A VLBA SEARCH FOR BINARY BLACK HOLES IN ACTIVE GALACTIC NUCLEI WITH DOUBLE-PEAKED OPTICAL EMISSION LINE SPECTRA

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ABSTRACT

We have examined a subset of 11 active galactic nuclei (AGNs) drawn from a sample of 87 objects that possess double-peaked optical emission line spectra, as put forward by Wang et al. and are detectable in the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) survey at radio wavelengths. The double-peaked nature of the optical emission line spectra has been suggested as evidence for the existence of binary black holes in these AGNs, although this interpretation is controversial. We make a simple suggestion that direct evidence of binary black holes in these objects could be searched for in the form of dual sources of compact radio emission associated with the AGNs. To explore this idea, we have used the Very Long Baseline Array to observe these 11 objects from the Wang et al. sample. Of the 11 objects, we detect compact radio emission from two, SDSS J151709 + 335324 and SDSS J160024 + 264035. Both objects show single components of compact radio emission. The morphology of SDSS J151709 + 335324 is consistent with a recent comprehensive multi-wavelength study of this object by Rosario et al. Assuming that the entire sample consists of binary black holes, we would expect of order one double radio core to be detected, based on radio wavelength detection rates from FIRST and very long baseline interferometry surveys. We have not detected any double cores, thus this work does not substantially support the idea that AGNs with double-peaked optical emission lines contain binary black holes. However, the study of larger samples should be undertaken to provide a more secure statistical result, given the estimated detection rates.

Key words: galaxies: active – galaxies: individual (SDSS J160024+264035, SDSS J151709+335324) – radio continuum: galaxies

1. INTRODUCTION

A study of a sample of 87 active galactic nuclei (AGNs) that display double-peaked optical emission line spectra, by Wang et al. (2009a, 2009b), shows evidence for correlations between the ratios of the shifts of the redshifted and blueshifted emission lines and the respective line strengths. Wang et al. (2009a) interpret these data as due to the existence of binary supermassive black holes in these AGNs, the result of hierarchical minor and/or major merging, as predicted by ΛCDM cosmology. Wang et al. (2009a) suggest that the typical separation of the dual black holes is approximately 1 kpc, representing an intermediate stage of merging systems.

The optical emission line data presented are striking in many cases and the suggestion that the AGNs may harbor binary black holes warrants further investigation using independent approaches. Wang et al. (2009a) cite some independent evidence that the sources in their sample contain binary black holes, from the occurrence of one X-shaped radio source in their sample of 87 AGNs (plus another X-shaped radio source with a similar optical host not in their sample). X-shaped radio sources have been suggested to be the result of binary black hole and accretion disk systems launching two sets of relativistic jets from the nuclear region of AGNs (Merritt & Ekers 2002), along different trajectories.

A far better direct tracer of binary black holes separated by 1 kpc in these AGNs could be dual compact radio cores, as revealed by high-resolution radio imaging. Compact cores would not only directly indicate the existence of black holes, but also easily allow the measurement of the separation of the black holes, further testing the suggestions of Wang et al. (2009a). Recently, other searches for AGNs with double-peaked emission lines have been made, based on methods very similar to those used by Wang et al. (2009a), Smith et al. (2010), and Liu et al. (2010), all based on the Sloan Digital Sky Survey (SDSS) Data Release 7 (DR7). However, very few studies to date have undertaken spatially resolved radio observations of these samples. The notable exception is the comprehensive study of SDSS J151709 + 335324 (an object that features in this paper) by Rosario et al. (2010). Liu et al. (2010) note the need for spatially resolved imaging at radio, X-ray, and optical wavelengths, for samples of AGNs with double-peaked optical emission line spectra.

Other previous work by Boronson & Lauer (2009) claims that SDSS 153636.22+044127.0 is a binary black hole system with separation of 0.1 pc. Gaskell (2010) advances an alternative model of double-peaked optical line emission from a disk. Also, Liu et al. (2010) and Rosario et al. (2010) discuss an explanation in terms of AGN outflows or jets. Follow-up imaging and spectroscopy of the Liu et al. (2010) sample by Shen et al. (2010) favor narrow-line region kinematics associated with single AGN systems as the explanation for the emission line profiles. Thus, multiple mechanisms for double-peaked optical emission lines appear to be plausible. A Very Long Baseline Array (VLBA) investigation of this class of AGNs using a direct search for binary black holes traced by dual compact radio cores is therefore a valuable test that can be undertaken in a straightforward manner. Determining the incidence of supermassive binary black hole systems is of interest due to their role in producing gravitational radiation that can potentially be detected by existing pulsar timing arrays and future gravity wave detectors.

In Section 2, we describe the selection criteria and the resulting sample of radio sources, the VLBA observations that were undertaken, and the results of the observations. In Section 3, we discuss these results within the context of a
binary black hole interpretation for these objects and discuss the individual objects.

2. SAMPLE SELECTION, OBSERVATIONS, AND RESULTS

We defined a set of radio sources selected from the Wang et al. (2009a) sample of 87 double-peaked optical emission line AGNs from the SDSS DR7 database. When we cross-correlated the positions of the Wang et al. (2009a) sample sources with the objects in the Faint Images of the Radio Sky at Twenty-centimeters (FIRST) database (flux density threshold for catalog of 1 mJy; Becker et al. 1995), we found that 11 of the sample objects were detected in FIRST, selecting those objects listed with radio emission within 5′′ of the SDSS position. The 5′′ positional matching radius is generous, as it is of order 10 times the FIRST positional accuracy. We found that the 11 sources with positional matches at 5′′ tolerance would have been matched with a much tighter tolerance of 1′′, as all matches were 0.8 or better. The 11 sources are listed in Table 1. It is worth noting that the X-shaped radio source in the Wang et al. (2009a) sample does not appear in Table 1 because of a 26′′ offset between the listed FIRST position and the SDSS position. Thus, this source does not meet our positional matching criterion. This individual object likely warrants very long baseline interferometry (VLBI) follow-up in its own right.

Observations of these 11 sources were undertaken with the VLBA over a 24 hr period on 2010 June 6 at a frequency of 1.4 GHz (observation code BT108). Nine of the 10 VLBA antennas were available for this experiment (the Pie Town antenna was not available). The observations consisted of 8 minute scans of the target sources, interspersed with 2 minute scans of nearby phase reference sources. Switching angles between target and reference pairs ranged between 0.6 and 2.4′. Each target and reference were observed while above the horizon at all VLBA stations. Therefore, over the 24 hr period, between 1 and 2 hr of integration time was obtained for each of the 11 targets. A typical (u, v) coverage is shown in Figure 1.

The observations were made with dual circularly polarized bands consisting of 4 × 16 MHz intermediate frequencies (IFs). Correlation took place using the DiFX software correlator in Socorro (Deller et al. 2007), producing visibilities in 32 × 0.5 MHz channels per IF at a correlator integration period of 2 s. At this time and frequency resolution, the accessible field of view for imaging extends far beyond the extent of the host galaxies.

The correlated data were analyzed initially in AIPS, using the standard calibration routines described in the AIPS Cookbook. The visibility amplitudes were calibrated using the $T_{\text{sys}}$ and gain values recorded at the VLBA stations. The phase reference sources were fringe-fitted and the solutions applied to the target source data. The resulting calibrated visibilities were written to disk as FITS files, for further imaging in DIFMAP (Shepherd et al. 1995).

The visibility data were inspected to note any strong detections. Only one detection was noted, for SDSS J151709+335324. From this strong detection, we could assess the impact of the time and angle switching between targets and phase reference calibrators, via consideration of self-calibration corrections for this object. For SDSS J151709+335324, with a switching angle of 1′′.2 to its reference source, we found that the self-calibrated phases produced a dirty image with peak brightness 10% higher than produced before self-calibration. Thus, while some loss of coherence was inflicted because of time and angle switching, it is minimal in terms of the overall sensitivity of the observations.

### Table 1

List of SDSS AGNs Observed with the VLBA

| Source           | R.A. (J2000) | Decl. (J2000) | $z$ | $S_{\text{20cm}}$ (mJy) | $S_{\text{VLBI}}$ (mJy) | (″ kpc$^{-1}$) |
|------------------|-------------|-------------|----|------------------------|-------------------------|----------------|
| SDSS J000249+004504 | 00 02 49.081 | +00 45 04.92 | 0.087 | 2.33 | <1.5 | 1.7 |
| SDSS J095833−005118 | 09 58 33.247 | −00 51 18.74 | 0.086 | 1.63 | <1.5 | 1.7 |
| SDSS J105653+331945 | 10 56 53.384 | +33 19 45.12 | 0.051 | 2.53 | <1.5 | 1.0 |
| SDSS J110957+020138 | 11 09 57.130 | +02 01 38.50 | 0.063 | 6.37 | <1.5 | 1.2 |
| SDSS J115249+190300 | 11 52 49.309 | +19 03 00.50 | 0.097 | 2.37 | <1.5 | 1.9 |
| SDSS J150452−521414 | 15 04 52.343 | −52 14 14.96 | 0.113 | 1.67 | <1.5 | 2.2 |
| SDSS J151659+051751 | 15 16 59.253 | +05 17 51.43 | 0.051 | 5.84 | <1.5 | 1.0 |
| SDSS J151709+335324 | 15 17 09.289 | +33 53 23.92 | 0.135 | 120.30 | 17 ± 2 | 2.6 |
| SDSS J152606+414014 | 15 26 06.161 | +41 40 14.39 | 0.008 | 70.62 | <1.5 | 0.1 |
| SDSS J155619+094855 | 15 56 19.285 | +09 48 55.26 | 0.068 | 1.50 | <1.5 | 1.3 |
| SDSS J160024+264035 | 16 00 24.368 | +26 40 35.25 | 0.090 | 19.47 | 1.8 ± 0.2 | 1.8 |

**Notes.** The source positions listed are the radio position from the FIRST catalog, accurate to approximately 0.5″. The flux densities listed from FIRST are integrated and have errors of approximately 10%.

![Figure 1. Typical (u, v) coverage for the VLBA observations.](https://example.com/figure1.png)
In DIFMAP, images were produced over a 2" field, centered on the FIRST position, using 4096 pixel images with pixel size of approximately 1 mas. This field is approximately eight times larger than the accuracy of the FIRST positions, easily adequate to detect compact emission if centered on the brightest components of the FIRST sources. The rms image noises were typically 0.5 mJy beam\(^{-1}\), giving a 3\(\sigma\) detection threshold of 1.5 mJy beam\(^{-1}\) (enough sensitivity to detect the weakest source in the sample if the full flux density was from compact components). It should be noted that in a relatively shallow VLBA survey such as reported here, the possibility exists to misidentify core jet, GHz-peaked spectrum or compact steep spectrum radio sources as double core AGNs. Any double core AGN detected here would need to be verified using further deep observations that determine the detailed structure of the source and the spectral indices of the double compact components.

Two of the sources were detected in imaging, SDSS J151709+335324 and SDSS J160024+264035. SDSS J160024+264035 consists of a single weak point source approximately 0.1" away from the listed FIRST position, with a flux density of 1.8 mJy. An image of SDSS J160024+264035 appears in Figure 2(a). SDSS J151709+335324 also has a single component morphology, of 17 mJy, shown in Figure 2(b). Errors on the measured flux densities are approximately 10\%, dominated by the uncertainty in the flux density scale.

Larger images were made for all objects, over a field of 4", to search for any strong extended emission. None was detected.

3. DISCUSSION

3.1. Double Radio Cores and Binary Black Holes in AGNs with Double-peaked Optical Emission Line Spectra

These observations have been made on the suggestion that binary black holes in AGNs with double-peaked optical emission line spectra may be revealed as double radio cores in high-resolution VLBI images.

From 87 double-peaked AGNs, 11 (13\%) were found to have radio emission at 1.4 GHz from the FIRST survey, above the detection threshold of 1 mJy, with optical/radio position matches better than 5\(\circ\). Previously, Best et al. (2005) found that the existence of optical emission lines is not a predictor of radio emission, rather the radio-detected fraction of galaxies is a strong function of stellar mass, with fractions ranging from almost 0\% to 30\%, with higher fractions corresponding to higher stellar masses, considering objects with radio luminosities at 1.4 GHz of >10\(^{25}\) W Hz\(^{-1}\). The corresponding radio luminosities for our sample typically lie between 10\(^{22}\) and 10\(^{24}\) W Hz\(^{-1}\), not identically matched to the Best et al. (2005) criterion, meaning that the prediction of detection fractions for our work based on the Best et al. (2005) work is somewhat uncertain. In other previous work, Lee et al. (2010) show that among Seyfert and LINER galaxies in SDSS, the radio-detected fraction ranges between approximately 2\% and 10\%, depending on the particular optical subclass and whether the FIRST or NVSS radio survey was used. Thus, the 13\% radio-detected fraction of the 87 double-peaked AGNs does not appear unusual in terms of the radio-detected fraction of the broader classes of emission line AGNs, with radio-detected fraction likely more dependent on stellar mass than emission line properties.

Of the 11 sources detected in FIRST, compact radio emission was detected in two, approximately 18\%. Previous work by Garrett et al. (2005) on a deep VLBI survey of the NOAO Bootes field shows that the detection rate of sub-mJy radio sources at 1.4 GHz is 8\% and for mJy radio sources is 29\%\(\pm\)11\%. In other VLBI surveys of FIRST sources, Porcas et al. (2004) found VLBI detection rates of 33\% and Wrobel et al. (2004) finds 60\%. The detection rate from our VLBI observations appears broadly consistent with this ensemble of previous work.

Thus, the sample of 87 AGNs does not appear to be special in terms of its radio properties. The incidence of radio emission and the incidence of compact radio emission appear similar to other samples previously studied.

Neither of the two objects detected have morphologies that unambiguously allow identification of binary black holes. Both are simple weak point sources, easily explained as emission from a single radio core, presumably relatively weak radio emission.
coincident with a black hole. Any companion black holes would have to have radio emission below the detection limit in our images, or be substantially further away than 4′.

Thus, we conclude that none of the 87 double-peaked AGNs from Wang et al. (2009a) contain an incidence of double radio cores at our detection sensitivity that would support the existence of binary black holes in these AGNs.

To estimate the expected detection rate of binary black holes in our sample, we proceed as follows. First, we assume that all 87 objects in the emission line sample host binary black holes. This is the most aggressive assumption possible and allows no other physical mechanism that produces similar optical emission line profiles. Given the radio detection rates from Best et al. (2005) and Lee et al. (2010) listed above, a detection probability for radio emission between 0% and 30% can be adopted. Further, the detection rates for compact radio structure from VLBI observations, given the existence of radio emission, are variously estimated to be between 10% and 60%, as described above. Given these probabilities and assuming that the probability of detectable compact radio emission is independent and identical for each of the two black holes in a binary system, the probability that both binary black holes will be detected as compact radio emission, for any given object from the parent sample is

\[ P(BBH) = P(RE) \cdot P(CRE|RE)^2, \]

where \( P(BBH) \) is the probability of detecting both binary black holes as compact radio sources, \( P(RE) \) is the probability that a black hole has detectable radio emission in FIRST, and \( P(CRE|RE) \) is the probability that a black hole has compact radio emission, given that it is detectable in FIRST. The second probability is squared due to being independent for each black hole. Thus, taking all the conservative assumptions and maximal estimates of these two probabilities (\( P(RE) = 0.3 \) and \( P(CRE|RE) = 0.6 \)) gives \( P(BBH) \sim 0.1 \). Taking mid-range estimates (\( P(RE) = 0.1 \) and \( P(CRE|RE) = 0.3 \)) gives \( P(BBH) \sim 0.01 \). Taking low estimates for \( P(RE) \) and \( P(CRE|RE) \) gives \( P(BBH) \ll 0.01 \). It is worth noting that even taking the maximal estimates of the probabilities will give a lower detection rate if the aggressive assumption that all double-peaked optical emission line galaxies contain binary black holes is relaxed.

Adopting the mid-range estimates for the detection probabilities appears a reasonable approach and gives \( P(BBH) \sim 0.01 \). Thus, under this assumption, at most one binary black hole could be expected from our current observations, using the calculations above and the physical interpretation of Wang et al. (2009a).

Clearly, the study of larger samples is required and future work will include similar observations of the samples of Liu et al. (2010) and Smith et al. (2010).

3.2. The Nature of the Radio Emission in SDSS J151709+335324

While no double radio cores or evidence for binary black holes were found in this sample, SDSS J151709+335324 has been the subject of a recent multi-wavelength study by Rosario et al. (2010). From FIRST, SDSS J151709+335324 has a flux density of 120 mJy at 1.4 GHz (Becker et al. 1995), with the FIRST image of the object showing that it consists of a single unresolved component at the angular resolution of the survey (~5′). The VLBA observations reported here reveal a single compact component, totaling approximately 17 mJy, ~13% of that seen in FIRST. SDSS J151709+335324 has a reported redshift of 0.135, obtained from the SDSS data. This redshift corresponds to a luminosity distance of 615 Mpc (based on \( H_0 = 73 \) km s\(^{-1}\) Mpc\(^{-1}\), \( \Omega_{\text{matter}} = 0.27 \), and \( \Omega_{\text{vacuum}} = 0.73 \)).

Recently, Rosario et al. (2010) presented a comprehensive multi-wavelength study of SDSS J151709+335324, including multi-frequency Very Large Array (VLA) images. Rosario et al. (2010) put forward two plausible explanations for their multi-wavelength data: (1) a multiple-AGN produced due to a massive dry merger or (2) a very powerful radio jet driven outflow that produces the different velocity components seen in optical spectra. Rosario et al. favor the second explanation, on the basis that their multi-frequency VLA images show prominent jet-like features and a compact core that remains bright at 22 GHz.

Rosario et al. (2010) calculate an astrometric position for the radio source of R.A. = 15:17:09.24228; decl. = +33:53:24.5663 (J2000), with an error of 25 mas. The single compact component detected with the VLBA is located at R.A. = 15:17:09; decl. = +33:53:24.5 (J2000) in our image, with an estimated 3σ error of approximately 120 mas. This error is entirely dominated by the uncertainty in the position of the phase reference calibrator used for this observation, which is approximately 40 mas according to the VLBA calibrator list, drawing from the best known position (Browne et al. 1998). Thus, the astrometric position of Rosario et al. (2010) coincides with the VLBA position of the brightest compact component within the positional errors.

Under the favored interpretation of Rosario et al. (2010), the compact radio component detected with the VLBA would represent the core and the origin of the jet that provides the energy to power the optical emission lines and the kinematic variations observed in the optical spectra.

We note alternative explanations for SDSS J151709+335324. An examination of other FIRST sources within 1.5 arcmin of SDSS J151709+335324 reveals nearby radio sources which, when taken together with SDSS J151709+335324, could be described as a classic FR-II radio galaxy morphology (Figure 3). If this is the case, SDSS J151709+335324 would be associated with one of the two hot spots of this radio galaxy (Figure 3) and the VLA images of Rosario et al. (2010) could be interpreted as describing a double hot spot structure. Such an interpretation admits a variation on the conclusions of Rosario et al. (2010). Instead of the emission line regions driven by a jet originating in SDSS J151709+335324, the emission line region could be powered by a jet that impinges on SDSS J151709+335324 from a distant origin. Examples of this are known, for example in PKS 0344–345 (Lenc 2009).

However, we note that under this interpretation, no host galaxy for the FR-II object can be identified in SDSS. We also note that while the compact VLBA component bears a resemblance to compact components seen in other FR-II hot spots, such as in Pictor A (Tingay et al. 2008), the luminosity of the compact components in SDSS J151709+335324 would have to be 10,000 times greater than those seen in Pictor A. For these two reasons, we find that this interpretation would appear to be unlikely. A further alternative scenario is that the VLA and VLBA emission arises from a dual AGN system, with one AGN revealing compact radio emission above our detection threshold (VLBA detection), but the second AGN having no such bright

1 http://www.vlba.nrao.edu/astro/calib/
compact emission (VLA centroid of emission). This alternative could be tested with deeper VLBA observations that seek to detect compact emission coincident with the VLA emission centroid, in addition to the compact emission detected in the observations presented here.

Further dedicated follow-up observations of SDSS J151709+335324 with the VLBA will be useful to provide better sensitivity and image quality for this object, and are being planned to possibly detect the jet emission near the core. Based on our data, interpreted in conjunction with the comprehensive data of Rosario et al. (2010), we conclude that the simplest explanation for this object is that the compact radio emission is related to the core of the galaxy.

4. CONCLUSION

We have imaged, using the VLBA, 11 of 87 AGNs with double-peaked optical emission line spectra and radio emission, suggested by Wang et al. (2009a) to harbor binary black holes. We used the images to search for double radio cores in these objects, as a direct tracer of binary black holes. The incidence of radio emission and compact radio emission in this sample appears typical and in agreement with previous studies. No evidence of double radio cores was found from our observations. Thus, no evidence for binary black holes was found. However, it is likely that, given the small probability of detection (under various assumptions), larger samples of double-peaked emission line galaxies will need to be studied with VLBI in order to make a useful statistical test.

Facility: VLBA

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