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EVN observations of the Binary Black-Hole candidate SDSS J1536+0441

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We present European VLBI Network (EVN) observations at 5 GHz of the candidate binary black-hole system SDSS J1536+0441. Both components, J1536+0441A and J1536+0441B, observed by the VLA at 8.5 GHz and separated by 0.97 arcsec are detected with high S/N, proving the presence of two compact AGNs with radio luminosity $L_R \sim 10^{40}$ erg s^{-1}. From a comparison with published 8.5 & 22.5 GHz flux densities, we derive an estimate of the radio spectral index of the two radio sources. Both sources have flat or inverted radio spectrum. In particular, J1536+0441A has a rising spectrum up to $\simeq$ 30 GHz, rest frame. Given the moderate brightness temperature derived from the flux and fitted size of J1536+0441A, we suggest that thermal free-free emission from an X-ray-heated disc may be powering the radio emission in J1536+0441A.

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1. Introduction

SDSS J153636.22+044127.0 (hereafter SDSS J1536+0441) is one of the binary black-hole candidates found in a search for quasars displaying broad-lines features at different redshifts in the Sloan Digital Sky Survey [4]. The optical spectrum shows two sets of broad emission lines at $z = 0.3889$ and $z = 3727$, and a third set of narrow absorption lines at the intermediate redshift $z = 0.3878$. Narrow emission lines were detected associated only with the higher redshift system. Radio observations carried out by the VLA at 8.5 GHz detected two components, separated by $0''.97$ (5.1 kpc), named J1536+0441A and J1536+0441B respectively [14]. High resolution optical imaging detected the optical counterpart of J1536+0441B, but any optical signature of an AGN in this object was unclear and not conclusive [7, 11]. Different interpretations were suggested in order to explain the rather complex optical features.

1. A black-hole binary (BHB) system within the same galaxy with a separation of 0.1 pc and masses of $\sim 10^7$ and $\sim 10^9$ $M_\odot$each with its own broad-line region and sharing the same narrow-line region [4, 11]. In this scenario J1536+0441B is an elliptical galaxy, that can be responsible for the absorption features detected in the overall optical spectrum but is not contributing to the broad-line emission.
2. A AGN pair separated by 5.1 kpc and probably residing in a moderately rich cluster of galaxies [7].
3. A double peaked emitter, albeit a peculiar one [5, 6, 9].

All these scenarios are critically discussed by Lauer & Boroson [11].

2. EVN Observations

To discriminate between the different interpretations given in the previous section is beyond the capability of the VLBI. An angular resolution of 0.02 mas coupled with a sensitivity of a few tens of microJy or better would be necessary to resolve and image the 0.1 pc BHB, and this is not yet possible. Nonetheless, pc-scale imaging of J1536+0441 can shed some light on the nature of the two radio sources. We decided to target SDSS J1536+0441 exploiting the high sensitivity of the EVN with the following main goals:

- Pinpoint the AGN/AGNs position.
- Identify the nature of the radio emission associated to the component J1536+0441B. At the time of our EVN proposal no optical counterpart was known for J1536+0441B.
- Image the parsec scale structure of J1536+0441A and J1536+0441B and derive the radio spectral index properties using the available VLA/VLBA data.

To fulfill these goals we observed SDSS J1536+0441 at 5 GHz on 2009 October 23 for about 5 hours (on-source time). The observations were carried out at the 1024 Mbit s^{-1} sustained bit rate reaching a 1σ r.m.s sensitivity of about 15μJy/beam with a resolution of about 10 mas. More details on the observations, data analysis and discussion can be found in [3].

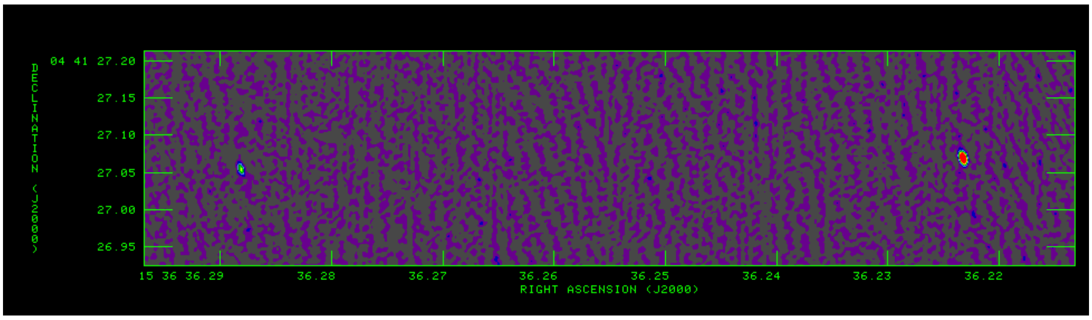

Figure 1: EVN image at 5 GHz of the SDSS J1536+0441 field. This image was obtained applying natural weighting yielding to a resolution of 14×7 mas at position angle 16°. The 1σ r.m.s. noise is 15 μJy/beam. J1536+0441A, on the right, has a peak flux of 0.62 mJy/beam, J1536+0441B, on the left, has a peak flux of 0.22 mJy/beam.

3. Results & Discussion

Figure 1 shows the 5 GHz EVN image of the J1536+0441 field. We detected with high signal-to-noise ratio both J1536+0441A and J1536+0441B (S/N = 40 and S/N =15, respectively). The field was also imaged with a different weighting scheme allowing better resolution ($\sim 7 \times 5$ mas) but a larger noise. The sources were fitted with two-dimensional elliptical Gaussians obtaining consistent results between images with different resolutions. The derived flux densities at 5 GHz, positions and errors are: for J1536+0441A $S = 0.72 \pm 0.06$ mJy, $\alpha(J2000) = 15^{\mathrm{h}}36^{\mathrm{m}}36^{\mathrm{s}}.2232$, $\delta(J2000) = +04^{\circ}41'27''.069$, and $\sigma_{\mathrm{VLBI}} = 0.003$ mas; for J1536+0441B, $S = 0.24 \pm 0.03$ mJy, $\alpha(J2000) = 15^{\mathrm{h}}36^{\mathrm{m}}36^{\mathrm{s}}.2881$, $\delta(J2000) = +04^{\circ}41'27''.054$, and $\sigma_{\mathrm{VLBI}} = 0.003$ mas. J1536+0441A appears slightly resolved with a deconvolved fitted size $\simeq 3.2 \times 2.5$ mas with an estimated error of 1 mas.

In Table 1 we have collected the radio flux densities available at different frequencies in the literature for J1536+0441A and J1536+0441B. Table 1 lists measurements made with different resolutions (arcsec scale for VLA obervations compared to milli-arsec scale for VLBI observations) and usually at different epochs. While it can be dangerous to draw conclusions on the details of the radio spectral properties of J1536+0441A and J1536+0441B, these data are adequate to describe the general trend of the spectral index of the two components. Moreover, the VLBA observations at 8.5 GHz [15] have been carried out 9 days earlier than our 5 GHz EVN observations and with a similar resolution (within a factor of a few), therefore these flux densities can be considered unaffected by variability or resolution issues.

J1536+0441 is not detected in the FIRST survey [13], and the flux density at 1.4 GHz in Table 1 is a 4σ upper limit at the position of the radio source. Since the resolution of the FIRST survey is 5 arcsec the upper limit includes both the radio components.

As far as concern J1536+0441B the only thing we can say is that the data so far available suggest a flat radio spectrum between 1.4 GHz and 8.5 GHz. The optical counterpart of J1536+0441B is very red [7, 11] and the detection of a pc-scale unresolved flat spectrum radio core with observed radio luminosity $L_R = \nu L_\nu = 0.6 \times 10^{40}$ erg s^{-1} at 5 GHz is best interpreted as an obscured AGN rather than an elliptical galaxy.

The almost contemporaneous radio flux densities measured on similar scales at 5 and 8.5 GHz

Comp.	1.4 GHz VLA mJy	5 GHz VLBI mJy	8.5 GHz VLBI mJy	8.5 GHz VLA mJy	22.5 GHz VLA mJy
J1536+0441A	< 0.6 (A+B)	0.72 ± 0.06	0.88 ± 0.12	1.17 ± 0.04	1.65 ± 0.11
J1536+0441B	< 0.6 (A+B)	0.24 ± 0.03		0.27 ± 0.02	

Table 1: Radio flux densities of J1536+0441A and J1536+0441B. The 1.4 GHz flux density is an upper limit from the FIRST Survey [13] including both components. The 8.5 GHz VLBI flux is from VLBA observations made in October 2009 [15]. The 8.5 GHz VLA flux is from [14]. The 22.5 GHz VLA flux is from [15].

allows us to better constrain the spectral shape of J1536+0441A. The radio spectrum is clearly inverted (with a spectral index $\alpha \simeq 0.4$ with $S(\nu) \propto \nu^{\alpha}$). The inverted spectrum is confirmed by the non-contemporaneous VLA data, with $\alpha = 0.35 \pm 0.08$ between 8.5 GHz and 22.5 GHz [15], yielding to an inverted spectrum up to $\simeq 30$ GHz rest-frame.

One possible origin of the inverted radio spectrum is synchrotron self-absorption. For self-absorption to occur, the brightness temperature must be comparable to the kinetic temperature of the synchrotron electrons. The measured brightness temperature for J1536+0441A, for which we have a deconvolved fitted size, is $T_b = 9 \times 10^6$ K. This value is too low to affect the radio spectrum unless the magnetic field is rather large [8]. An alternative interpretation of the inverted radio spectrum of J1536+0441A is thermal free-free emission from a disk wind [8, 2]. As shown in the model developed by Blundell & Kuncic [2], high brightness temperatures ($T_b \sim 10^7$ K) can arise from a thermal plasma provided that it is hot ($T_e \gtrsim 10^7$ K) and marginally optically thin ($\tau_\nu^{ff} \lesssim 1$). In this scenario, we can expect a link between the radio and X-ray emission. A correlation between radio luminosity at 5 GHz (L_R) and bolometric 0.2-20 keV X-ray luminosity (L_X), with $L_R/L_X \sim 10^{-5}$ indeed has been found in nearby Seyferts and radio quiet quasars [12, 10]. For J1536+0441A the radio luminosity at 5 GHz, as derived from our observations is $L_R = \nu L_{5GHz} = 1.9 \times 10^{40}$ erg s^{-1}. Using the X-ray luminosity measured by *Swift* [1], we obtain $L_R/L_X = 1.4 \times 10^{-5}$, assuming all the X-ray emission is associated to J1536+0441A.

4. Summary

We have presented the 5GHz EVN observations of the candidate binary black-hole system J1536+0441. We have detected two compact cores associated with the sources J1536+0441A and J1536+0441B separated by 0.97 arcsec (5.1 kpc). The main results can be summarized as follows.

1. A flat spectrum radio nucleus, unresolved on the pc-scale, and with a radio luminosity of 0.6×10^{40} erg s^{-1} is found at the position of J1536+0441B, suggesting that J1536+0441B is most likely an obscured AGN rather than a passive elliptical galaxy.

2. At the position of J1536+0441A we detect a slightly resolved radio nucleus. From almost contemporaneous 5 & 8.5 GHz observations we derive a spectral index of $\alpha \simeq 0.4$ (with $S_\nu \propto \nu^{\alpha}$). From a comparison with VLA observations the rising spectrum continues up to 22.5 GHZ ($\simeq 30$ GHz rest frame). Given the rather modest measured brightness temperature ($T_b = 9 \times 10^6$ K), we suggest that the inverted spectrum can be explained not as synchrotron self-absorption but as thermal free-free emission from a disk wind.

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3. We derive a value of $L_R/L_X = 1.4 \times 10^{-5}$ that is totally consistent with the correlation found for radio-quiet quasars and Seyfert galaxies.

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