PARSEC-SCALE LOCALIZATION OF THE QUASAR SDSS J1536+0441A, A CANDIDATE BINARY BLACK HOLE SYSTEM

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ABSTRACT

The radio-quiet quasar (RQQ) SDSS J1536+0441 shows two broad-line emission systems, recently interpreted as a binary black hole (BBH) system with a subparsec separation; as a double-peaked emitter; or as both types of systems. The NRAO Very Long Baseline Array was used to search for 8.4 GHz emission from SDSS J1536+0441A, focusing on the optical localization region for the broad-line emission, of area 5400 mas2 (0.15 kpc2). One source was detected, with a diameter of less than 1.63 mas (8.5 pc) and a brightness temperature $T_b > 1.2 \times 10^7$ K. New NRAO Very Large Array photometry at 22.5 GHz, and earlier photometry at 8.5 GHz, gives a rising spectral slope of $\alpha = 0.35 \pm 0.08$. The slope implies an optically thick synchrotron source, with a radius of about 0.04 pc, and thus $T_b \sim 5 \times 10^{10}$ K. The implied radio sphere at the rest frequency 31.2 GHz has a radius of 800 gravitational radii, just below the size of the broad-line region in this object. Observations at higher frequencies can probe whether or not the radio sphere is as compact as expected from the coronal framework for the radio emission of RQQs.

Key words: black hole physics – quasars: individual (SDSS J153636.22+044127.0) – radio continuum: general

1. MOTIVATION

Binary black hole (BBH) systems with subparsec scales are predicted in merging scenarios for galaxy evolution and also factor prominently in predictions for the gravitational wave background (e.g., Colpi & Dotti 2009). But can such BBH systems be found? A promising search method—identifying candidate BBH systems through their optical broad-line emission properties—recently yielded three such candidates: SDSS J153636.22+044127.0 (Boroson & Lauer 2009), SDSS J092712.65+294344.0 (Bogdanovic et al. 2009; Dotti et al. 2009), and SDSS J105041.35+345631.3 (Shields et al. 2009).

In this Letter, we focus on SDSS J153636.22+044127.0 (SDSS J1536+0441 hereafter), a quasar at a redshift $z = 0.388$ (Boroson & Lauer 2009). For the assumed flat cosmology, the inferred 0.1 pc separation subtends 0.02 mas (Boroson & Lauer 2009). This quasar has also been interpreted as a lone double-peaked emitter (DPE; Gaskell 2010; Chornock et al. 2010) or as twin DPEs with a subparsec separation (Tang & Grindlay 2009). The emission lines from a DPE are thought to arise from rotational motion in a relativistic accretion disk. SDSS J1536+0441 is radio quiet (RQ), and our imaging of it at 8.5 GHz (Wrobel & Laor 2009) revealed two faint sources, SDSS J1536+0441A and J1536+0441B, separated by 0.97 (5.1 kpc) with each source being unresolved with a diameter of less than 0.37 (1.9 kpc). It is now clear that SDSS J1536+0441A is hosted by the radio-quiet quasar (RQQ), while SDSS J1536+0441B is hosted by a companion radio-loud elliptical galaxy (Decarli et al. 2009; Lauer & Laor 2009).

In the BBH scenarios for SDSS J1536+0441A (Boroson & Lauer 2009; Tang & Grindlay 2009), each of the two broad-line emission systems is itself a quasar. Recent optical spectroscopy finds that the broad-line emission systems have relative positions that localize them to 3σ bands of full width 90 mas (470 pc) along a position angle (P.A.) of 48° (Chornock et al. 2010) and 60 mas (310 pc) along a P.A. of 90° (T. Boroson, 2010, private communication). The resulting parallelogram localizes SDSS J1536+0441A to an area of 5400 mas2 (0.15 kpc2). Improvements in the localization of the emission from SDSS J1536+0441A would further test its candidacy as a BBH system. In this Letter, we use measurement techniques at radio frequencies to investigate the compactness of SDSS J1536+0441A, first by seeking evidence for a synchrotron-self-absorbed spectrum and then by direct imaging with mas resolution to localize the emission on parsec scales. Our new imaging is presented in Section 2 and its implications are explored in Section 3. A summary appears in Section 4.

2. NEW IMAGING

The CfA configuration of the NRAO Very Large Array (VLA; Thompson et al. 1980) was used under proposal code AL739 to observe SDSS J1536+0441A and J1536+0441B for 2 hr near transit on UT 2009 May 27. We followed the strategies described by Wrobel & Laor (2009), except that for our new observations the center frequency was 22.5 GHz, the switching time was 120 s, and the amplitude scale was set to an accuracy of about 5%. The elliptical Gaussian resolution, 0′′96 times 0′′81 at P.A. −89°, was sufficient to obtain photometry for each source. We will report elsewhere on SDSS J1536+0441A, the flux density was $S = 1.65 \pm 0.11$ mJy and comparison with the 8.5 GHz value (Wrobel & Laor 2009) implies a rising spectrum with index $\alpha = 0.35 \pm 0.08$ ($S \propto \nu^\alpha$). The 2009 December 31 release of the NRAO AIPS software was used for calibration and imaging.

The NRAO Very Long Baseline Array (VLBA; Napier et al. 1994) was used for 5 hr under proposal code BL168 on 2009 October 14 UT to search for 8.4 GHz emission from SDSS J1536+0441A. Phase-referenced observations were made in the nodding style, using 32 MHz per circular polarization. A 120 s scan of SDSS J1536+0441A was preceded and followed by a scan of SDSS J1536+0441B.
60 s scan of the reference source J1539+0430, favorably located at a switching angle of 0.

Figure 1. VLBA image of Stokes I emission from SDSS J1536+0441A at a frequency of 8.4 GHz and spanning 20 mas (104 pc). The rms noise is 0.056 mJy beam$^{-1}$ (1σ) and the hatched ellipse shows the Gaussian beam dimensions atFWHM. Geometric-mean beam width is 1.63 mas (8.5 pc) atFWHM. Contours are at $-6, -4, -2, 2, 4, 6, 8, 10, 12,..., 14$ times 1σ. Negative contours are dashed and positive ones are solid. The image peak is 0.79 mJy beam$^{-1}$. Linear gray scale spans from $-0.24$ mJy beam$^{-1}$ to 0.79 mJy beam$^{-1}$.

3. IMPLICATIONS

3.1. Size of the Radio Sphere

From the new VLA photometry, the RQQ SDSS J1536+0441A has a rising spectrum with index $\alpha = 0.35 \pm 0.08$ at rest frequencies of tens of gigahertz. (This is consistent with our prior suggestion that the overall spectrum of A and B was flat or rising between 1.4 GHz (White et al. 1997) and 8.5 GHz (Wrobel & Laor 2009).) SDSS J1536+0441A thus resembles the 45%–50% of RQQ that show flat or rising integrated spectra at similar frequencies (Barvainis et al. 1996; Ulvestad et al. 2005). This spectrum suggests that SDSS J1536+0441A is compact enough to be synchrotron self-absorbed, as expected in the coronal framework for RQQ (Laor & Behar 2008). SDSS J1536+0441A has a bolometric luminosity of $L_{bol} = 1.5 \times 10^{46}$ erg s$^{-1}$ (Boroson & Lauer 2009) and a 22.5 GHz luminosity density of $L_R = 8.6 \times 10^{50}$ erg s$^{-1}$ Hz$^{-1}$. Applying Equation (22) of Laor & Behar (2008), for a homogeneous synchrotron source with equipartition between magnetic and photon energy densities, implies a radio sphere of radius about 0.04 pc at a rest frequency of 31.2 GHz, and thus $T_b \sim 5 \times 10^{10}$ K. This is just below the Readhead (1994) limit of $T_b \sim 10^{11}$ K, expected for equipartition between the electron energy density and the magnetic energy density within the radio sphere. The 0.04 pc radius corresponds to about 800 gravitational radii for a $10^9 M_\odot$ BH, a mass thought to be applicable to SDSS J1536+0441A (Lauer & Boroson 2009; Tang & Grindlay 2009). The radius of the radio sphere implies that the 31.2 GHz emission arises just within the optical broad-line emission region (BLR) discussed in Section 3.2.

The spectral index of this RQQ is clearly too shallow to be a homogeneous source and likely implies a superposition of emission from an inhomogeneous source, as commonly adopted for flat-spectrum radio-loud systems (e.g., Phinney 1985). Given the newly measured flat spectral index for SDSS

\[\text{http://sundog.stsci.edu/top.html}\]
J1536+0441A, its ratio of radio-to-X-ray (Arzoumanian et al. 2009) luminosities drops from $5.9 \times 10^{-5}$ (Wrobel & Laor 2009) to $1.2 \times 10^{-5}$, putting it close to the $10^{-5}$ average ratio characterizing lower-luminosity active galactic nuclei, a ratio expected in the coronal framework for the radio emission from RQQ (Laor & Behar 2008).

Some RQQs are time variables (Barvainis et al. 2005), so our inference of a rising spectrum for SDSS J1536+0441A is weakened by using non-simultaneous photometry. However, for the source to have an optically thin spectral index steeper than $\alpha = -0.5$, the flux density at either 8.5 or 22.5 GHz would need to vary by a factor greater than 2 between the 100 days separating the measurements. Causality arguments would then imply a size upper limit of 100 $(1 + 0.388) \approx 70$ light days, or 0.06 pc. In this case, both the steep spectrum and the high variability brightness temperature, $T_b > 10^{10}$ K, would exclude a thermal free–free origin for the radio emission.

From the new VLBA imaging (Figures 1 and 2), a single source was detected at 8.4 GHz within the 470 pc by 310 pc localization region for the broad-line emission (Chornock et al. 2010; T. Boroson, 2010, private communication). The VLBA detection has a geometric-mean diameter of less than 8.5 pc and a rest-frame brightness temperature, modified for an elliptical Gaussian, of $T_b > 1.2 \times 10^7$ K. The ratio of the VLA and VLBA flux densities near 8 GHz is broadly consistent with unity. This VLBA recovery of all the VLA signal but time variability remains a concern. For now, we tentatively assign the VLA-derived spectral index, $\alpha = 0.35 \pm 0.08$, to the VLBA detection. Then the isotropic power at a rest frequency of 8.4 GHz is $P_\nu = 2.9 \times 10^{23}$ W Hz$^{-1}$. This VLBA detection has a power and $T_b$ limit at the low end of the values reported for other RQQs detected with the VLBA (Blundell et al. 1996; Blundell & Beasley 1998; Ulvestad et al. 2005). The crude estimate made above for a synchrotron-self-absorbed size is also consistent with the VLBA detection.

The implications of the above findings are examined below, first within the context of BBH scenarios for SDSS J1536+0441A (Boroson & Lauer 2009; Tang & Grindlay 2009) and then within the context of it being a lone DPE (Gaskell 2010; Chornock et al. 2010).

3.2 Binary Black Hole Scenarios

Our VLBA findings are consistent with the projected separation of the two quasars being less than 8.5 pc. The VLBA localization area for SDSS J1536+0441A is 82 pc$^2$, improving over the emission-line localization area by a factor of about 1800. The VLBA detection appears to have a rising, synchrotron-self-absorbed spectrum, which bodes well for imaging it at higher resolutions to improve the localization further. Optical spectroscopic monitoring of SDSS J1536+0441A implies an orbital period longer than about 200 years (Lauer & Boroson 2009). Unfortunately, such a long period means that VLBA monitoring could not usefully constrain the astrometric wobble of SDSS J1536+0441A.

The twin DPE model of Tang & Grindlay (2009) reproduces the observed H$\beta$ line profile by emission from a disk extending from 7000 down to 800 gravitational radii. Thus, the size of the radio sphere at 31.2 GHz is just below the inner boundary of the BLR. Since the size of an optically thick radio sphere scales as $f_{v}^{0.4}/v$ (e.g., Equation (22) of Laor & Behar 2008), observations at millimeter wavelengths will allow us to probe the radio sphere on smaller scales, potentially down to the optically emitting region at a few tens of gravitational radii. If the source remains optically thick, then submillimeter observations can probe down to the X-ray-emitting region at a few gravitational radii.

The VLBA detection of the RQQ SDSS J1536+0441A represents the first parsec-scale localization of a candidate BBH system identified through its broad-line properties. This VLBA detection also demonstrates that parsec-scale localizations of candidate BBH systems need not be restricted to radio-loud objects like the radio galaxy 0402+379 with its 7 pc separation (Rodrìguez et al. 2006).

Our VLBA findings cannot exclude additional sources with $T_b < 4.5 \times 10^6$ K in the same field of view. Such a value is atypically low compared to other RQQs detected with the VLBA (Blundell et al. 1996; Blundell & Beasley 1998; Ulvestad et al. 2005). But those studies targeted RQQs stronger than several millijanskys and were thus biased toward detecting higher brightness temperatures. Several RQQs were not detected in the survey of Blundell & Beasley (1998), with brightness temperature limits similar to the present study. This suggests that the effects of source resolution could also contribute to non-detections of RQQs.

3.3. Lone Double-peaked Emitter Scenario

The lone DPE scenario for the RQQ SDSS J1536+0441A (Gaskell 2010; Chornock et al. 2010) requires the presence of only one quasar. The line profiles for SDSS J1536+0441A do not make it an unusual DPE however (Chornock et al. 2010; Lauer & Boroson 2009). As a class, DPEs are rare, constituting only 4% of the spectroscopically selected sample at $z < 0.332$ of Strateva et al. (2003). Yet 76% of those DPEs are RQ like SDSS J1536+0441A. Using 1.4 GHz detections from White et al. (1997), Strateva et al. (2003) tabulate 1.4 GHz luminosities for 18 RQ DPEs and report typical values of several times $10^{39}$ erg s$^{-1}$. SDSS J1536+0441AB is not detected by White et al. (1997) and the 1.4 GHz luminosity is less than $7.2 \times 10^{39}$ erg s$^{-1}$, a limit consistent with detected RQ DPEs in Strateva et al. (2003). Moreover, except for SDSS J1536+0441A, no RQQs detected with the VLBA (Blundell et al. 1996; Blundell & Beasley 1998; Ulvestad et al. 2005) are known to exhibit DPEs, so it is impossible to say whether or not the VLBA detection of SDSS J1536+0441A is in any way unusual. In this regard, VLBA imaging of the DPE sample of Strateva et al. (2003) would be a useful undertaking. As the VLBA detection of SDSS J1536+0441A demonstrates, such imaging is feasible for both RQ and radio-loud DPEs.

4. SUMMARY

Our VLBA search for 8.4 GHz emission from the RQQ SDSS J1536+0441A found only one source within the localization region, of area 0.15 kpc$^2$, for the broad-line emission. The VLBA detection has a diameter of less than 8.5 pc and a $T_b > 1.2 \times 10^7$ K. This detection of SDSS J1536+0441A represents the first parsec-scale localization of a candidate BBH system identified through its broad-line properties. The VLBA photometry at a rest frequency of 31.2 GHz yields a rising spectrum, consistent with synchrotron self-absorption, which implies a radius of about 0.04 pc for the radio sphere, and $T_b \sim 5 \times 10^{10}$ K. The observed compact flat-spectrum radio sphere is consistent with the trait predicted in the coronal framework for RQQs. The radio sphere at 31.2 GHz happens to be just inside the estimated inner boundary for the BLR, of 800 gravitational radii, in this object.
It would be useful to investigate the spectrum at higher frequencies, corresponding to the millimeter and the submillimeter range, to determine where the spectral slope steepens as the source becomes optically thin. This will establish the size of the most compact synchrotron-emitting region and potentially allow a direct exploration of relativistic electrons in the accretion disk corona. We plan such investigations using the Expanded VLA (Perley et al. 2009) and the Atacama Large Millimeter/submillimeter Array (Wootten & Thompson 2009).

Concerning the BBH scenarios for SDSS J1536+0441A, the VLBA detection is consistent with a quasar separation of less than 8.5 pc. No additional sources with $T_b = 4.5 \times 10^6$ K or more are found within the localization region for the broad-line emission.

Concerning the lone DPE scenario for SDSS J1536+0441A, its emission-line profiles do make it an unusual DPE. But as no other RQ DPEs have been imaged on parsec scales, it is impossible to say whether or not the VLBA detection of SDSS J1536+0441A is in any way unusual.

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Facilities: VLA, VLBA

REFERENCES

Arzoumanian, Z., Lowenstein, M., Mushotzky, R. F., & Gendreau, K. C. 2009, ATel, 1931

Barvainis, R., Lehar, J., Birkinshaw, M., Falcke, H., & Blundell, K. M. 2005, ApJ, 618, 108
Barvainis, R., Lonsdale, C., & Antonucci, R. 1996, AJ, 111, 1431
Blundell, K. M., & Beasley, A. J. 1998, MNRAS, 299, 165
Blundell, K. M., Beasley, A. J., Lucy, M., & Garrington, S. T. 1996, ApJ, 468, L91
Bogdanovic, T., Eracleous, M., & Sigurdsson, S. 2009, ApJ, 697, 288
Boroson, T. A., & Lauer, T. R. 2009, Nature, 458, 53
Chornock, R., et al. 2010, ApJ, 709, L39
Colpi, M., & Dotti, M. 2009, arXiv:0906.4339v1
Decarli, R., et al. 2009, ApJ, 703, L76
Dotti, M., Montuori, C., Decarli, R., Volonteri, M., Colpi, M., & Haardt, F. 2009, MNRAS, 398, L73
Gaskell, M. 2010, Nature, 463, E1
Laor, A., & Behar, E. 2008, MNRAS, 390, 847
Lauer, T. R., & Boroson, T. A. 2009, ApJ, 703, 930
Napier, P. I., Bagri, D. S., Clark, B. G., Rogers, A. A. E., Romney, J. D., Thompson, A. R., & Walker, R. C. 1994, Proc. IEEE, 82, 658
Perley, R., et al. 2009, Proc. IEEE, 97, 1448
Phinney, E. S. 1985, Astrophysics of Active Galaxies and Quasi-Stellar Objects, ed. J. S. Miller (Mill Valley, CA: Univ. Science Books), 453
Readhead, A. C. S. 1994, ApJ, 426, 51
Rodriguez, C., Taylor, G. B., Zavala, R. T., Peck, A. B., Pollack, L. K., & Romani, R. W. 2006, ApJ, 646, 49
Shields, G. A., et al. 2009, ApJ, 707, 936
Strateva, I. V., et al. 2003, AJ, 126, 1720
Tang, S., & Grindlay, J. 2009, ApJ, 704, 1189
Thompson, A. R., Clark, B. G., Wade, C. M., & Napier, P. J. 1980, ApJS, 44, 151
Ulvestad, J. S., Antonucci, R. R., & Barvainis, R. 2005, ApJ, 621, 123
White, R. L., Becker, R. H., Helfand, D. J., & Gregg, M. D. 1997, ApJ, 475, 479
Wootten, A., & Thompson, A. R. 2009, Proc. IEEE, 97, 1463
Wrobel, J. M., & Ho, L. C. 2006, ApJ, 646, L95
Wrobel, J. M., & Laor, A. 2009, ApJ, 699, L22
Wrobel, J. M., Taylor, G. B., Rector, T. A., Myers, S. T., & Fassnacht, C. D. 2005, AJ, 130, 923