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# DISCOVERY OF RADIO EMISSION FROM THE QUASAR SDSS J1536+0441, A CANDIDATE BINARY BLACK HOLE SYSTEM

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## ABSTRACT

The radio-quiet quasar SDSS J1536+0441 shows two broad-line emission systems that Boroson and Lauer interpret as a candidate binary black hole system with a separation of 0.1 pc (0.02 mas). From new VLA imaging at 8.5 GHz, two faint sources, separated by 0.″97 (5.1 kpc), have been discovered within the quasar's optical localization region. Each radio source is unresolved, with a diameter of less than 0.″37 (1.9 kpc). A double radio structure is seen in some other radio-quiet quasars, and the double may be energized here by the candidate 0.1 pc binary black hole system. Alternatively, the radio emission may arise from a binary system of quasars with a projected separation of 5.1 kpc, and the two quasars may produce the two observed broad-line emission systems. Binary active galactic nuclei with a kpc-scale separation are known from radio and X-ray observations, and a few such system are expected in the Boroson and Lauer sample based on the observed clustering of quasars down to the 10 kpc scale. Future observations designed to distinguish between the 0.1 pc and 5 kpc scales for the binary system are suggested.

*Key words:* quasars: individual (SDSS J153636.22+044127.0) – radio continuum: general – X-rays: general

## 1. MOTIVATION

The quasar SDSS J153636.22+044127.0, at a redshift 0.388, shows two broad-line emission systems separated in velocity by 3500 km $s^{-1}$ (Boroson & Lauer 2009). This unique quasar is interpreted as a binary black hole system with a separation of 0.1 pc and masses of $10^{7.3}\ M_\odot$ and $10^{8.9}\ M_\odot$. The subparsec scale is significant, as it suggests that this close binary system shares a common narrow-line emission region and has also solved its so-called final parsec problem. For the assumed flat cosmology,[3] the 0.1 pc binary subtends 0.02 mas. An alternative interpretation for SDSS J153636.22+044127.0 (SDSS J1536+0441 hereafter) is that it represents two unrelated quasars viewed, by chance, along similar sight lines. Boroson & Lauer (2009) use the optical localization region—a circle of radius 1″ —to rule out this alternative interpretation with a probability of 0.0032.

New high-quality spectroscopy by Chornock et al. (2009) revealed a broad feature redshifted by 3500-4500 km $s^{-1}$ in H$\alpha$ and H$\beta$, which raises a third option that SDSS J1536+0441 is a "double-peaked emitter" (DPE), such as seen in Arp 102B (Halpern & Filippenko 1988) and 3C 390.3 (Eracleous & Halpern 1994). The peculiar emission profile in a DPE may originate from a thin Keplerian gaseous disk (also proposed for SDSS J1536+0441 by Gaskell 2009). However, as noted by Chornock et al. (2009), a DPE shows two broad components of comparable strength, unlike seen here.

It is clearly important to observe this quasar with subarcsecond resolution, for two reasons. First, the 0.1 pc binary hypothesis can be ruled out if two widely separated sources are detected. Second, if observations with subarcsecond resolution detect only a single source, then the random-projection estimate would drop below 0.0032, serving to strengthen the 0.1 pc binary hypothesis.

SDSS J1536+0441 is not detected in 1.4 GHz sky surveys, so its flux density is less than 1 mJy at 5″ resolution (White et al. 1997) and less than 2.5 mJy at 45″ resolution (Condon et al. 1998). Following Ivesic et al. (2002), combining the 1 mJy upper limit at 1.4 GHz with the *i*-band magnitude (Boroson & Lauer 2009) means that SDSS J1536+0441 has a radio-to-optical ratio less than unity, implying that it is a radio-quiet quasar. Fortunately, such a classification does not exclude it from being detected at radio frequencies and observed with subarcsecond resolution. Section 2 of this Letter reports new VLA[4] (Thompson et al. 1980) imaging of SDSS J1536+0441 at subarcsecond resolution, leading to the discovery of two sources separated by 0.″97 (5.1 kpc). The implications of this discovery are explored in Section 3. Section 4 closes with a summary of this work and suggestions for future directions.

## 2. VLA IMAGING

The B configuration of the VLA was used, under proposal code AL738, to observe SDSS J1536+0441 near transit on UT 2009 February 17 and 20. Observations were phase referenced to the calibrator J1534+0131 whose positional accuracy was less than 2 mas. The switching angle was 3° and the switching time was 280 s. The center frequency was 8.4601 GHz, abbreviated as 8.5 GHz hereafter. The a priori pointing position for the quasar was centered 3″ north of the SDSS name-derived position to avoid any phase-center artifacts. Observations were made assuming a coordinate equinox of 2000. Data were acquired with a bandwidth of 100 MHz for each circular polarization. Observations of 3C 286 were used to set the amplitude scale to an accuracy of about 3%. The net exposure times for SDSS J1536+0441 were 6020 s and 6080 s on 2009 February 17 and 20, respectively. Twenty-five antennas provided data of acceptable quality.

The data were calibrated using the 2009 December 31 release of the NRAO AIPS software. No polarization calibration or self-calibrations were performed. After calibration, each day's

[3] $H_0 = 71$ km $s^{-1}$ $Mpc^{-1}$ and $\Omega_m = 0.27$, implying a luminosity distance of 2.1 Gpc, an angular size distance of 1.1 Gpc and a scale of 5.2 kpc per arcsec.

[4] Operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

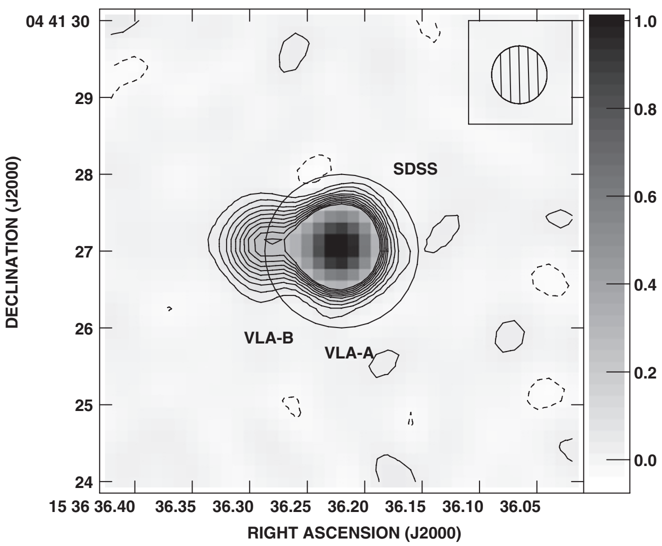


**Figure 1.** VLA image of Stokes $I$ emission from SDSS J1536+0441 at a frequency of 8.5 GHz and spanning 6″ (31 kpc). SDSS position is marked with a circle of radius 1″. Labels identify sources VLA-A and VLA-B. Uniform weighting with a robustness parameter of zero was used, giving an rms noise of 0.013 mJy beam$^{-1}$ ($1\sigma$) and Gaussian beam dimensions at FWHM of 0.″75 × 0.″72 at a position angle of 1.°3 (hatched ellipse). Geometric-mean beamwidth is 0.″73 (3.8 kpc) at FWHM. Contours are at −6, −4, −2, 2, 4, 6, 8, 10, 12, … 20 times $1\sigma$. Negative contours are dashed and positive ones are solid. Image peak is 1.15 mJy beam$^{-1}$. Linear grayscale spans −0.05 mJy beam$^{-1}$ to 1.0 mJy beam$^{-1}$.

visibility data for SDSS J1536+0441 were concatenated. The AIPS task imagr was applied to the concatenated data to form and deconvolve images of the Stokes $I$ emission. A variety of weighting schemes were applied to the visibility data, converging on the image given in Figure 1 that optimizes the balance between sensitivity and resolution.

Figure 1 shows two radio sources, labeled VLA-A and VLA-B. Elliptical-Gaussian fits to those sources in the image plane yielded the following integrated flux densities, positions, and one-dimensional position errors: for VLA-A, $S = 1.17 \pm 0.04$ mJy, $\alpha(J2000) = 15^h36^m36\overset{s}{.}222$, $\delta(J2000) = +04°41'27\overset{''}{.}06$, and $\sigma_{\rm VLA} = 0\overset{''}{.}1$; for VLA-B, $S = 0.27 \pm 0.02$ mJy, $\alpha(J2000) = 15^h36^m36\overset{s}{.}288$, $\delta(J2000) = +04°41'27\overset{''}{.}09$, and $\sigma_{\rm VLA} = 0\overset{''}{.}1$. For each source, the flux-density error is the quadratic sum of the 3% scale error and the fit residual, while the position error is the quadratic sum of a term due to the phase-calibrator position error (less than 0.″002), the signal-to-noise ratio (S/N) (less than 0.″02), and the phase-referencing strategies (estimated to be 0.″1). The image fits indicated that each source was unresolved and, given the high S/N data, this was taken to imply a diameter of less than 0.″37, corresponding to half of the geometric-mean beamwidth at FWHM quoted in Figure 1. Sources VLA-A and VLA-B have a summed flux density of $1.44 \pm 0.05$ mJy. The image fits also yielded a relative source separation of $0\overset{''}{.}97 \pm 0\overset{''}{.}03$.

## 3. IMPLICATIONS

From the new VLA data, the 8.5 GHz emission from SDSS J1536+0441 consists of two sources, VLA-A and VLA-B, with radio luminosities, $L_R = \nu L_\nu$, at 8.5 GHz of $5.2 \times 10^{40}$ erg s$^{-1}$ and $1.2 \times 10^{40}$ erg s$^{-1}$, respectively. Each source is unresolved, with a diameter of less than 0.″37 (1.9 kpc) and, as Figure 1 shows, lies within the quasar's optical localization region (Boroson & Lauer 2009). VLA-A and VLA-B are separated by 0.″97 (5.1 kpc). These could be two related radio sources, both energized by the candidate 0.1 pc binary system. Alternatively, VLA-A and VLA-B could be independent radio sources originating from a binary quasar system, with a projected separation of 5.1 kpc. The implications of these two interpretations are explored separately in Sections 3.1 and 3.2. As mentioned in Section 1, SDSS J1536+0441 is a radio-quiet quasar as defined by Ivesic et al. (2002), and its properties will be analyzed within that context. Finally, in Section 3.3 the available data for SDSS J1536+0441 will be used to explore a specific framework for radio-quiet quasars recently proposed by Laor & Behar (2008).

### 3.1. VLA-A and VLA-B Powered by a 0.1 pc Binary

The radio emission from VLA-A and VLA-B could represent two related sources, with a projected separation of 0.″97 (5.1 kpc) and with both radio sources ultimately being energized by the candidate 0.1 pc binary. When imaged at subarcsecond resolution, other radio-quiet quasars at similar redshifts and luminosities are known to exhibit double, triple, and linear radio structures on scales of a few kiloparsecs (Kellermann et al. 1994; Kukula et al. 1998), making a radio-double scenario plausible for J1536+0441.

If either VLA-A or VLA-B coincide with the energizing 0.1 pc binary, then the localization of that binary could be improved from the optical diameter of 2″ (Boroson & Lauer 2009) to the radio diameter of less than 0.″37. However, by analogy with the Kukula et al. (1998) radio doubles with accurate optical astrometry, the 0.1 pc binary in J1536+0441 could be located between VLA-A and VLA-B. Therefore, a conservative value for the radio localization area is a region extending about 1″ east–west and less than 0.″8 north–south (the major axis of the Gaussian restoring beam), leading to a radio localization area of less than 0.8 arcsec$^2$. The area of the optical localization region is 3.1 arcsec$^2$ (Boroson & Lauer 2009), so the new 8.5 GHz imaging has improved the localization by a factor of at least 3.9.

As mentioned in Section 1, SDSS J1536+0441 was less than 1 mJy at 1.4 GHz at 5″ resolution (White et al. 1997). In contrast, the summed flux density for VLA-A and VLA-B is $1.44 \pm 0.05$ mJy at 8.5 GHz (Section 2). Comparing these values suggests that the overall spectral index for SDSS J1536+0441 is flat, or even rising, with frequency. This could indicate that VLA-A, the stronger of the two 8.5 GHz sources, is sufficiently compact to be synchrotron self-absorbed and thus resemble components in some other radio-quiet quasars (Barvainis et al. 1996; Kukula et al. 1998; Ulvestad et al. 2005). Such compact emission could also hint that VLA-A marks the location of the candidate 0.1 pc binary, implying an even smaller radio localization for it and also strengthening its similarities to the radio galaxy 0402+379 that hosts a 7 pc binary (Rodriguez et al. 2006). Some radio-quiet quasars do exhibit time variability (e.g., Barvainis et al. 2005), so this inference of a flat or rising overall spectrum for VLA-A is weakened by not having simultaneous measurements at 1.4 and 8.5 GHz. But if the spectral index estimate is inexact due to variability on a decade timescale then, from causality arguments, the inference about small-scale radio emission still stands.

### 3.2. VLA-A and VLA-B Powered by a 5 kpc Binary

The detection of two point sources at radio frequencies also raises the possibility that the emission originates from two quasars 0″.97 apart, or at a projected separation of 5.1 kpc. Boroson & Lauer (2009) noted that the probability for such a random projection in their sample is 0.0032. Therefore, the two quasars are most likely not due to a random projection, but are likely physically related, i.e., a binary quasar system.

A remarkable radio-loud case of a binary system of active galactic nuclei (AGNs) is seen in 3C 75, where two systems of two-sided jets emanate from two close point sources with a projected separation of ∼7.5 kpc (Owen et al. 1985). Compact binary AGNs were also revealed with *Chandra* observations of nearby systems. Particularly clear cases are NGC 6240 with a ∼1 kpc separation (Komossa et al. 2003), and Mrk 463 with a ∼3.8 kpc separation (Bianchi et al. 2008). Thus, SDSS J1536+0441 may be another example of a compact binary AGN system.

A systematic study of the abundance of binary quasars in the SDSS was carried out by Hennawi et al. (2006), who found a projected correlation function of the form $(R_{\rm prop}/0.43\,{\rm Mpc}\,h^{-1})^{-1.48}$ on scales of 10–40 kpc in proper length (proper length is used given the absence of a Hubble flow on these small scales). Extrapolating to 5 kpc (using $h = 0.71$), we get a correlation function of 1175, i.e., an observed surface density 1175 larger than expected for random projection. Using the random-projection estimate of 0.0032 (Boroson & Lauer 2009), the expected observed number is actually 3.76, i.e., 3–4 such binaries are expected. The study of Hennawi et al. is based on quasars with a mean $z \sim 1.5$ due to the smaller number of quasars at lower $z$, and it does not extend down to 5 kpc due to the fiber angular resolution limit. However, the study of Hennawi et al. indicates that the probability to find a 5 kpc binary quasar in the sample used by Boroson & Lauer (2009) is of the order of unity.

Each of the two quasars in the binary may be contributing its broad-line emission system to the total light, producing the double broad-line system discovered by Boroson & Lauer (2009). Thus, rather than having a binary black hole system on a scale of 0.1 pc, we may have a binary quasar system on a 5 kpc scale, most likely residing within two strongly interacting galaxies.

The velocity separation of 3500 km s$^{-1}$ (Boroson & Lauer 2009) is rather large, but not implausible in a cluster of galaxies. About half the clusters studied by Carlberg et al. (1996) show such an extent of velocities. The maximum velocity differences in the quasar binaries studied by Hennawi et al. (2006) is 1870 km s$^{-1}$, but that study imposed a cap of 2000 km s$^{-1}$ on the binary velocity separation. At a projected relative velocity of 3500 km s$^{-1}$, two galaxies cannot form a bound system, so the term binary quasar here does not refer to a physically bound binary system.

### 3.3. *The Radio/X-ray Connection*

For some small X-ray and radio selected samples of radio-quiet AGNs, a link between the radio and X-ray emission has been suggested by the correlation between the radio and the X-ray luminosities (Brinkmann et al. 2000; Salvato et al. 2004; Wang et al. 2006). While intriguing, such a radio/X-ray connection should be verified by using an unbiased survey. The PG quasar sample is a complete optically selected sample (Boroson & Green 1992), making it independent of radio and X-ray biases. Laor & Behar (2008) have used these radio-quiet PG quasars to demonstrate that (a) the radio and the X-ray luminosities are correlated over a large range of AGN luminosity and (b) the correlation follows $L_R/L_X \sim 10^{-5}$, the well-established correlation for coronally active cool stars (Guedel & Benz 1993), where $L_R = \nu L_\nu$ at 5 GHz and $L_X$ is in the 0.2–20 keV band. For cool stars, the $L_R/L_X \sim 10^{-5}$ relation is accepted as a manifestation of coronal heating by energetic electrons following magnetic reconnection that subsequently gives rise to X-ray emission. By analogy with cool stars, Laor & Behar (2008) conjecture that the radio emission in radio-quiet AGNs may also be related to coronal magnetic activity.

This coronal framework can be tested for SDSS J1536+0441 by making use of its recent *Swift* observation by Arzoumananian et al. (2009), carried out in 2009 February 4 and 5, just two weeks before our VLA observations. Arzoumananian et al. (2009) measure a 0.5–10 keV luminosity of $5 \times 10^{44}$ erg s$^{-1}$, with a spectral slope of −1.5. This gives $\nu L_\nu = 2.3 \times 10^{44}$ erg s$^{-1}$ at 1 keV, and thus $L_X$ of $1.4 \times 10^{45}$ erg s$^{-1}$ (see Laor & Behar (2008) for the conversion of $\nu L_\nu$ at 1 keV to $L_X$). The total radio luminosity we find at 8.5 GHz is $6.4 \times 10^{40}$ erg s$^{-1}$, which extrapolates to $L_R = 8.3 \times 10^{40}$ erg s$^{-1}$, assuming a spectral slope of −0.5. We therefore get $L_R/L_X = 5.9 \times 10^{-5}$ which falls within the range of ratios seen by Laor & Behar (2008) for the radio-quiet PG quasars. Thus, SDSS J1536+0441 follows the radio/X-ray relation of optically selected radio-quiet quasars.

## 4. SUMMARY AND FUTURE DIRECTIONS

The radio-quiet quasar SDSS J1536+0441 has two broad-line emission systems that Boroson & Lauer (2009) interpret as a candidate binary black hole system with a separation of 0.1 pc (0.02 mas). Our new VLA imaging at 8.5 GHz reveals two sources, separated by 0″.97 (5.1 kpc), within the quasar's optical localization region. Each radio source has a diameter of less than 0″.37 (1.9 kpc).

Other radio-quiet quasars do exhibit double structures, suggesting that the radio double in SDSS J1536+0441 could be energized by the candidate 0.1 pc binary. Alternatively, the radio emission may arise from a binary system of quasars with a projected separation of 5.1 kpc, and those two quasars may be responsible for the two observed broad-line emission systems. Binary AGNs with kpc-scale separations are known from radio and X-ray observations, and a few such systems are expected in the Boroson & Lauer (2009) sample based on the observed clustering of quasars down to a scale of 10 kpc.

Interestingly, the Balmer emission line profiles shown by Chornock et al. (2009) are noticeably different than those in Boroson & Lauer (2009). For H$\beta$, the peak of the r component is about 40% of the peak of b component, as measured above the "valley" between the r and b components, while in Boroson & Lauer (2009) it is about 60%. Similarly, for H$\alpha$ the r peak is about 75% of the b peak in Chornock et al. (2009), while in Boroson & Lauer (2009) it is about 95%. These could be due to profile variability, but it could also be due to different contributions of two point sources to the total spectrum, due to different slit positions in the Boroson & Lauer (2009) and Chornock et al. (2009) spectra.

If the 5 kpc binary interpretation is correct then ground-based adaptive optics imaging in the visible band, with subarcsecond resolution, should clearly show two point sources, and spectroscopy of those sources should exhibit two different spectra, each one with a single broad emission-line system. Deep optical imaging on arcsecond scales may also reveal the nature of the host galaxy, and whether strongly interacting galaxies are involved.

Deep optical imaging on arcminute scales can establish whether or not SDSS J1536+0441 resides in a cluster. Boroson & Lauer (2009) noted two nearby galaxies with similar photometric redshifts, which may indicate the presence of such a cluster. However, a cluster is likely in both the 0.1 pc and 5 kpc binary interpretations, as a binary black hole also requires an earlier merger. The only difference between the two interpretation is the timescale since the merger occurred, which can be a fraction of the Hubble time for a 0.1 pc binary. On such a timescale, the immediate environment may relax, but the larger scale cluster environment evolves independently of the merger process.

Follow-up radio observations at other frequencies and epochs, as well as with higher angular resolutions, can help distinguish between the 0.1 pc and 5 kpc binary interpretations. Specifically, demonstrating that each radio source has a flat spectrum, is time variable, and remains compact at higher resolution would strongly support the 5 kpc binary interpretation. In contrast, in the 0.1 pc binary case, one (or both) of the radio sources would be expected to be steady in time, have a steep spectrum, and begin to show an outflow-like structure when examined with higher resolution; a flat-spectrum source paired with a steep-spectrum source would suggest a core-jet morphology.

If the 5 kpc binary interpretation is correct, then SDSS J1536+0441 may form the first known compact binary quasar of two luminous broad-line systems, unlike the earlier X-ray-discovered compact systems where one or both of the AGNs are partly obscured, or broad emission lines are missing altogether.

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