

Search for Binary Black Hole Candidates from the VLBI Images of AGNs

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Abstract. We have searched the core-jet pairs in the VLBI scales (<1 kpc), from several VLBI catalogues, and found out 5 possible Binary Black Hole (BBH) candidates. We present here the search results and analyse the candidates preliminarily. We plan to study with multi-band VLBI observation. We also plan to carry out optical line investigation in future.

Key words. Binary black hole—radio continuum: jets pair.

1. Introduction

In the co-evolution scenario of galaxies and their supermassive black holes, galaxy–galaxy mergers would end up forming Binary Black Holes (BBHs). Close binary black holes are important in astrophysics and they would be the strongest gravitational wave sources in the Universe. As the binary orbiting black holes give off gravitational waves, their orbit decays and the orbital period decreases. This stage is called binary black hole inspiral. Galaxy–galaxy merging systems are mostly found in optical and X-ray images. In radio, it is less efficient in identifying active nuclei pairs of merging systems, because most of them are radio-quiet. However, an advantage in radio is the Very Long Baseline Interferometry (VLBI) which can resolve the close binary system at pc scale, if the nuclei are radio loud. In >1 kpc scales, the frequency of double nuclei of merging galaxies was estimated to be $\sim 1\%$ in the optical samples (Wang *et al.* 2009; Liu *et al.* 2013). Assuming that 10% of the AGNs are radio-loud in optical sample, the detection rate of twin-jet pairs in radio reduces to $\sim 0.1\%$ in the optical selected sample. A similar fraction ($\sim 0.1\%$) is expected in the radio selected sample for both the double nuclei being radio loud.

The VLBI can image the radio jets of AGN at pc scales, providing an unprecedented high resolution probe to close binary black holes. Even if the detection rate is as low as $\sim 0.1\%$, with up-to-date large VLBI databases one would still be able to find out close binary radio jet pairs launched from binary black holes. Such a VLBI search for close binary radio cores done from the geodetic VLBI database, found only one binary core system from the 3114 sources (Burke-Spolaor 2011). The detection rate seems less than that estimated above by a factor of 3. We have

searched the core-jet pairs from astrophysical databases, and present the preliminary results in this paper.

2. Radio jets pairs as BBH signatures

It is more efficient to find binary AGNs in <10 kpc than in 10–100 kpc scales, suggesting that simultaneous fuelling of both black holes is more common as the binary orbit decays through shorter spacings (Smith *et al.* 2010). If both nuclei are radio loud, in <1 kpc scales, the VLBI is the most efficient probe to find the compact inspiral cores. However, in a relatively small sample of AGNs with double-peaked optical emission lines, Tingay & Wayth (2011) have not detected compact double cores with the VLBA. Burke-Spolaor (2011) searched for flat spectrum double cores in large geodetic VLBI database, and found only one, i.e. B0402+379. The apparent deficit of double cores at the small spacings is not clear, but it could be due to one of the double cores being obscured/absorbed or very weak. Independent searches with different strategies from different samples are needed to confirm whether the deficit is real.

Our strategy of searching for BBH candidates is looking for not only flat spectrum double cores, but also twin-jet pairs. Double twin-jets are found more frequently in >1 kpc scales than in the VLBI scale, e.g. the 19 X-shaped radio sources and 100 X-shaped candidates (Cheung 2007), and the double–double radio galaxies (e.g. Liu *et al.* 2003), whereas their radio cores are often absent or weak probably due to large viewing angles. The VLBI databases in our searches are the MOJAVE database (Lister *et al.* 2009), the Pearson-Readhead survey and the first Caltech-Jodrell Bank survey (PR + CJ1, e.g. Xu *et al.* 1995), the second Caltech-Jodrell Bank survey (CJ2, e.g. Henstock *et al.* 1995), the CJF sample (Britzen *et al.* 2007), the VLBApls sample (Fomalont *et al.* 2000), and the VIPS sample (Helmboldt *et al.* 2007). The resulted candidates from ~ 2000 sources are summarized in Table 1. We define a spectral index with $S \propto \nu^\alpha$.

3. Comments on individual BBH candidates

We found 6 possible BBH candidates from our intensive searches, and they have shown features like double core-jets or a compact core plus a core-jet. We comment and analyse preliminarily these sources as follows:

Table 1. The 6 BBH candidates. The numbers in the last column are catalogues: 1 – MOJAVE, 2 – CJ1, 3 – CJF, 4 – VLBApls, 5 – VIPS.

Name	Other	Id	z	Cat
J0405 + 3803	B2 0402 + 379	G	0.055046	(3, 4)
J1001 + 5540	4C55.19	G	0.003723	(5)
J1158 + 2450	PKS 1155 + 251	Q	0.201600	(1, 4, 5)
J1215 + 3448	B2 1213 + 350	Q	0.857000	(2, 3, 4, 5)
J1632 + 3647	B2 1630 + 35			(5)
J2253 + 1608	3C454.3	Q	0.859000	(1, 4)

B2 0402 + 379: This is a previously suggested supermassive BBH system which shows a compact radio core and a nearby compact symmetric object (Rodríguez *et al.* 2006). Two components of HI absorption lines were found, which support the BBH model of the source (Morganti *et al.* 2009).

4C55.19 (J100157.93 + 554047.8): The host is a nearly edge-on spiral galaxy NGC 3079 with a LINER nucleus, which is classified as a Seyfert 2 galaxy and a low luminosity AGN. The VIPS image at 5 GHz exhibits three compact components. The southeast one (A) and the northwest one (B) are consistent with the detections of global VLBI by Sawada-Satoh *et al.* (2000). The third component in the northeast of the VIPS image has a position angle close to the minor axis of the galaxy, which may either relate to a fresh outflow, or might be a young supernova remnant. This component was not detected by Sawada-Satoh *et al.* (2000). Mostly likely the component B is the core and A is a jet as suggested by them, but the component A is more compact and brighter than B in the 5 GHz VIPS image, indicating a strong variability of the components compared with the 5 GHz image of Trotter *et al.* (1998). The jet is misaligned with the short axis of the galaxy, the radio ‘core’ is at about 0.5 pc west to the galactic nucleus according to Trotter *et al.* (1998), implying that this radio core is probably a secondary core in a BBH system. Hagiwara *et al.* (2004) found two OH absorption components in the central region, but its relation to a possible BBH system needs further investigation.

PKS 1155 + 251 (SDSS J11584 + 2450): The quasar is point-like in both the NVSS and FIRST images, and shows a slight extension along southeast–northwest with the VLA D-array (Tremblay *et al.* 2008). They reclassified this source as a CSO and discussed a possible shrinking of the source from new VLBA observations at 4.84, 8.34 and 15.13 GHz. However, the complex structure of the source was not fully explained with the CSO scenario, for the exotic diffuse emission towards the west which is perpendicular to the CSO jet axis. The 15 GHz images in Tremblay *et al.* (2008) and in the MOJAVE showed that the southern brightest component is quite compact, although its spectral index is steep as estimated from the 15 GHz and lower frequencies (note that the compact component embedded in the jet/diffuse emission may lead to an overestimate of its flux densities at the lower frequencies), a spectral index between 15 and 43 GHz is vital to clarify its nature. The spectrum of the source total flux density shows a flat spectrum in <3 GHz in the NED, this flat spectrum is not consistent with the usual steep spectrum of CSO. Furthermore, there seems to be a jet in the west connected to the southern-end component. Therefore, possibly the southern-end component is a core. In this scenario, the source has two cores and jets. The diffuse emission in the west could be due to the precession of the binary system. We measured the separation between the two candidate cores with the MOJAVE data at three epochs 1995.4, 1999.5 and 2001.3. The resulted separation is within 3.38 ± 0.13 mas, in supporting the non-expansion between the central core component and the southern brightest component (Tremblay *et al.* 2008). Kellermann *et al.* (1998) also considered that this complex source had two split jets. We keep the source as a possible BBH candidate for future VLBI monitoring and optical line study.

B2 1213 + 350 (SDSS J121555.60 + 344815.2): The quasar shows a point-like in the NVSS image, while has a short jet towards northeast in the FIRST image. The

VLBI images at 1.6 and 5 GHz from the CJ1 showed a strong hotspot-jet association in the north and a compact component in the south. The 5 GHz VIPS image revealed a short jet from the southern ‘core’ candidate. The southern one is likely the core and the northern part is the jet/hotspot. However, the northern feature seems to be jetted to the southeast and then the jet curved towards northeast. The overall radio spectrum of the source is -0.35 (1.4 GHz to 30 GHz) from the NED. From our estimate, the spectral indices of both the northern bright component and the southern core are flat from the 2.3/8.4 GHz RRFID VLBI data and the 5 GHz VLBApls data, so an alternative scenario could still be possible that the northern part harbors a secondary core. We keep it as a BBH candidate for further observations. We study in detail, high frequency VLBI observations at 43 GHz that are needed to classify this source.

B2 1630 + 35: No optical and high energy band information is available for this source. The radio spectrum shows a peaked shape around 1 GHz – a GPS source (Marecki *et al.* 1999). Both the NVSS and FIRST images show unresolved features. The 5 GHz VIPS image exhibits a northern compact component and southeastern core-jet like feature. No VLBI images at other frequencies are available for a spectral index estimate of the components. Multi-band high resolution VLBI observations should be able to classify the source.

3C454.3: This is a highly variable quasar through whole electromagnetic spectrum. Total flux density has a slightly peaked spectrum around 1 GHz. The kpc scale radio image indicates a core-jet to northwest. The 15 GHz MOJAVE images revealed overall core-jets aligning with the kpc scale jet. The VLBA features are complex, with the first part: the east-end core-jet with diffuse ring emission widely around the jet within 5 mas, and the second part: a possible secondary ‘core’-jet like feature beyond 5 mas in the northwest. We measured the secondary ‘core’ position with respect to the primary core from the MOJAVE data and found that the angular distance is stable with 6.0 ± 0.5 mas in the past 17 years. The source was a BBH system as suggested by Britzen *et al.* (2012), for its ring-like feature around the primary core-jet. We have a different view that the secondary BH might be located at 6 mas northwest of the primary core. In this scenario, the ring-like feature may have resulted from a kind of reflection of the primary jets by the accretion disk of the secondary BH. A more detailed modelling will be given in future.

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