B0850+054

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B0850+054: a new gravitational lens system from CLASS

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ABSTRACT

We report the discovery of a new gravitational lens system from the CLASS survey. Radio observations with the VLA, WSRT and MERLIN show that the radio source B0850+054 is composed of two compact components with identical spectra, a separation of 0.7 arcsec and a flux density ratio of 6:1. VLBA observations at 5 GHz reveal structures that are consistent with the gravitational lens hypothesis. The brighter of the two images is resolved into a linear string of at least six subcomponents, whilst the weaker image is radially stretched towards the lens galaxy. UKIRT *K*-band imaging detects an 18.7-mag extended object, but the resolution of the observations is not sufficient to resolve the lensed images and the lens galaxy. Mass modelling has not been possible with the present data and the acquisition of high-resolution optical data is a priority for this system.

Key words: gravitational lensing – quasars: individual: B0850+054.

1 INTRODUCTION

The Cosmic Lens All-Sky Survey (CLASS) (Browne et al. 2002; Myers et al. 2002) is a survey of flat-spectrum sources with a flux density in excess of 30 mJy at 5 GHz. 22 lenses have been found in CLASS from a total of 16 503 sources observed. The main aim of this survey is to identify gravitational lens systems. These can be used to constrain the cosmological parameters H_0 (e.g. Biggs et al. 1999; Fassnacht et al. 1999; Koopmans et al. 2000), Ω_0 and λ_0 (e.g. Kochanek 1996; Helbig et al. 1999; Chae et al. 2002) and galaxy mass profiles (e.g. Rusin & Ma 2001; Cohn et al. 2001).

CLASS B0850+054 has a 5-GHz GB6 (Gregory et al. 1996) flux density of 68 mJy and a two-point spectral index[1] between 1.4 and 5 GHz of $\alpha = -0.2$, thus satisfying the criteria for inclusion in the CLASS sample. The original 8.5-GHz VLA snapshot (30 s on source) revealed two compact components separated by 0.7 arcsec, with a flux density ratio of $\sim$6 : 1. Here we present follow-up observations of B0850+054 in the radio, optical and infrared ranges that leave little doubt that B0850+054 is a lens system.

2 RADIO OBSERVATIONS

B0850+054 has been observed with the VLA, the Multi-Element Radio-Linked Interferometer Network (MERLIN), the Very Long Baseline Array (VLBA) and the Westerbork Synthesis Radio Telescope (WSRT). A summary of the observations presented in this paper is given in Table 1.

2.1 VLA

The VLA data consist of observations at 5, 8.5 and 15 GHz. At each frequency two channels of 50-MHz bandwidth were used and the target observed for approximately 10 min. Initial calibration was performed with the NRAO AIPS package and the data were then mapped and self-calibrated using DIFMAP (Shepherd 1997). The resulting maps are shown in Fig. 1. These show that the source consists

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[1] We define the spectral index, α, such that $S_\nu \propto \nu^\alpha$.

Table 1. Radio observations of B0850+054 presented in this paper.

Date	Array	ν (GHz)
1998 Mar 15	VLA	8.5
2000 Oct 07	VLBA	5.0
2001 Jan 27	MERLIN	5.0
2002 Feb 04	WSRT	0.360
2002 Apr 14	VLA	5.0
2002 Apr 14	VLA	8.5
2002 Apr 14	VLA	15.0

of two compact components aligned approximately north–south. As is customary, the brighter of the two components is denoted as image A and the other image as B. The results of model fitting to the (u, v) data in DIFMAP, using an unresolved point (delta) component to represent each image, are presented in Table 2. We also tabulate the flux density ratios, demonstrating that the spectral index of each component is the same.

2.2 MERLIN

The MERLIN 5-GHz observations were taken over a period of 9 h, with a bandwidth of 16 MHz, and were phase-referenced. The data were calibrated in AIPS and mapped and self-calibrated in DIFMAP; a map made from naturally weighted data is shown in Fig. 1. As with the VLA data we model fit using DIFMAP and show the results in Table 2. The higher resolution of MERLIN allows a more accurate estimation of the image separation (679 ± 1 mas) and also allows us to detect signs of resolution in image A. For this reason we fit an elliptical Gaussian to image A, whilst still modelling image B with a delta component. No evidence for polarization of the images has been found down to the noise limit. This implies that the polarization of the lensed radio source is <1 per cent (5 σ) at 5 GHz.

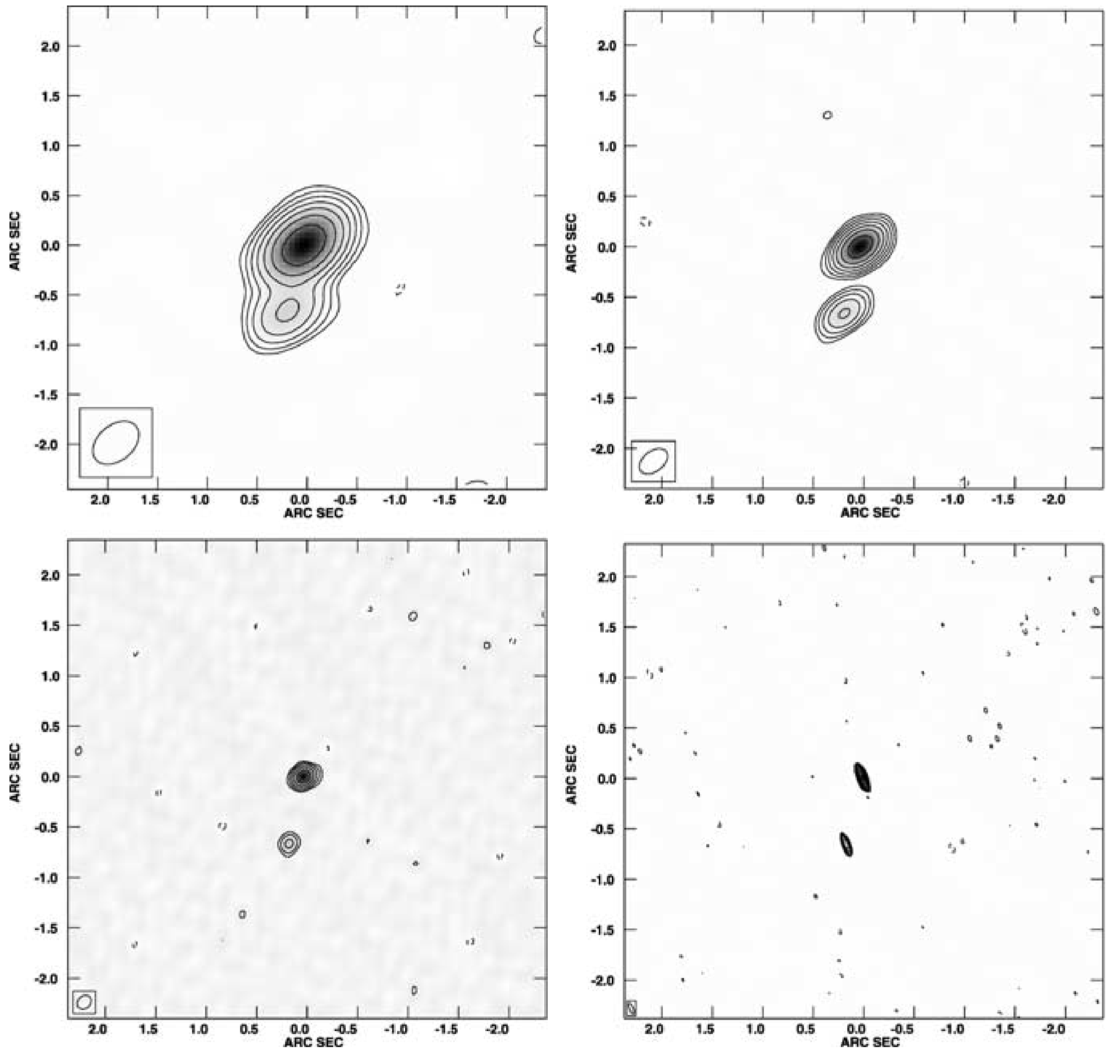

Figure 1. VLA and MERLIN maps of B0850+054. Top left: VLA 5-GHz map with a restoring beam of 524 × 356 mas^2 at a position angle of −49°.9. The data are uniformly weighted and the rms noise in the map is 157 µJy beam^{-1}. Top right: VLA 8.5-GHz map with a restoring beam of 317 × 200 mas^2 at a position angle of −51°.6. The data are uniformly weighted and the rms noise in the map is 121 µJy beam^{-1}. Bottom left: VLA 15-GHz map with a restoring beam of 153 × 123 mas^2 at a position angle of −46°.2. The data are uniformly weighted and the rms noise in the map is 288 µJy beam^{-1}. Bottom right: MERLIN 5-GHz map with a restoring beam of 114 × 38 mas^2 at a position angle of 22°.2. The data are naturally weighted and the rms noise in the map is 100 µJy beam^{-1}. All maps are plotted on the same angular scale and each has the restoring beam plotted in the bottom left-hand corner. Contours are plotted at multiples (−1, 1, 2, 4, 8, 16, etc.) of 3σ where σ is the off-source rms noise in the map. Image A is the northernmost of the two components.

Table 2. Results of model fitting to the MERLIN and VLA data. The VLA data were model fitted assuming delta components for both A and B, whilst the MERLIN data were fitted with an elliptical Gaussian to A and a delta component to B. Included are the flux densities of images A and B, their flux ratio, their separation (r) and their orientation (θ) measured in degrees east from north. We adopt errors of 3 per cent on the VLA 5- and 8.5-GHz flux densities and 5 per cent on the MERLIN 5 GHz and VLA 15 GHz.

ν (GHz)	Array	$S_{\nu,\mathrm{A}}$ (mJy)	$S_{\nu,\mathrm{B}}$ (mJy)	$S_{\nu,\mathrm{A}}/S_{\nu,\mathrm{B}}$	r (mas)	θ (deg)
5	MERLIN	49.0	8.1	6.0 ± 0.4	679 ± 1	166.5 ± 0.1
5	VLA	55.1	9.0	6.1 ± 0.3	683 ± 8	166.2 ± 0.7
8.5	VLA	40.4	6.6	6.1 ± 0.3	679 ± 5	166.6 ± 0.4
15	VLA	26.2	4.4	6.0 ± 0.4	680 ± 8	166.6 ± 0.7

2.3 VLBA

Phase-referenced observations were taken with the VLBA at a frequency of 5 GHz for a total of 12 h. A total bandwidth of 32 MHz was observed in four separate, but contiguous, bands of 8 MHz each. The data rate was 128 Mb s^{-1}. Calibration and mapping took place within AIPS following standard procedures. Naturally weighted maps of images A and B of 0850+054 are shown in Fig. 2. Image A is found to have a total length of approximately 20 mas and consists of a bright 'core' region (containing two subcomponents of similar brightness) near to its eastern extremity and several bright knots to the west of this. To the east of these subcomponents there is a short extension, which is most probably a counterjet. As expected for a demagnified version of A, image B is relatively compact. It is, however, resolved north–south, suggesting that with higher resolution the subcomponents in the jet could be mapped.

2.4 WSRT

In order to obtain a low-frequency flux density measurement of B0850+054, observations were made with the WSRT with its broadband '92-cm' system for two periods of 2 h, separated by approximately 4 h. Three of the eight 5-MHz bands were affected by radio-frequency interference (RFI) and discarded. After mapping and self-calibrating we detected a source of 50 ± 5 mJy close to the position of the target. Owing to the very elongated beam at this declination the possibility of confusion with unrelated sources is significant. After searching the 1.4-GHz NVSS (Condon et al. 1998) and FIRST (Becker, White & Helfand 1995) surveys, both of which detect B0850+054, we identified a ∼14-mJy confusing source 22 arcsec west and 144 arcsec north of B0850+054, well within the WSRT beam. As this source is also detected in our VLA data at 5 and 8.5 GHz, together with the 1.4-GHz flux densities we are able to calculate its spectral index, $\alpha = -0.8$.

Assuming that the spectrum of this source does not turn over, its flux density at 360 MHz would be ∼41 mJy, thus suggesting that it is contributing significantly to the measured WSRT flux density. We have aligned the right ascension reference frame of the WSRT 360-MHz image with that of the NVSS using six sources that are common to both. The scatter in this relative astrometry is less than 1 arcsec and from it we have determined that the WSRT detection lies approximately midway between the NVSS positions of the two sources. Therefore, we conclude that each contributes approximately equally to the combined flux density and adopt a value of 25 ± 5 mJy for B0850+054 at 360 MHz.

3 UKIRT OBSERVATIONS

Service observations with the United Kingdom Infra-Red Telescope (UKIRT) in the K band (2.2 μm) were taken on the nights of 2001

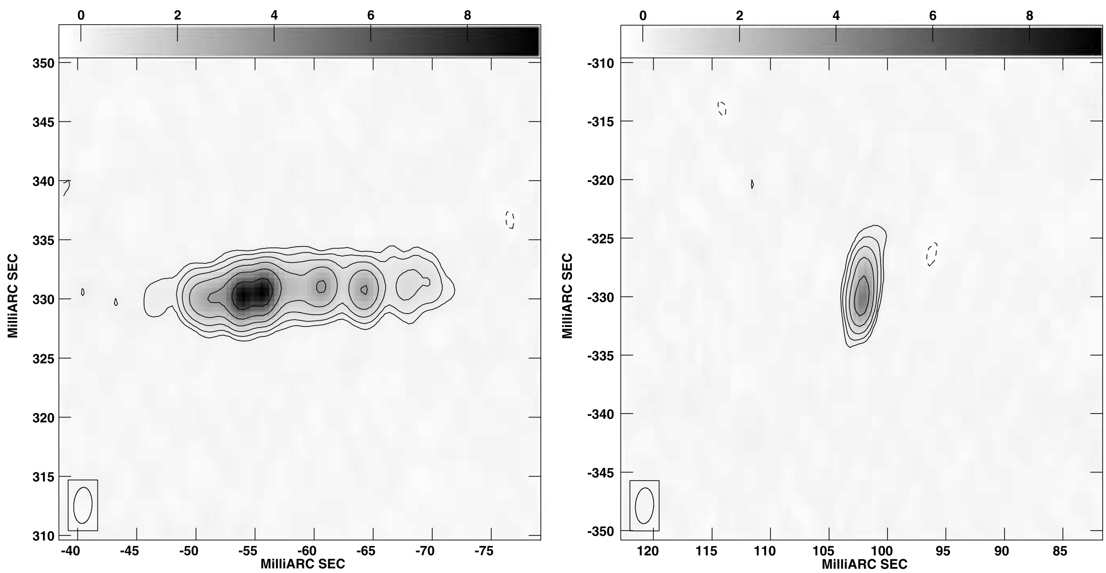

Figure 2. VLBA 5-GHz maps of image A (left) and image B (right) of B0850+054. The maps are uniformly weighted and both are plotted on the same angular scale. The restoring beam is shown in the bottom left-hand corner of each map and has a FWHM of 3.1 × 1.6 mas^2 at a position angle of −3°.8. Contours are plotted at multiples (−1, 1, 2, 4, 8, 16, etc.) of 3σ, where σ is the off-source rms noise in the map (50 μJy beam^{-1}). The grey-scale represents surface brightness in units of mJy beam^{-1}. Positions are offset from 08$^{\mathrm{h}}$52$^{\mathrm{m}}$53$^{\mathrm{s}}$.5772, +5°15′15″.329 (J2000).

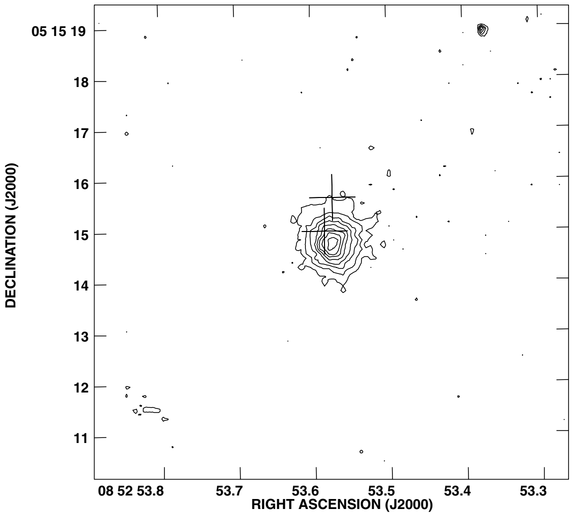

Figure 3. UKIRT *K*-band image of B0850+054. Contours are plotted at the background sky level plus linearly increasing multiples (−1, 1, 2, 3, etc.) of three times the off-source rms noise. The crosses mark the position of the A and B components.

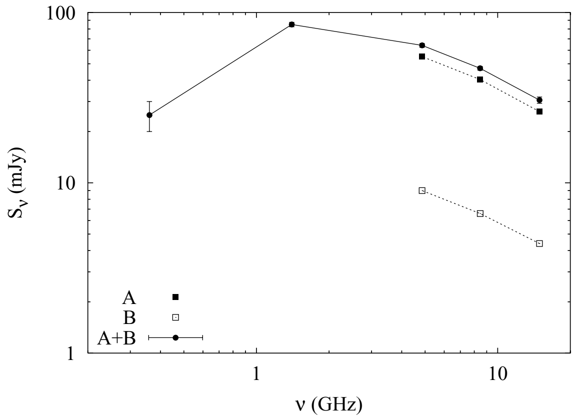

Figure 4. Radio spectrum of B0850+054. The solid line shows total flux densities (A+B) whilst below this the individual A and B flux densities are plotted where possible.

March 17 and 18 using the UKIRT Fast-Track Imager (UFTI). The observations on both nights were made using a mosaic mode, with each mosaic consisting of nine 60-s pointings with an offset between each of 10 arcsec. A total of nine mosaics were obtained over the two nights. Short observations (20 s) of the standard star FS15 were taken on each night so that the data could be flux calibrated. Data reduction was performed using the UKIRT pipeline analysis tool, ORAC-DR. The *K*-band image resulting from the sum of all mosaics is shown in Fig. 3.

We detect an 18.7-mag source at the location of the radio images, but unfortunately the seeing is not adequate to resolve the radio images. From measurements of the sizes of stars in the field we measure a seeing-disc size of approximately 0.6 arcsec, only marginally less than the separation between the radio components. The source is, however, extended, with a major axis (FWHM ∼ 0.8–0.9 arcsec) that is aligned approximately north–south ($\theta \sim 10^\circ$). As this is similar to the orientation of the lensed images it is likely that some lensed emission has been detected. We have attempted to accurately align the radio and UKIRT images using the position of one of the stars in the UKIRT field that has been measured with the Carlsberg Automatic Meridian Circle (D. W. Evans, private communication). The positions of the radio components are also plotted in Fig. 3. The accuracy of our astrometry is set by the positional accuracy of the Carlsberg star which, with a positional uncertainty of approximately 150 mas, means that we cannot be certain whether most of the emission we see is from the lens or the lensed images.

4 DISCUSSION

We have presented radio and infrared observations of the CLASS source B0850+054. In this section we describe the evidence that leads us to believe that this source is, in fact, a doubly imaged lensed system.

The most convincing evidence is provided by the radio data. Our VLA, MERLIN and WSRT measured flux densities at 15, 8.5, 5 and 0.325 GHz, plus the 1.4-GHz NVSS measurement are plotted as a function of frequency in Fig. 4. Below 5 GHz the existing maps do not have the resolution to enable us to separate the A and B images, therefore only a total A+B flux density is plotted. At frequencies ⩾5 GHz the excellent agreement between the radio spectra of A and B is clear and the flux ratios in Table 2 confirm that the two components have identical spectra to within the errors.

Further support for the lensing hypothesis comes from a consideration of surface brightness arguments. As a lens system preserves surface brightness, the weaker image must be the more compact one as demonstrated particularly well by the VLBA data. Moreover, the extension of B along the line of the A–B separation is characteristic of gravitational lensing and the lack of detectable polarization in each image is also consistent with the lensing hypothesis.

A spectrum taken with the W. M. Keck I telescope has measured a redshift for the lensing galaxy of $z_l = 0.59$ (McKean et al., in preparation), based on the detection of Ca *H*- and *K*- and *G*-band absorption and a 4000-Å break. Also detected is a single emission line, which is almost certainly associated with the lensed radio source. The most likely identification for this line is Mg II ($z_s = 1.14$), though it could possibly be Lyα ($z_s = 3.93$). Assuming that Mg II is the correct identification, the image separation together with the measured lens redshift and a source redshift of 1.14 predicts a *K* magnitude for the lens galaxy of 17.9,[2] close to the measured UKIRT magnitude of 18.7. Unfortunately, the present optical data do not provide enough constraints (in particular, the galaxy position relative to the lensed images is unknown) to make any attempt at mass modelling fruitful.

From Fig. 4 it can be seen that the source spectrum has a turnover at approximately 1 GHz, thus making it a member of the gigahertz peaked spectrum (GPS) class. Low flux density variability is a generally recognized characteristic of GPS sources, as is low polarization (O'Dea 1998) and so B0850+054 seems consistent with the GPS identification. The source is <1 per cent polarized, and would also appear to be only moderately variable, if at all. Flux density measurements from the VLA and MERLIN data, the GB6 survey and the Parkes–MIT–NRAO (PMN) survey (Griffith et al. 1995), all at 5 GHz, are identical to within their errors. At 8.5 GHz, recent monitoring with the VLA (six epochs over 3 months) found no evidence for significant variability. Furthermore, an intrinsic size for the GPS source of ∼10 mas (as measured from the VLBA map of image A

[2] Invoking the Faber–Jackson relation (Faber & Jackson 1976) and assuming that an L^* galaxy at $z = 0.6$ has a *K* magnitude of 16.4.

and corrected for a lens magnification of ∼2, a plausible value) is consistent with the frequency and flux density (also corrected for the lens magnification) of the turnover using the relation found by Snellen et al. (2000) for GPS sources.

5 SUMMARY AND FUTURE WORK

We have discovered a new lens system during the course of the CLASS survey, B0850+054. It consists of two images of a GPS radio source with a separation of 0.7 arcsec and a flux density ratio of ∼6:1. UKIRT *K*-band imaging does not resolve the lens galaxy and the lensed images, but a lens galaxy redshift of 0.59 has been measured using the W. M. Keck telescope.

A priority for future work is the acquisition of a high-resolution optical/infrared image either with the *HST* or with ground-based adaptive optics. Knowing the relative positions of the lens and the lensed images will enable detailed mass modelling to be undertaken. We also plan higher-resolution VLBI observations to look for the substructure in image B that must be there. At the same time we hope to detect motion of the subcomponents. There is the exciting possibility, if B0850+054 is really a two-sided object, of being able to measure the advance speeds of the approaching and receding jets, made more easily visible by the lens magnification. When combined with measurement of the relative flux densities of the receding and approaching components, this opens up the prospect of an independent constraint on the Hubble constant (e.g. Taylor & Vermeulen 1997).

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