The rise and fall of a binary AGN candidate: the story of PSO J334.2028+1.4075

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Abstract

Apparently periodic optical variations of the luminous high-redshift (z=2.06) quasar PSO J334.2028+1.4075 (FBQS J2216+0124) led Liu et al. (2015) to interpret the variability as the orbital period of a binary supermassive black hole (SMBH) residing in a single circumbinary accretion disk. The proposed orbital separation was around 0.006 pc, and the possible inspiral time about 7 years in the rest frame of the quasar. Such objects would be of high interest as the difficult-to-find end products of binary SMBH evolution, and potential sources of gravitational waves. However, extending the time baseline of the variability study, Liu et al. (2016) later found that the periodicity of PSO J334.2028+1.4075 does not remain persistent. Foord et al. (2017) did not find evidence for the binary active galactic nucleus scenario based on *Chandra* X-ray observations. The object has also been studied in detail in the radio (Mooley et al. 2018) with the Karl G. Jansky Very Large Array (VLA) and the Very Long Baseline Array (VLBA), revealing a lobe-dominated quasar at kpc scales, and possibly a precessing jet, which may retain PSO J334.2028+1.4075 as a binary SMBH candidate. Here we report on our 1.7-GHz observation with the European VLBI Network (EVN) which complements the high-resolution VLBA data taken at higher frequencies, show our new 6-GHz VLA image, and discuss the current knowledge about the nature of this interesting object.

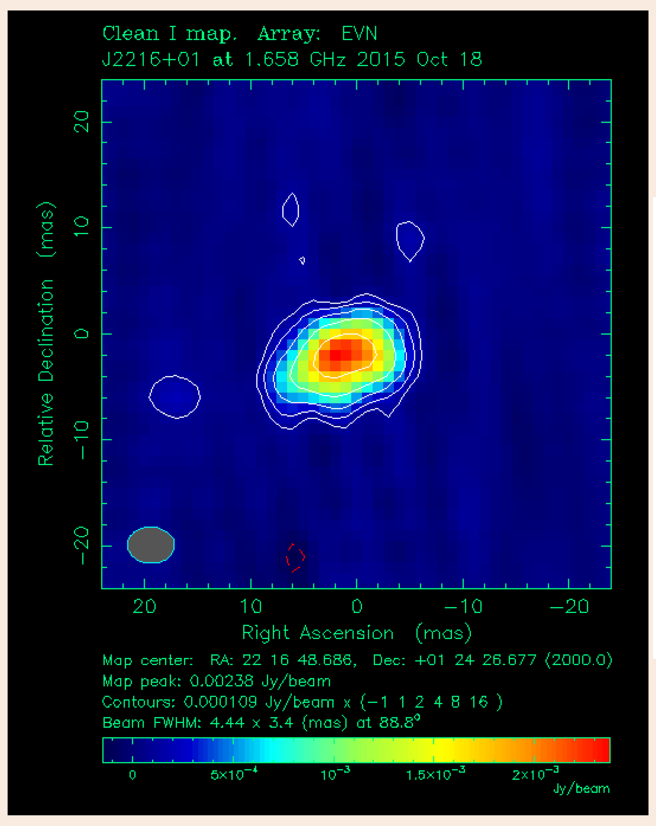
Since it is extremely rare to find **supermassive black hole binaries** (SMBHBs), the discovery of PSO J334.2028+1.4075 (PSO J334 in short) attracted considerable interest. Supermassive black holes reside in large elliptical galaxies. Their mass could reach 10^9–10^{10} solar masses. They are thought to be the product of galaxy mergers. Although SMBHBs might seem as common objects, it is problematic to detect them through direct or indirect observations, especially at small separations. An indirect approach is to look for periodic optical light curves. A famous SMBHB candidate identified with this method is OJ287, where the periodicity is thought to be caused by the secondary black hole passing through the accretion disk of the primary (e.g. Lehto and Valtonen 1996).

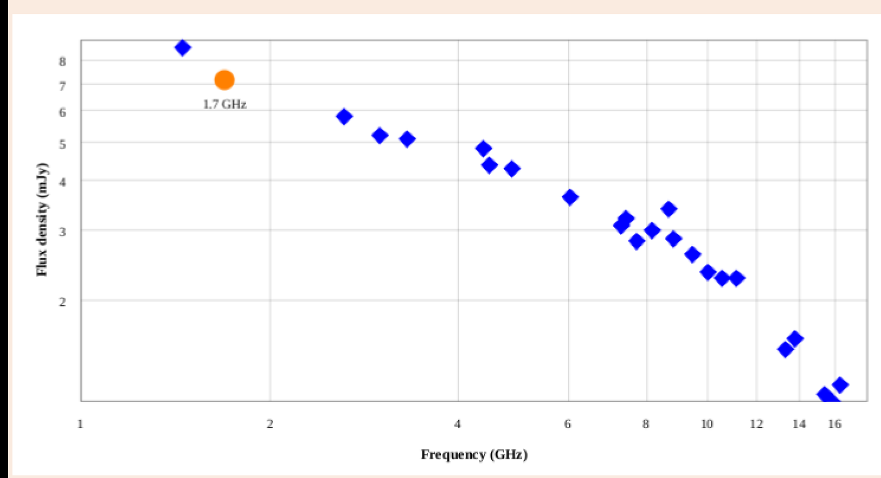
The SMBHB candidate quasar PSO J334 was selected via a systematic search in the data of the Pan-STARSS1 Medium Deep Survey. Based on the observed period in the **variation of the optical flux (~542 days)** and the estimated black hole mass (~10^{10} solar masses, with a mass ratio of $0.05<q<0.25$), Liu et al. (2015) determined an **orbital separation of 0.006 pc.** According to this, the coalescence of the SMBHB would occur in approximately 7 years in the rest frame of the quasar. Unfortunately, none of our instruments are capable of resolving the two components at such small separation. So the evidences of the second component could only be indirect.

As a result of a more detailed examination, following Vaughan et al. (2016), who have pointed out that the detected 2.6 cycles are not sufficient to claim sinusoidal variations, Liu et al. (2016) later found no proof of PSO J334 being a binary AGN system.

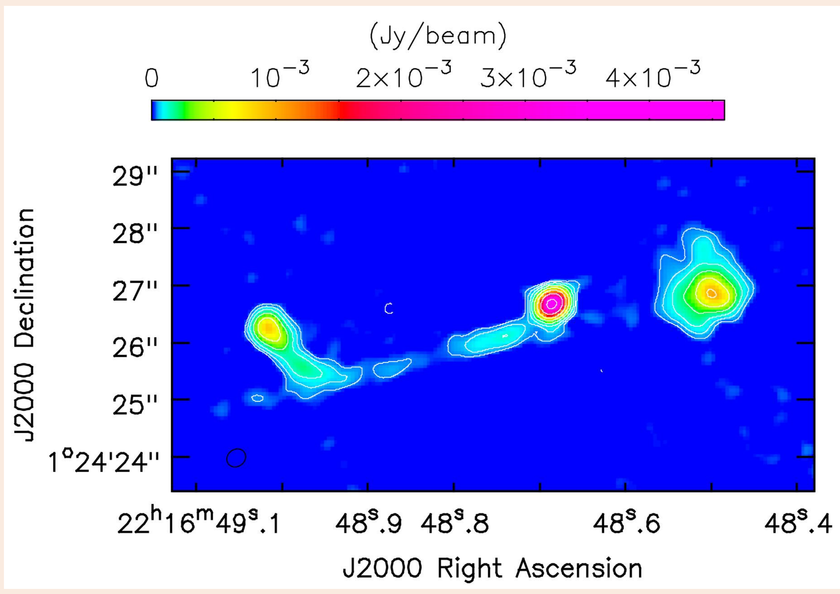
Mooley et al. (2018) examined the radio source at several radio frequencies with the **VLA and the VLBA radio interferometers**. With the VLBA, they managed to resolve the quasar into two components: a more **compact core, and a jet component** at a distance of 3.6 mas, corresponding to 30 pc linear separation on the sky. According to the VLA images, the rather extended jet and lobe structure is stretching 66 kpc from the opposite sides of the core. What is more, the **39° difference between the position angles of the outer lobes and the inner jet** is so significant that it might suggest, among other possible physical scenarios, a second SMBH's disturbing effect on the jet. So, despite the outcome of the most recent optical light curve analysis, PSO J334 can still be considered a SMBHB candidate.

Foord et al. (2017) studied multi-wavelength observations, aiming to determine the accretion mode of the quasar. They did not find any feature that would distinguish PSO J334 from single AGNs. However, there are still scenarios allowing that the object is a SMBHB.





Our **1.7-GHz EVN observation** of PSO J334, involving 12 radio telescopes (Jb Wb Ef Mc O8 Sh Ur Tr Sv Zc Bd Hh) was made on 2015 Oct 18 (experiment RSF08). The data were calibrated in AIPS and imaged in Difmap. The image shows a **single component slightly resolved in the east–west direction**, with the peak brightness of 2.38 mJy/beam. The lowest contour is at 3σ noise level. The sctructure is consistent with the higher-frequency VLBA images of Mooley et al. (2018). We also **fitted a circular Gaussian component** to the radio source whose **7.1 mJy flux density** is in agreement with the radio spectrum presented by Mooley et al. (2018).



We also observed PSO J334 with the **VLA A-configuration array** on 2016 Oct 26. Here we show our 6-GHz image (peak brightness 4.61 mJy/beam, lowest contour at 5σ noise level of 30 μJy/beam, restoring beam size 0.35" x 0.3" at -53° position angle). On the eastern side of the core, the image indicates a **remarkably straight jet up to ~5" from the core** where it bends sharply and terminates in a hot spot. This structure seems hard to reconcile with the jet precession suggested by Mooley et al. (2018).

While the results of our 1.7-GHz EVN observation are consistent with the ones presented by Mooley et al. (2018), our VLA image suggests an arcsec-scale jet possibly interacting with and deflected by the dense ambient medium. There is no evidence for a helical structure of a precessing jet. **This, and recent studies from the literature indicate that PSO J334 is likely not a SMBHB.**

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