We present the first pc-scale radio imaging of the radio-quiet candidate binary black hole system SDSS J1536+0441. The observations were carried out by the European VLBI Network at a frequency of 5 GHz, allowing the imaging of SDSS J1536+0441 with a resolution of ~10 mas (~50 pc). Two compact radio cores are detected at the position of the kpc-scale components VLA-A and VLA-B, proving the presence of two compact active nuclei with radio luminosity $L_R \sim 10^{40}$ erg s$^{-1}$, thus ruling out the possibility that both radio sources are powered by a 0.1 pc binary black hole. From a comparison with published 8.5 GHz flux densities, we derived an estimate of the radio spectral index of the two pc-scale cores. Both cores have a flat or an inverted spectral index, and at least for the case of VLA-A we can rule out the possibility that synchrotron self-absorption is responsible for the inverted radio spectrum. We suggest that thermal free–free emission from an X-ray-heated disk wind may be powering the radio emission in VLA-A.

**Key words:** galaxies: active – quasars: individual (SDSS J153636.22+044127.0) – radio continuum: general
phase-referenced to the calibrator J1539+0430 with a duty cycle of 5 minutes. The total time on source for SDSS J1536+0441 was about 5 hr. The strong and compact sources J1613+3412 and J0154+4743 were used as fringe finders and bandpass calibrators.

The data were correlated and calibrated at the JIVE correlator. Standard a priori gain calibration was performed using the phase reference source. Further data inspection, flagging, and imaging were performed by the authors using the NRAO AIPS software. No polarization or self-calibrations were performed.

The amplitude calibration was refined using the phase reference calibrators.

Figure 1 shows the field of SDSS J1536+0441 imaged with the EVN at 5 GHz using natural weighting, which resulted in a resolution of $12 \times 7$ mas at position angle $10^\circ$. VLA-A (on the right) and VLA-B (on the left) are clearly distinguishable with S/N of 50 and 15, respectively.

Figure 2. Contour plots of components VLA-A (right) and VLA-B (left) of SDSS 1536+0441. The beam size is $12 \times 7$ mas at position angle $10^\circ$. The $1\sigma$ rms noise is about 0.015 mJy beam$^{-1}$. First contour is three times the noise and each inner contour is $\sqrt{2}$ times brighter.

3. RESULTS AND DISCUSSION

Figure 1 shows the field of SDSS J1536+0441 imaged with the EVN at 5 GHz using natural weighting, which resulted in a beam of $12 \times 7$ mas in position angle $10^\circ$ and a $1\sigma$ rms noise of 15 $\mu$Jy beam$^{-1}$. Both radio sources, VLA-A and VLA-B following the notation used by WL09, are clearly detected with signal-to-noise ratios (S/N) of 50 and 15, respectively. Contour plots of VLA-A and VLA-B are shown in Figure 2.

We also imaged the two radio sources with a slightly better resolution ($7 \times 6$ mas) but worse sensitivity, using a different $u-v$ data weighting function. These images are not shown here, but both set of images were used to find consistent fitted Gaussian parameters for VLA-A and VLA-B. The sources were fitted with two-dimensional elliptical Gaussians. The flux densities, positions, and errors are: for VLA-A, $S = 0.72 \pm 0.06$ mJy, $\alpha(J2000) = 15^{h}36^{m}36^{s}22.32$, $\delta(J2000) = +04^{o}41^{\prime}27^{\prime\prime}069$, and $\sigma_{\text{VLBI}} = 0.003$ mas; for VLA-B, $S = 0.24 \pm 0.03$ mJy, $\alpha(J2000) = 15^{h}36^{m}36^{s}28.81$, $\delta(J2000) = +04^{o}41^{\prime}27^{\prime\prime}054$, and $\sigma_{\text{VLBI}} = 0.003$ mas. VLA-A appears slightly resolved when fitted with a single elliptical Gaussian component. The deconvolved fitted sizes are $\theta_{\text{VLA-A}} \simeq 3.2 \times 2.5$ mas with an estimated error of 1 mas. The high S/N for this component provides a high level of confidence for the deconvolved fitted size. There is some indication that also VLA-B could be slightly resolved with a deconvolved size of about 2 mas, but in this case given the limited S/N this value should be considered as an upper limit.

The positions are in excellent agreement with those determined by WL09. The separation between the two components is confirmed to be 0.97.

One of the goals of the proposed EVN observations was to determine the origin of the radio emission in VLA-B and in particular if it could be associated with VLA-A, e.g., as being a compact jet/hot-spot or a mini-lobe ejected by VLA-A. No extended emission is detected in the region between the two compact radio sources. Given the compactness of VLA-B on the pc-scale we can now confirm without any doubt that VLA-A and VLA-B are two compact AGNs and we can rule out the possibility that both radio sources are powered by a 0.1 pc binary black hole (see WL09).

Comparing our flux densities at 5 GHz with those obtained by WL09 we can derive an estimate of the radio spectral index between these two frequencies. It certainly can be speculative to draw conclusions on the radio spectral index of VLA-A and VLA-B based on observations made at different resolutions and epochs, but it is a first step, waiting for more appropriate observations, and it is illustrative of the general trend of the spectral properties. As far as radio variability is concerned, the VLA 8.5 GHz and the very long baseline interferometry (VLBI) 5 GHz observations are separated by 8 months, and significant variability (e.g., $\simeq 20\%$ with a few cases with larger variations) is observed on such a time range in radio-quiet and radio-loud quasars (Barvainis et al. 2005). Keeping in mind this limitation, it is worth noting that the flux density of VLA-A at 5 GHz, 0.72 mJy, is lower than the 1.17 mJy measured at 8.5 GHz, while the flux density of VLA-B is rather constant: 0.27 mJy at 8.5 GHz compared with 0.24 mJy at 5 GHz. Both sources would have flat or inverted radio spectra, and VLA-A in
particular would exhibit a strongly rising radio spectrum. WL09 already suggested that VLA-A could have an inverted radio spectrum to explain the non-detection of the radio source in the 1.4 GHz FIRST sky survey (White et al. 1997) and our 5 GHz observations confirm this possibility. Another possibility is that we are missing flux in the 5 GHz VLBI observations. If there is some extended emission (on the scale of $\approx 100$ mas), our VLBI observations might not be deep enough or have the adequate $u-v$ coverage to detect it. This possibility is rather improbable since a significant amount of extended, and therefore steep, spectrum emission at 5 GHz should have been detected in the 1.4 GHz FIRST sky survey given the 1 mJy threshold of the VLA survey. Therefore, in the remaining discussion we will assume that any missing flux is not significantly affecting the derived spectral indices.

With the measured flux densities at 5 and 8.5 GHz, VLA-A would have a spectral index $\alpha \approx -0.9$ (with $S(\nu) \propto \nu^{-\alpha}$). Such an inverted spectrum, even if found in a few radio quiet quasars, is quite unusual (Barvainis et al. 1996; Kukula et al. 1998; Ulvestad et al. 2005). Synchrotron self-absorption is the most invoked cause to explain the flat or inverted spectra in radio-loud or radio-quiet AGNs. For self-absorption to occur, the brightness temperature must be comparable to the kinetic temperature of the synchrotron electrons. The brightness temperature in Kelvin is (e.g., Ulvestad et al. 2005)

$$T_b = 1.8 \times 10^9 (1+z) \left( \frac{S_\nu}{1 \text{ mJy}} \right) \left( \frac{\nu}{1 \text{ GHz}} \right)^{-2} \left( \frac{\theta_1 \theta_2}{1 \text{ mas}} \right)^{-1}$$

which for VLA-A gives $T_b = 9 \times 10^6$ K and for VLA-B $T_b \geq 6 \times 10^6$ K (assuming an upper limit for the size of VLA-B of $2 \times 2$ mas). These brightness temperatures, at least for VLA-A for which we have a measured fitted size, are too low to affect the spectra unless the magnetic fields are unrealistically high (Gallimore et al. 1996).

The optical counterpart of VLA-B is very red (Decarli et al. 2009a; Lauer & Boroson 2009) and with the detection of a pc-scale flat spectrum radio core with observed radio luminosity $L_R = \nu L_\nu$ at 5 GHz of $0.6 \times 10^{40}$ erg s$^{-1}$ is best interpreted as an obscured AGN rather than an elliptical galaxy. The brightness temperature of VLA-B is only a lower limit since the size is not constrained and we cannot rule out the possibility of synchrotron self-absorption affecting the flat radio spectrum as well as the contribution of thermal free–free absorption/emission.

The low-brightness temperature of VLA-A rules out synchrotron self-absorption as the origin of the inverted radio spectrum. Free–free absorption should be discarded as well, since the view to the AGN is obscured in VLA-A where we see optical continuum emission from the AGN and the broad-line region. We suggest that the radio emission from VLA-A could be interpreted as thermal free–free emission from a disk wind (Gallimore et al. 1996; Blundell & Kuncic 2007). The disk wind is heated by the X-ray continuum and therefore we can expect a link between the radio and X-ray emission. Panessa et al. (2007) found a linear correlation between radio ($L_R$ at 5 GHz) and X-ray ($L_X$) core luminosities in an optically selected sample of nearby Seyfert. This result was confirmed and extended to radio-quiet quasars by Laor & Behar (2008) using the carefully selected and almost complete Palomar–Green quasar sample. They found that $L_R/L_X \sim 10^{-5}$, where $L_R$ is the radio luminosity at 5 GHz and $L_X$ is the bolometric 0.2–20 keV X-ray luminosity. Quite remarkably, the same correlation, known as the Güdel–Benz relation (Güdel & Benz 1993), holds for coronally active stars, therefore covering a range of about 15 orders of magnitude in luminosity. WL09 used the X-ray luminosity measured by Swift (Arzoumanian et al. 2009) and extrapolated the 5 GHz luminosity from their 8.5 GHz measurement assuming a radio spectral index $\alpha = 0.5$, obtaining $L_R/L_X = 5.9 \times 10^{-5}$. Having a direct measure of the core flux density at 5 GHz we can refine this measurement. The observed monochromatic luminosity at 5 GHz of VLA-A is $L_{5\text{GHz}} = 3.8 \times 10^{30}$ erg s$^{-1}$ Hz$^{-1}$, and the radio luminosity at 5 GHz is $L_R = \nu L_{5\text{GHz}} = 1.9 \times 10^{40}$ erg s$^{-1}$ which gives $L_R/L_X = 1.4 \times 10^{-5}$, assuming all the X-ray emission is associated with VLA-A.

These VLBI observations were not meant to solve the so-far unsatisfactory interpretation of the puzzling properties of SDSS J1536+0441. The debate is still open about all the possible scenarios summarized in Section 1. What is now clear is that both VLA-A and VLA-B are powered by their own AGN, and this should be taken into account in future analysis. Further radio observations are necessary to confirm the spectral shape of the radio cores and therefore the origin of the radio emission.

4. SUMMARY

We have presented the first VLBI pc-scale imaging of the candidate binary black hole system SDSS J1536+0441 observed by the EVN at 5 GHz. Both the VLA-A component, associated with SDSS J1536+0441, and the companion object, VLA-B, at 0.97 east of the quasar are detected with high $S/N$ (50 and 15, respectively). The two radio nuclei appear barely resolved and no extended larger-scale emission is detected. The main results can be summarized as follows.

1. We detect a flat spectrum pc-scale radio nucleus at the position of VLA-B confirming that both VLA-A and VLA-B are powered by their own AGN. Given the radio and optical properties, VLA-B is most likely associated with an obscured AGN rather than a passive elliptical galaxy.
2. At the position of VLA-A, we detect a slightly resolved radio nucleus with a strongly rising spectrum with $\alpha \approx -0.9$ between 5 and 8.5 GHz. We rule out synchrotron self-absorption as the cause of the inverted radio spectrum because the derived brightness temperature of VLA-A is too low. We suggest that thermal free–free emission from a disk wind provides the simplest explanation for the inverted radio spectrum in VLA-A.
3. We derive a value of $L_R/L_X = 1.4 \times 10^{-5}$ for VLA-A that is totally consistent with correlation found for radio-quiet quasars and Seyfert galaxies (Panessa et al. 2007; Laor & Behar 2008).

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Facility: EVN

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