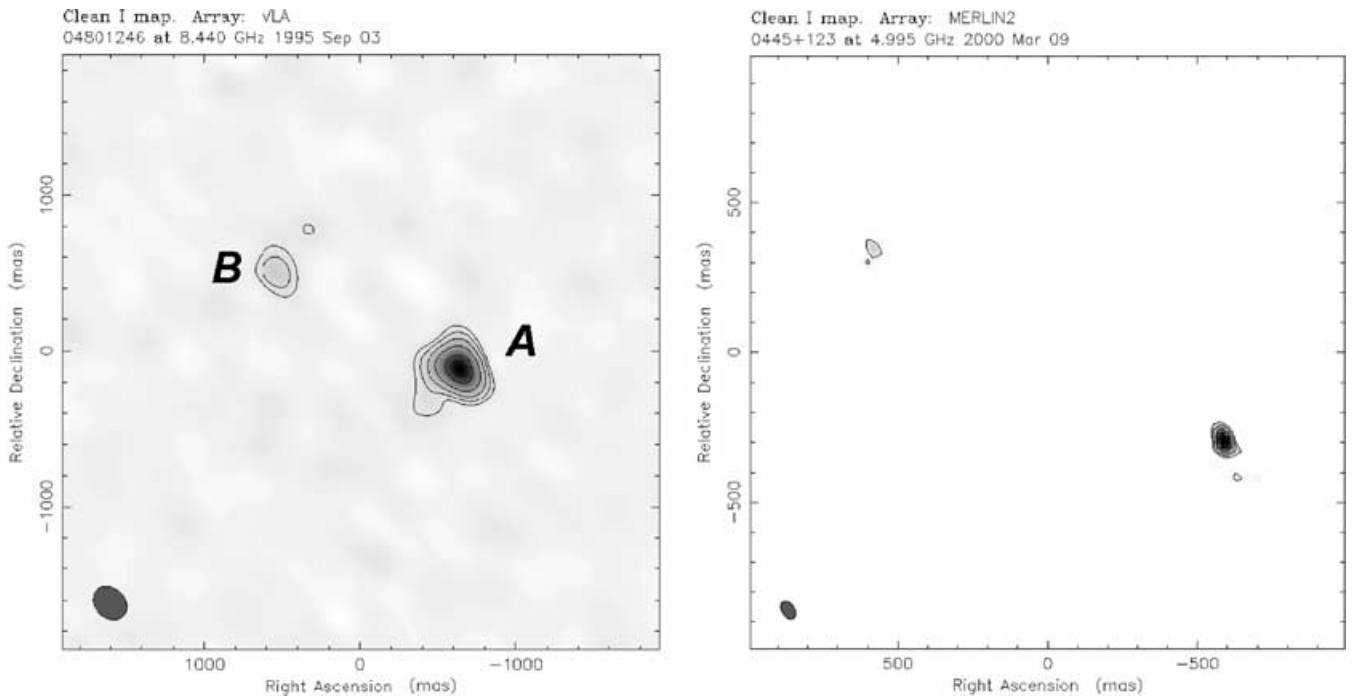
Component	RA (J2000)	Dec (J2000)	$S_5$ (MERLIN)	$S_5$ (VLBA)	$S_{8.4}$ (V95)	$S_{8.4}$ (V99)	$S_{15}$ (V99)
A	04 48 21.990	+12 27 55.409	25.0	16.6	27.1	24.5	32.0
B	04 48 22.070	+12 27 56.018	4.2	2.7	3.7	4.4	4.3

Sources surviving this stage of the selection process were then mapped at a resolution of 2 mas with the Very Long Baseline Array (VLBA). Browne et al. (2003) describes the candidate selection criteria and follow-up procedures in greater detail.

In this paper we describe the follow-up observations of one of these candidates, CLASS B0445+123, which lead us to the conclusion that it is a two-image gravitational lens system.

## 2 RADIO OBSERVATIONS

CLASS B0445+123 was first imaged with the VLA in 1995 during the second phase of CLASS and follow-up observations were carried out using VLA, MERLIN and VLBA. The data were calibrated using AIPS (Astronomical Image Processing System, distributed by the US National Radio Astronomy Observatory) and then mapped and self-calibrated in DIFMAP (Shepherd 1997). A summary of all



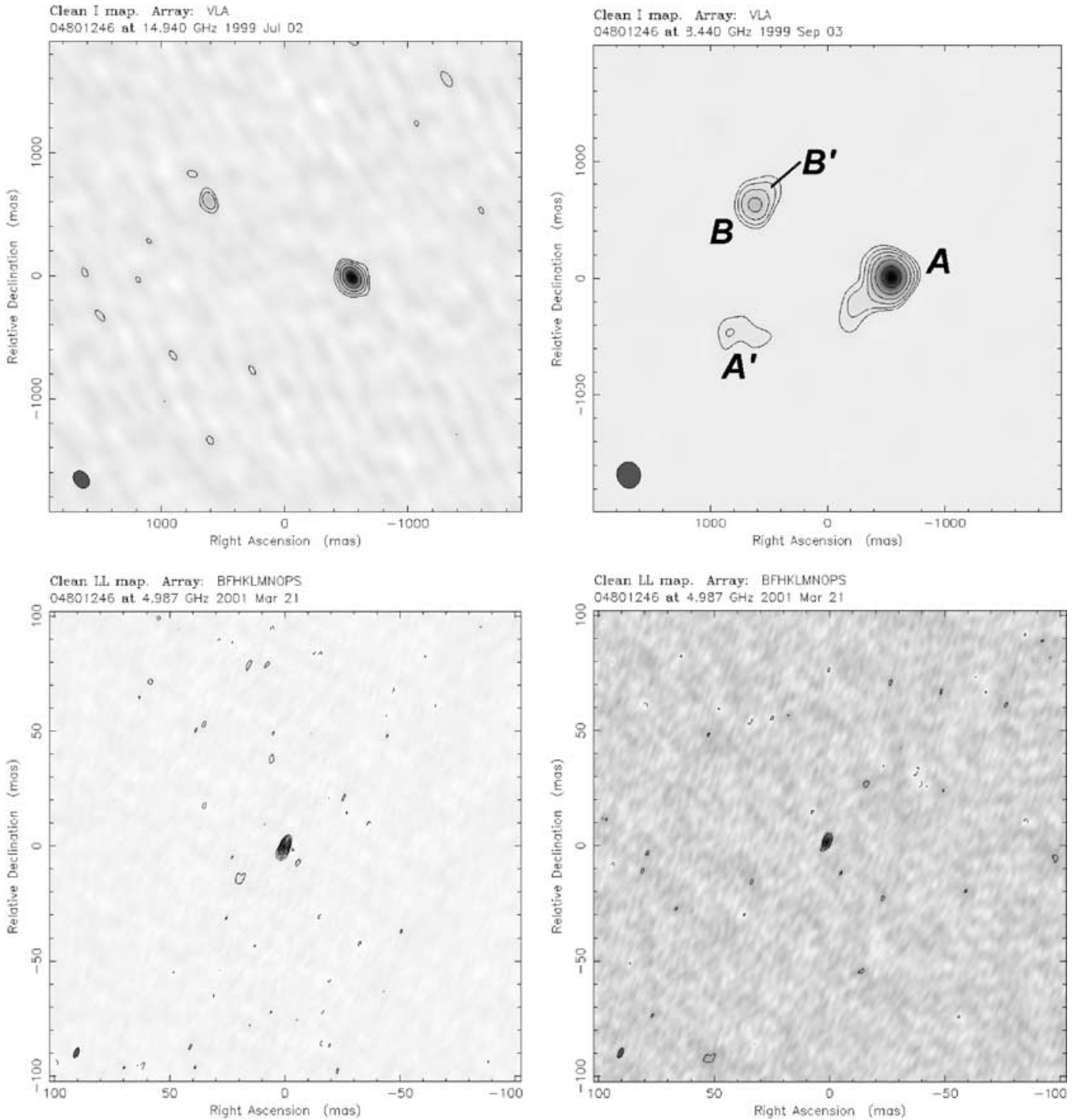
**Figure 1.** Left: original VLA (8.4-GHz) discovery map. Contours are at 4, 8, 16, 32, 64 per cent of the peak flux density of  $0.0261 \text{ Jy beam}^{-1}$  and the rms noise is  $300 \mu\text{Jy beam}^{-1}$ . Right: MERLIN (5-GHz) follow-up map. Contours are plotted at 12, 24, 48, 92 per cent of the peak flux density of  $0.0259 \text{ Jy beam}^{-1}$ . The rms noise level is  $280 \mu\text{Jy beam}^{-1}$ .

the observations made of B0445+123 is given in Table 1 and the flux densities of both components for each observation are listed in Table 2.

### 2.1 VLA

B0445+123 was observed with the VLA in its largest, ‘A’ configuration on 1995 September 3. Myers et al. (2002) describe the

VLA observations and the processing carried out on the CLASS data in greater detail. The original VLA image (Fig. 1, left) shows two distinct components with a separation of 1.34 arcsec and a flux density ratio of 7.3 : 1. The brighter and fainter components are given the designations A and B, respectively, according to the usual convention, and they have a combined flux density at 8.4 GHz of 30.8 mJy. Component A appears slightly extended towards the south-east.



**Figure 2.** Top left: VLA 15-GHz follow-up map; contours are plotted at 5, 10, 20, 40, 80 per cent of the peak flux density of  $0.0284 \text{ Jy beam}^{-1}$ . Top right: VLA 8.4-GHz follow-up map; contours are at 2, 4, 8, 16, 32, 64 per cent of the peak flux density of  $0.0225 \text{ Jy beam}^{-1}$ ;  $\sigma_{\text{rms}} \simeq 20 \mu\text{Jy beam}^{-1}$ . Bottom: VLBA (5-GHz) snapshots of component A (left) and B (right), contours are plotted at  $-3, 3, 6, 12, 24, 48 \times \sigma_{\text{rms}} \simeq 170 \mu\text{Jy beam}^{-1}$  for A and  $-3, 3, 6, 12 \times \sigma_{\text{rms}} \simeq 140 \mu\text{Jy beam}^{-1}$  for B.

Further observations were made in 1999 at 15 and 8.4 GHz (Fig. 2, top left and top right, respectively). Deep observations at 8.4 GHz show a clear extension to the south-east of component A, including a weaker component A', and signs of a corresponding elongation (B') of component B to the north-west.

## 2.2 MERLIN

Snapshot observations of B0445+123 were made on 2000 March 9 with MERLIN at a frequency of 5 GHz and a resolution of 50 mas. The data were phase calibrated using the source B0441+106 with a switching cycle of 3 min on source to 2 min on the calibrator. Fig. 1, top right, shows the MERLIN map after self-calibration in DIFMAP. The two components seen in the VLA images were detected.

## 2.3 VLBA

The two components of B0445+123 were imaged individually at 5 GHz with the VLBA at a resolution of 2 mas on 2001 March 21. Fig. 2, bottom left and bottom right, show the VLBA maps of components A and B, respectively. The observations show no structure or extension to either component and give a separation of 1340 mas. The 5-GHz flux densities of the components measured with the VLBA are considerably lower than that measured with MERLIN. This could be because either the source has low surface brightness emission, which is not detected in the high-resolution VLBA observations, or because the source is variable. More observations of B0445+123 are necessary in order to determine which is the case.

## 3 OPTICAL OBSERVATIONS

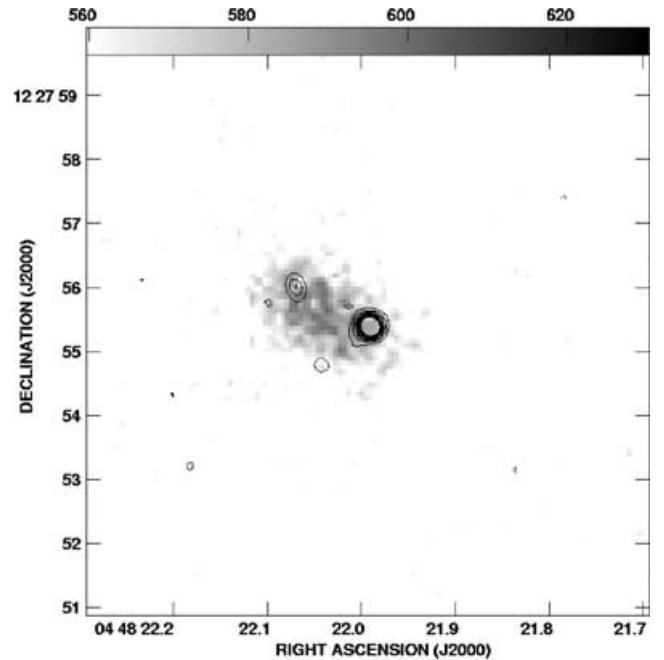
The Automated Plate Measuring machine (APM, Irwin, Maddox & McMahon 1994) catalogue obtained from Palomar Observatory Sky Survey 1 shows no associated optical components at the position of B0445+123, indicating that any counterpart must have a blue magnitude of  $\geq 21$  (the limiting magnitude detected by the APM).

An optical image in the *R* band was obtained with the William Herschel Telescope (WHT) on La Palma during service observations. The observing conditions were photometric and the seeing was 1.0 arcsec. The observations show a fuzzy blob approximately 1.7 arcsec in diameter at the position of the radio components and extended in the same orientation. Fig. 3 shows the WHT image of B0445+123 with contours from the original 8.4-GHz VLA observations overlaid. Astrometric calibration was performed in GAIA<sup>1</sup> using the seven objects in the field also detected on the APM. The random astrometric error is  $\pm 0.3$  arcsec comparable to the  $\sim 0.5$ -arcsec offset from the radio reference frame. By comparison with Landolt standard star 93-407 (Landolt 1992) the object was found to have an *R*-band magnitude of  $21.8 \pm 0.4$ .

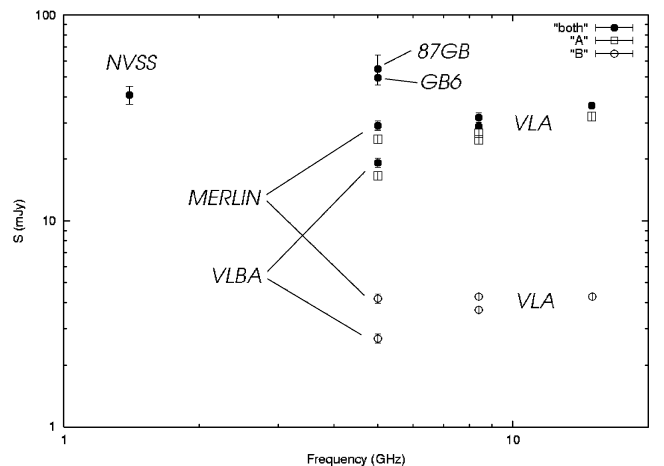
An optical spectrum was obtained with the 10-m Keck Telescope and the LRIS spectrograph on 2001 November 17. Strong continuum emission was present, with a redshift of 0.557 resulting from detections of Ca H, K and Mgb lines, but there are no obvious emission lines that might indicate a redshift for a lensed object (McKean et al. 2002, in preparation).

## 4 DISCUSSION: IS CLASS B0445+123 A LENS SYSTEM?

The radio spectra for the components (Fig. 4) confirm that both have similar spectral indices as required by the lensing hypothesis. The



**Figure 3.** Contours from the VLA discovery map overlaid on the optical picture obtained with the WHT. The contours are plotted at  $-10$  to  $+10$  (in steps of 1)  $\times 1$  mJy beam<sup>-1</sup>. The line AB is at an angle of  $62.5^\circ$  from the north. The radio/optical registration is believed to be accurate to  $\pm 0.3$  arcsec

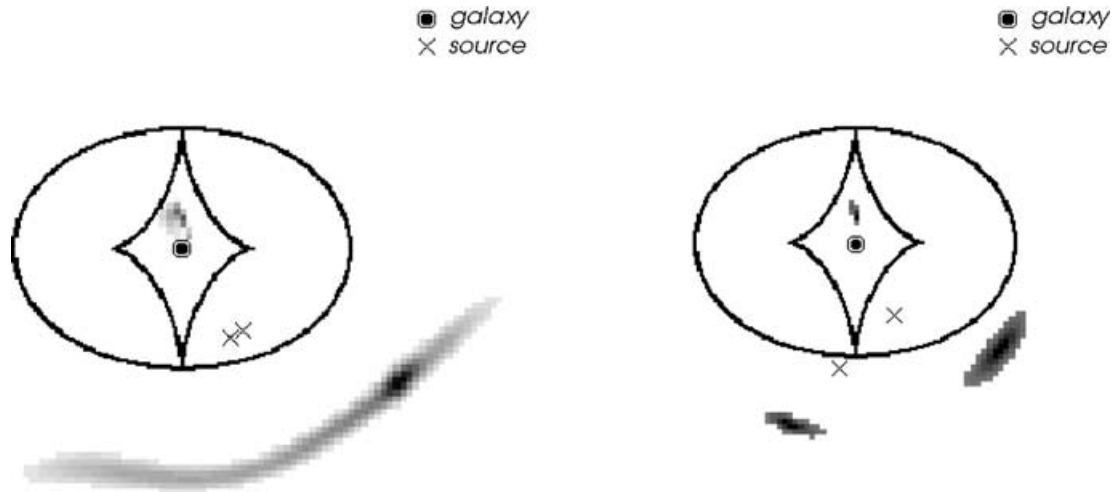


**Figure 4.** Radio spectra of the two components of B0445+123. Note that the 5-GHz MERLIN and VLBA observations have very different resolutions and at least some of the difference in flux densities results from extended emission being resolved out in the VLBA observations.

presence of two or more components separated by  $\sim 1$  arcsec, each compact on milliarcsecond scales and with near identical radio spectra (Fig. 4) has so far proven to be a 100 per cent reliable indicator of gravitational lensing within CLASS (Browne et al. 2003). Only one system with two components with milliarcsecond-scale structure is thought to be a binary quasar – CLASS B0827+525 (Koopmans et al. 2000).

The fact that the optical object seen in the WHT image is extended in the same orientation as the radio components and is larger than the separation of the two radio components suggests that some emission

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**Figure 5.** Simple models for B0445+123. In the model on the left, both core and jet lie within the outer caustic, while in the model on the right, the jet lies outside the caustic such that only the core is doubly imaged.

from both a lensing galaxy and at least one image is being detected. This is also consistent with the lensing hypothesis. If the object were a binary quasar, optical emission would be expected to be centred on one or other (or both) of the radio point sources.

From the above arguments, we conclude that CLASS B0445+123 is highly likely to be a gravitationally lensed system. With this assumption, we now try to produce a plausible lens model for the structure seen in the 8.4-GHz radio map (Fig. 2).

Fig. 5 shows two possible simple mass models for B0445+123. Each one shows the positions of the lensing galaxy and the background sources with the caustics and image positions overlaid. In both models the background source has two components, a compact core and a jet. They differ in that in the first both core and jet lie within the outer caustic and thus both are doubly imaged, while in the second, only the core is doubly imaged. To first order, both models reproduce the structure seen in the 8.4-GHz follow-up maps (see Fig. 2). The fact that the first model can reproduce the slight extension to the north-west of component B suggests that this is the more likely of the two.

Although preliminary lens models of the system can reproduce the radio structure, we emphasize that, because of the dearth of observational constraints, we are only using the modelling to show that the lens hypothesis is plausible. However, with deep MERLIN observations in the  $L$  band we would expect to see much more of the extended substructure in the images. This, together with a high-resolution optical image to tie down the relative astrometry of the lens and the images, would mean that B0445+123 has the potential to be an interesting system for determination of an accurate lens model and in which to search for the effects of the substructure in the lens predicted by cold dark matter galaxy formation scenarios (e.g. Metcalf 2003).

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