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A deep radio observation of the gravitational lens candidate QSO 2345 + 007

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ABSTRACT

The double QSO 2345 + 007 comprises two optical components separated by 7.1 arcsec, and is the most prominent 'dark matter' gravitational lens candidate. Despite being known for more than a decade, optical spectroscopy and imaging have been unable to determine whether this double QSO is a binary QSO or a gravitational lens system. In this note we report a deep VLA observation of this system, yielding a map with a noise level of 8.5 μJy beam^{-1}. We have a 4σ detection of a radio source within 0.4 arcsec of the optical position of the brighter A-component of the QSO, but no significant detection of any radio counterpart of the B-component. Given that the flux ratio in the optical waveband is $\sim$3–4, the gravitational lens hypothesis for this system would predict a radio flux of image B of $\lesssim$10 μJy. The non-detection of the B-component is thus consistent with, but does not prove, the lens interpretation.

Key words: cosmology: observations – dark matter – gravitational lensing.

1 INTRODUCTION

The double QSO 2345 + 007, the third known gravitational lens candidate, was discovered by Weedman et al. (1982) in a spectroscopic quasar survey. The two quasars are separated by about 7 arcsec, which makes this the QSO lens candidate with the largest image separation. A and B have similar line profiles and have the same redshift of $z_s = 2.15$ to within 15 ± 20 km s^{-1}. While this argues in favour of the lensing hypothesis (Steidel & Sargent 1991), nevertheless there are some differences in the two spectra which cause legitimate doubts (compare Steidel & Sargent 1991 with Steidel & Sargent 1990) on the lensing interpretation. The suggestion (Nieto et al. 1988) that the B-component is itself a close double with separation 0.4 arcsec further complicated the picture, but has not been verified by other ground-based observations (Weir & Djorgovski 1991) or *Hubble Space Telescope* (*HST*) imaging (Falco 1994).

Deep imaging of the field (Tyson et al. 1986; see also McLeod, Rieke & Weedman 1994) has revealed no obvious candidate for a lensing galaxy, yielding strong limits on the mass-to-light ratio of any potential lens between the images. If 2345 + 007 is indeed a lensing system, the lens must have unusual properties, or must be hidden at the position of one of the images so as to be outshone by the QSO. A third possibility is that the lensing is mainly due to a cluster of galaxies of high mass-to-light ratio, with only a relatively small galaxy between the images. This possibility has received further support by the report (Bonnet et al. 1993) of coherent distortions of background galaxies around the field of 2345 + 007, which indicate the presence of a massive galaxy cluster in this direction. Fischer et al. (1994) obtained an extremely deep image of the field surrounding 2345 + 007 and detected a faint ($B_J = 25$ mag) galaxy close to image B, as well as a statistically significant enhancement of faint galaxies around the QSO images. Mellier et al. (1994) also found an excess of faint blue galaxies in the field, centred on the shear field obtained by Bonnet et al. (1993). These imaging results support the lensing hypothesis for this system. From the absorption-line spectra of the two QSO images (Foltz et al. 1984; Steidel & Sargent 1990, 1991), the probable redshift of the deflector is estimated to be $z_d \sim 1.49$.

2345 + 007 is a very interesting and important object for gravitational lensing studies for at least two reasons. First, the large image separation implies that the lens is both massive and compact. For example, the lensing models considered by Fischer et al. (1994), assuming $z_d \sim 1.49$, suggest either that the galaxy near image B has a huge velocity dispersion ($\approx$850 km s^{-1}), or, if the galaxy overdensity is taken into account as a cluster at the same redshift, that this cluster must be extremely massive and compact. Alternatively, there can be an additional deflector at a different (lower) redshift, as indicated by three redshift measurements of galaxies in the field (Bonnet et al. 1993). Secondly, 2345 + 007 was the first double QSO for which correlations of the absorption spectra of the two objects were used to put constraints on the sizes of absorbing clouds (e.g. Foltz et al. 1984; Steidel & Sargent 1991). The results of this analysis depend critically on whether the object is lensed.

For the above reasons, it is of great interest to confirm the lensing nature of 2345 + 007. Whereas the support for the lensing hypothesis summarized above may appear convincing, 'very good gravitational lens candidates', based on spectroscopic evidence, have had in the past to be reclassified as binary QSOs (e.g., Djorgovski et al. 1987). Also, there are some spectral differences between the A- and B-components: e.g. the line-to-continuum ratios for various emission lines differ significantly (Steidel & Sargent 1991). While such differences can be attributed to intrinsic variability of the QSO coupled with the difference in light-traveltime (estimated to be of the order of a few years), to gravitational microlensing of the continuum (e.g. Wambsganss 1994, and references therein) and/or the broad-line region (Nemiroff 1988; Schneider & Wambsganss 1990), or to extinction in the lensing galaxy as indicated by colour differences between the images, the possibility that 2345 + 007 is a true binary QSO cannot at present be ruled out.

In an attempt to clarify the nature of 2345 + 007, we have obtained a deep radio image of this system with the VLA. A detection of radio counterparts for both components with about the same flux ratio as in the optical would provide a strong argument in favour of the lensing nature of the system. In addition, we were also motivated by the quest for the magnification ratio of the two images, assuming the system to be a lens. In the optical regime, the flux ratio varies with time and is different for the optical continuum and the broad emission lines (e.g. Steidel & Sargent 1991). These flux ratio changes can be explained by intrinsic variations of the QSO or by microlensing. The radio flux ratio shoud be less affected by these phenomena.

In Section 2 we describe the observations, and in Section 3 we present the results, which are discussed in Section 4.

2 OBSERVATIONS AND DATA REDUCTION

We observed 2345 + 007 on 1994 September 25 for 9 h at 8.4 GHz, using the VLA in its B/C-configuration with a total bandwidth of 100 MHz. The array configuration and the observing frequency were chosen to optimize sensitivity and resolution ($\sim$2.5 arcsec) for the image separation of 7.1 arcsec. The phase centre of the observations was at RA(J2000) $23^{h}48^{m}19\overset{s}{.}33$, Dec.(J2000) $+00°57'18\overset{''}{.}90$, which is located between the A- and B-images. 3C 48 was observed twice for flux density calibration (with an assumed flux density of 3.30 Jy). Since self-calibration is not possible for 2345 + 007, frequent phase calibration is essential. J0006 − 0623 was observed for 2 min every 15 min to calibrate the instrumental phases.

The data were analysed using the NRAO AIPS software package. The flux density of J0006 − 0623 was found to be 2.812 ± 0.009 Jy. We used both uniform and natural weighting of the data to make maps using the program MX.

3 RESULTS

The map made using natural weighting of the data is presented in Fig. 1. The noise in this map is 8.5 μJy which is close to the expected thermal noise. The brightest source in the field is an 80 ± 10 μJy source at RA(J2000) $23^{h}48^{m}15\overset{s}{.}943$, Dec.(J2000) $+00°56'11\overset{''}{.}70$, and lies outside the region shown in Fig. 1. The errors on positions are about 0.3 arcsec in each coordinate. The crosses on Fig. 1 mark the location of images A and B (derived from processing the optical positions as given by Weedman et al. 1982). We detect a source with a flux density of 35.0 ± 10 μJy at RA(J2000) $23^{h}48^{m}19\overset{s}{.}597$, Dec.(J2000) $+00°57'21\overset{''}{.}70$, which is within 0.4 arcsec of 2345 + 007A (RA $23^{h}48^{m}19\overset{s}{.}57$, Dec. $+00°57'21\overset{''}{.}6$; coordinates provided by P. Hewett from the APM sky catalogue). We do not detect any significant emission at the position of 2345 + 007B (RA $23^{h}48^{m}19\overset{s}{.}20$, Dec. $+00°57'17\overset{''}{.}8$). From source counts at 8.4 GHz at μJy levels, we expect about two sources brighter than 35 μJy in our field of 204.8 × 204.8 arcsec^2 (Windhorst et al. 1993). The probability that one of them lies within a radius of 0.5 arcsec of the position of our quasar is 4.07×10^{-5}. Thus we conclude that 2345 + 007A has been detected from the positional coincidence.

4 DISCUSSION

If 2345 + 007 is a gravitationally lensed QSO, then, for a radio flux of $S_A = 35 \pm 10$ μJy for the A-component, we expect the flux of the B-component to be S_A/r, where $r = \mu_A/\mu_B$ is the magnification ratio between the two images. The magnification ratio can be estimated from the optical flux ratios, which, however, change in time and are different for the optical continuum and the emission lines. The values for r quoted in the literature (see Weir & Djorgovski 1991) range from $\sim$2.5 to $\sim$4.0. Assuming a value closer to the upper end of the quoted range, as is justified by the fact that the Mg II line (which is a low-ionization line supposedly emitted at fairly large radii within the broad-line region and so least affected by microlensing) indicates $r \sim 4$ (Steidel & Sargent 1990), the expected radio flux of image B is about 10 μJy. Unfortunately, this is at the noise level of our maps. The fact that we do not detect the B-component is thus consistent with the lensing hypothesis. However, it does not provide the kind of strong proof that we were seeking.

In terms of the radio-to-optical flux ratio, 2345 + 007A appears to be a normal radio-quiet QSO. It is well known that about 10 per cent of optically selected QSOs are radio-loud, while the rest have fairly weak radio emission. Kellermann et al. (1989) observed all QSOs from the Bright Quasar Survey (BQS: Schmidt & Green 1983) with the VLA and detected 82 per cent of the QSOs above a flux level of 200 μJy. The BQS QSOs are all brighter than $B \lesssim 16.2$. The A-image of 2345 + 007 is about 3.5 mag fainter than the typical QSO from the BQS. Therefore,

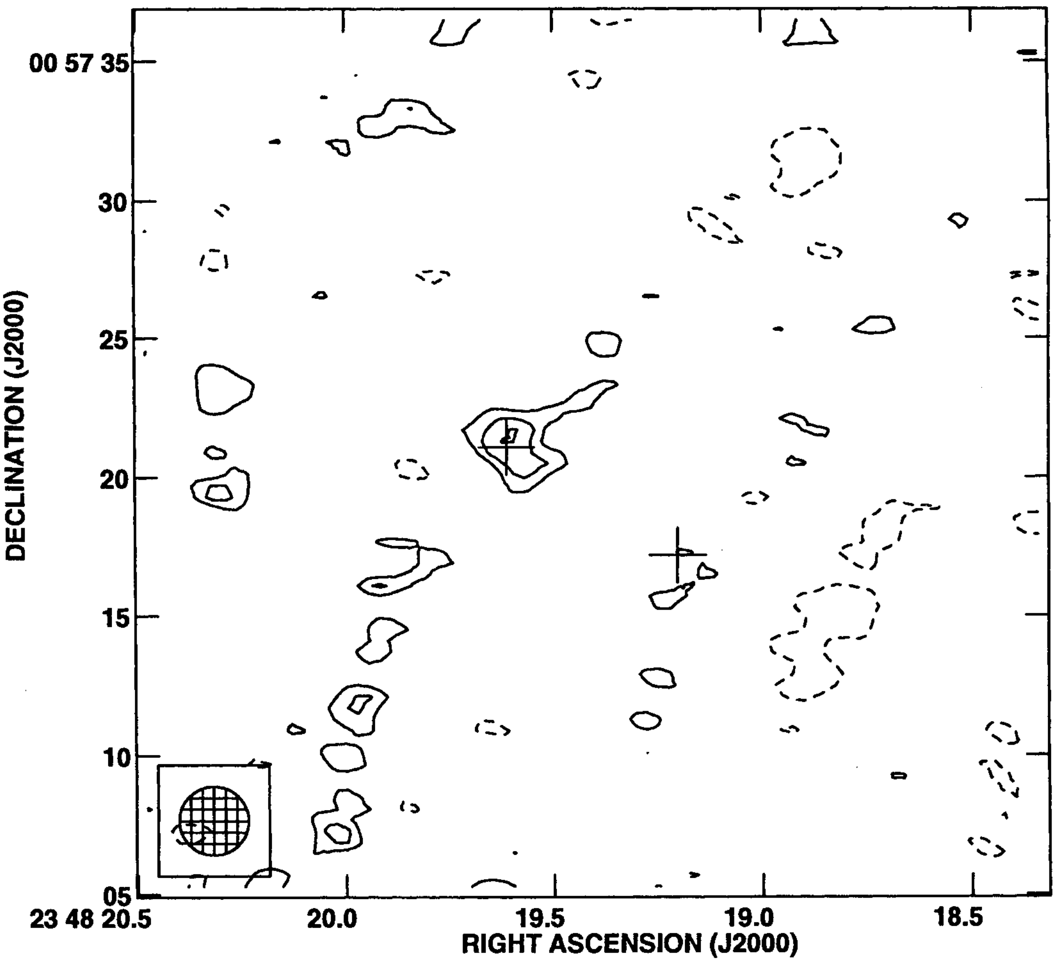

Figure 1. 8.4-GHz VLA map of 2345+007 with a resolution of 2.5 arcsec. The contour levels plotted in multiples of 16 μJy beam^{-1} are −2, −1, 1, 1.5, 2, 2.5, 3. Negative contours are dashed. The rms noise in the map is 8.5 μJy beam^{-1}. The restoring beam is shown on the lower left-hand corner. The crosses mark the optical positions of the two images.

assuming that the radio-to-optical flux ratio does not strongly depend on the optical brightness of a QSO, we expect the radio flux density of the A-image to be ~50 μJy. The observed radio flux of 35 μJy makes this object quite typical for its class. The B-image too is then consistent with being a typical radio-quiet QSO.

Despite the observational evidence described in the Introduction that 2345+007 is a gravitational lens system, some doubts remain. It is perhaps better to take a conservative position on this issue since the implications if the object is truly lensed are substantial. Even though a candidate lens galaxy has been observed (Fischer et al. 1994), its properties and/or the properties of the associated cluster have to be quite unusual to cause the large observed image splitting. In particular, if the lens redshift were $z_d = 1.49$ as indicated by the rich absorption system at this redshift in the spectra of the A- and B-images, it woud indicate an enormously massive and compact mass concentration at quite an early epoch, which would have implications for current cosmological models. For example, it is well known that a low-density universe allows the formation of clusters at higher redshifts than does a flat universe (e.g., Richstone, Loeb & Turner 1992; Bartelmann, Ehlers & Schneider 1993). Also, one of the strongest constraints in mixed cold and hot dark matter models comes from the presence of compact structures at early epochs (e.g. Cen & Ostriker 1994).

Although improving the existing optical and radio observations of 2345+007 will require a substantial effort, in view of the important astrophysical implications of the lensing nature of this object, deeper observations of this spectacular (in terms of image separation) gravitational lens candidate are worth pursuing.

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