PROCEEDINGS OF SCIENCE

A suspected Dark Lens revealed with the e-EVN

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The e-VLBI technique offers a unique opportunity for users to probe the milliarcsecond (mas) scale structure of unidentified radio sources, and organise quick follow-up observations in case of detection. Here we report on e-EVN results for a peculiar radio source that has been suggested to act as a gravitational lens. However the lensing galaxy has not been identified in the optical or the IR bands so far. Our goal was to look for an active galactic nucleus (AGN) in this suspected dark lens system. The results indicate strong AGN activity, and rule out the possibility that the radio source itself is gravitationally lensed.

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1. A Dark Lens candidate

In a campaign to study the optical properties of faint VLA FIRST (Faint Images of the Radio Sky at Twenty-Centimeters) sources with the Hubble Space Telescope, Russell et al. [1] identified an optical arc 4 arcseconds away from FIRST J121839.7 +295325 (hereafter J1218+2953). There was no optical identification of the radio source itself. The possible relation between the two objects was further investigated by Ryan et al. [2], who proposed that the arc may be a gravitationally lensed image and the radio source may belong to the lensing object. There are two major difficulties with this interpretation. First of all the lensing galaxy is not seen. Moreover the redshifts of the radio source and the optical arc are not known. Ryan et al. [2] estimated a redshift range of $0.8 < z < 1.5$ for the radio source on the basis that the galaxy is not seen in the optical ($z > 0.8$), but it has a relatively bright radio flux density ($z < 1.5$). They carried out photometric redshift measurements of the optical arc with the SAO Multi-Mirror Telescope. A weak spectral break was seen at around 4300 Å, which could be due to the Balmer/4000 Å break at $z \sim 0.13$, or due to the Lyman-break at $z \sim 2.5$. Probability analysis showed that the Lyman-break is much more likely, which suggests that the arc is located at a high redhsift. Obviously, if the spectral break is related to the Balmer series then the redshift is much smaller and the two objects are unrelated.

Ryan et al. [2] carried out gravitational lens modelling and found that the mass distribution must be elliptical to produce such a long arc. However the observed sub-structure within the arc, and especially a bright knot at the end, cannot be easily explained by gravitational lensing. They predict a secondary image which appears close to a pointlike source in the HST image, but this is likely due to a "hot pixel". According to the model, the enclosed mass within the Einstein-radius of 1.3 arcseconds is $10^{12\pm0.5} M_{\odot}$.

It is not clear how such a massive object may remain hidden. Even if there is strong obscuration by dust, there should be an infrared counterpart detected. IR imaging with the SAO Wide-field camera showed no galaxy with limiting magnitudes of $J = 22.0$ mag and $H = 20.7$ mag [2]. Ryan et al. conclude that either there is an early-type galaxy with significant amount of dark matter, or this could be a massive system with an AGN that is completely obscured, with dynamic mass-to-light ratio exceeding 100 $M_{\odot} L_{\odot}^{-1}$.

2. VLBI imaging of FIRST J1218+2953

2.1 Short e-EVN observations

We applied for short e-EVN observations in December 2008, to test the AGN hypothesis for J1218+2953. The total flux density of the source at 1.6 GHz is 33 mJy, which can be easily detected with limited EVN resources if it is compact. The observations took place on 23 January 2009 at a data rate of 512 Mbps with 2-bit sampling, dual polarization, and lasted for 2 hours. The array consisted of Cambridge and Knockin (MERLIN telescopes, limited to 128 Mbps), Jodrell Bank MkII, Medicina, Onsala, Torun and the Westerbork Synthesis Radio Telescope (WSRT). The target was phase-referenced to the nearby calibrator J1217+3007. The data were pipelined and then imaged in Difmap [3]. The source was detected and was resolved to two components, separated by about 500 mas (see Fig. 1).

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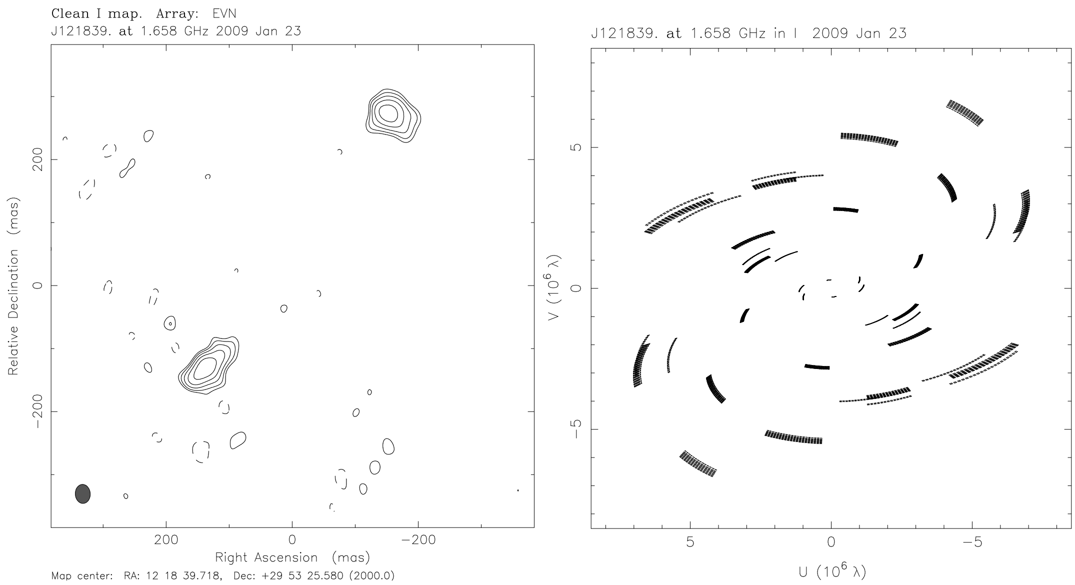

Figure 1: Left: naturally weighted image of J1218+2953 from 2 hours of short e-EVN observations at 1.6 GHz. The first contour is drawn at 0.4 mJy/beam, the following ones are multiples of this by $\sqrt{2}$. The beam was 30.3 $\times$ 23.8 mas, oriented at PA 3.3 degrees. The peak brightness was about 2.3 mJy/beam. The total cleaned flux density recovered was less then 15 mJy. Right: *uv*-coverage of the observations. The shortest MERLIN baselines (Jb2-Cm-Kn) are a great value for imaging of sources extending to several mas. However in this case the short observations were still not enough to recover most of the flux density.

This result opened up new possibilities for the interpretation of the radio source. Although it was not predicted from the "best-fit" gravitational lens model of Ryan et al., one may speculate that these two components are gravitationally lensed images of the same background source that gives rise to the optical arc images, or perhaps a completely unrelated background source. Alternatively, we may see a core-jet system or a medium-size symmetric object (MSO). To distinguish between these scenarios we put in an observing proposal by the 1 February 2009 deadline (just 8 days following the e-EVN observations), for full-track e-EVN observations at 5 and 1.6 GHz.

2.2 Follow-up experiments

J1218+2953 was observed at 5 GHz on 24-25 March for 8 hours. The array this time included the 100m Effelsberg telescope as well. Four telescopes (Ef, On, Tr, Wb) sent data to the correlator at 1024 Mbps rate, the rest at 512 Mbps or lower. The 1.6 GHz observations were carried out on 21-22 April 2009 at 512 Mbps data rate. In the array Knockin was replaced by Darnhall, the 76m Lovell Telescope was used instead of the MkII in Jodrell Bank, and Arecibo joined as well (for 2 hours and 20 minutes). These observations and the data processing were similar to the short project described above. In addition, we reduced the synthesis array data from the WSRT that was obtained during the VLBI run.

The 5 GHz image resolves the South-East component into an elongated, slightly curved jet-like structure, which does not point towards the North-West component (see Fig. 2). There is no very compact component that could be firmly identified as a core. The total cleaned flux density is only 3 mJy compared to the total WSRT flux density of 9 mJy, indicating that most of the source is resolved out in this image. The 1.6 GHz image reveals an even more complex, but more continuous structure. The total cleaned flux density was about 20 mJy, close to the total WSRT flux density of 27 mJy.

3. Interpretation of the results

These preliminary e-EVN results show that the radio source near the optical arc has a complex structure. The spectrum of the components is steep; that of the faint component near the phase centre is somewhat flatter. Because of the apparent quasi-continuous structure, the various components are likely not gravitationally lensed images of an unrelated background source.

Comparing the total cleaned flux density of about 20 mJy to the WSRT flux density of 27 mJy, it is evident that most of the flux density is recovered at 1.6 GHz with the EVN. This indicates that the radio source and the optical arc cannot be lensed image pairs of the same background object, because in that case most of the radio flux density would be present near the optical arc since that image is strongly magnified (if the arc is indeed a lensed image).

Further, gravitational lensing should be achromatic; thus were the pair of components to the SE and NW in the 1.6 GHz image (Fig. 2, bottom panel) lensed images, the flux density ratio of the inner:outer components of each should be similar, a condition that is clearly violated.

The most likely scenario is that the images show a single compact steep-spectrum (CSS) source (projected linear size $< 20\ h^{-1}$ kpc), that might be categorized as a medium-size symmetric object (MSO, projected linear size $> 1\ h^{-1}$ kpc) as well [4]. There is thus evidence for AGN activity in the radio source. Note that if the optical arc is lensed by an object related to this AGN, then the mass-centre of the lens should be at the position of the AGN, which constrains further modelling of the system.

Finally we note that this research benefited strongly from two aspects of the (e-)EVN: the additional short MERLIN spacings were of great use in recovering flux density on several-hundred mas scales, and the simultaneous recording of WSRT synthesis array data was very important for the intepretation of our results.

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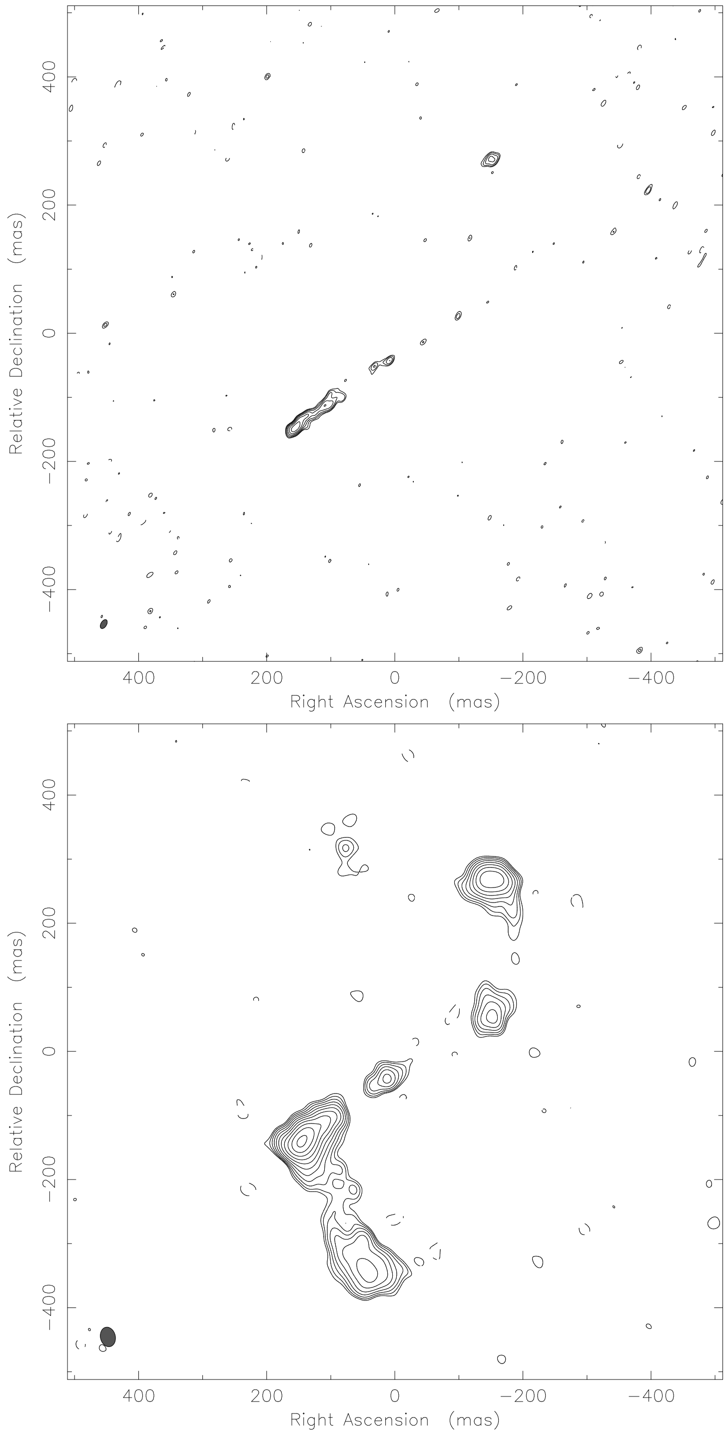

Figure 2: Full-track 5 GHz (top) and 1.6 GHz (bottom) e-EVN maps of J1218+2953. The peak brightnesses are 360 μJy/beam and and 2.7 mJy/beam, respectively. The lowest contour levels are set at the 3 sigma noise level (49 μJy/beam and 75 μJy/beam, respectively) and they increase by a factor of $\sqrt{2}$. Both maps were naturally weighted; at 1.6 GHz a Gaussian taper was applied additionally, with half amplitude at 10 Mλ. The beam was 15.4 $\times$ 8.8 mas, oriented at PA -30.5 degrees at 5 GHz, and 30.9 $\times$ 23.3 mas, oriented at PA -13.3 degrees at 1.6 GHz.