VLBI radio structure and core-brightening of the high-energy neutrino emitter TXS 0506+056

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ABSTRACT

We report on the radio-brightening of the blazar TXS 0506+056 in temporal coincidence with the IC-170922A high-energy neutrino detection by the IceCube Neutrino Observatory. Very long baseline interferometry (VLBI) data at 15 GHz spanning 16 epochs between January 2009 and May 2018 were analysed in order to reveal the radio structure of the blazar TXS 0506+056 (z = 0.3365). This flaring γ-ray blazar has been recently identified as the source of the high-energy neutrino event IC-170922A, also supported by the excess of cosmic neutrinos between September 2014 and March 2015 reported by the IceCube Collaboration. Our investigations indicate that the radio flux density of the TXS 0506+056 VLBI core has been abruptly brightening since January 2016, producing an accumulated fourfold increase until the most recent observation. Further, the radio jet-components maintain peculiar quasi-stationary core separations and the structure of the jet ridge line, as well as the flux density variation along it is indicative of a jet curve at the region 0.5 – 2 mas from the VLBI core. These features support a helical jet structure and a small inclination angle, which is less than 7° based on the average brightness temperature of the core. The radio jet pointing towards the Earth is the key property of the blazar TXS 0506+056 enabling multimessenger observations. The radio-brightening coincident with the high-energy neutrino detection is similar to the one reported for the blazar PKS 0723-008 and IceCube event ID5.

Key words: Galaxies: BL Lacertae objects: Individual: TXS 0506+056 – Physical Data and Processes: neutrinos – Radio continuum: galaxies – Techniques: interferometric

1 INTRODUCTION

Since the discovery of the cosmic high-energy (HE) neutrinos extensive studies have been carried out aiming to identify their origins. Active galactic nuclei (AGN, powered by supermassive black holes (SMBHs), are in principle prominent candidates, being able to produce the dominant isotropic neutrino background between 10^4–10^10 GeV (Stecker et al. 1991).

Blazars, a subclass of AGN (Urry & Padovani 1995), are characterized by their relativistic jet pointing close to the Earth’s line of sight. Blazars are highly variable sources, radiating from radio to γ-rays. Due to the relativistic motion of ionized plasma in the jet seen at small inclination angles, beaming of the electromagnetic radiation makes blazars appear much brighter than they would be intrinsically. Very long baseline interferometry (VLBI) observations reveal superluminally outward moving objects in a number of relativistic jets. Such superluminal motions are only apparent, indicating projection effects.

Two years ago Kadler et al. (2016) reported that a major outburst of the blazar PKS B1424–418 occurred in temporal and positional coincidence with the third PeV-energy neutrino event (ID35) detected by the IceCube Neutrino Observatory. ID35 was a shower-type event, with average median angular error of 15.7°.

Cross-correlating different radio catalogues with the arrival direction of the track-type neutrinos detected by the IceCube Neutrino Observatory (Aartsen et al. 2014; Schoenen & Raedel 2013), the blazar PKS 0723-008 was identified as the source of the HE neutrino event ID5 (Kun, Biermann & Gergely
Figure 1. Flux density ($S$), core separation ($r$), position angle ($\theta$) and width ($d$) of jet components C1, C2, C3, C4, as well as flux density, and width of the VLBI core plotted against time. The vertical dashed line indicates the detection of the HE neutrino event IceCube-170922A.

For this type of events the average median angular error of the parent neutrino is $\lesssim 1.5^\circ$, meaning its source can be determined more accurately, than for the shower-type events. Along this blazar three other candidates were found (the corresponding HE neutrino events are given in brackets): BL Lac object PKS B1206-202 ($z = 0.404$; ID8), PKS B2300-254 ($z$ and type unknown; ID18), quasar PKS B2224+006 =4C+00.81 ($z = 2.25$; ID44).

Recently IceCube Collaboration et al. (2018) reported on the multimessenger observations of the flaring $\gamma$-ray blazar TXS 0506+056 ($z$=0.336; Paiano et al. 2018), coincident with the HE neutrino event IceCube-170922A. The deposited energy was $\sim$ 290 TeV in a track-type event. Observations from radio frequencies to $\gamma$-rays suggest TXS 0506+056 is the source of HE neutrinos. The IceCube Collaboration (2013) investigated 9.5 years of IceCube neutrino observations to search for excess emission at the position of TXS 0506+056. They found excess of HE neutrinos at the position of TXS 0506+056 between September 2014 and March 2015.

The IceCube Collaboration et al. (2018) presented radio observations on TXS 0506+056 by the Owens Valley Radio Observatory and the Very Large Array, at 15 GHz and 11 GHz, respectively. The flux density curve ends 23 days after the detection of the HE neutrino event IceCube-170922A, and does not show increase above average values. Our aim was to check the radio jet characteristics employing VLBI data. In particular, we have employed the radio interferometric measurements provided by the "Monitoring Of Jets in Active galactic nuclei with VLBA Experiments" (MOJAVE) survey (Lister et al. 2009). This is a long-term monitoring program in operation since 1994, with the aim to observe the brightness and polarization variability of AGN jets across the northern celestial sphere.

2 ANALYSIS OF THE ARCHIVAL MOJAVE/VLBA INTERFEROMETRIC DATA

Archival calibrated data of TXS 0506+056 at 15 GHz, provided by the MOJAVE programme (Lister et al. 2009, 2013, 2018), were obtained for 16 epochs between 2009.016 and 2018.412. The measurements were performed with the Very Long Baseline Array (VLBA), an interferometer array consisting of 10 radio telescopes with a diameter of 25 m each. The array employs VLBI technique, reaching a resolution better than 1 milliarcsec at 15 GHz. Standard DIFMAP tasks (Shepherd, Pearson & Taylor 1994) were used to perform the model-fitting on the VLBI data, employing Gaussian components to build up the surface brightness distribution of the jet. To decrease the degrees of freedom during the model-fit and to remain consistent through the epochs, we used only circular Gaussian components to fit the brightness profile of the jet.

We identify four components, C1, C2, C3, C4, in a region extending up to 4 mas in projection from the core ($\approx$ 20 pc, using the cosmological parameters from Planck Collaboration et al. 2016). Increasing numbers indicate larger distances to the VLBI core. The integrated flux density, position angle (measured from North, through East), core separation and FWHM-width of the VLBI jet components are against their observing epochs presented in Fig. 1. Error-estimation of these parameters was performed in the same way as in Kun et al. (2014).
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The top-left panel of Fig. 1 shows the integrated flux density of the core and the four jet components. IceCube reported the identification of an excess of cosmic neutrinos in the position of TXS0506+056 between September 2014 and March 2015. It seems the brightness of the core started to increase after this excess, in the beginning of 2016, and produced a fourfold-increased apparent brightness till 2018.5. The core doubled its flux density between the two epochs being most close to the detection time of the HE neutrino event IceCube-170922A.

The bottom-left panel of Fig. 1 shows the core separation of the jet components as function of time. This plot reveals the components maintain quasi-stationary core separations during the observations. This is very similar in nature that S5 1803+784 exhibits {Britzen et al. }{2010} {Kun et al.}

Figure 2. Relative xy-coordinate maps of the jet of TXS 0506+056 at 15 GHz, taking the core and components C1, C2, C3, C4 into account. Observing epochs can be found in the upper right corner of the maps. In three epochs a faint additional component can be seen (2009.418, 2010.867, 2015.680). The two epochs after the detection of HE neutrino event IceCube-170922A are framed (2018.305, 2018.412).

Figure 3. Flux density the core and the four jet components are plotted against their core separation (excluding the last two epochs, when the brightness of the core was doubled). The flux density of the ridge line is decreasing measured from the core, then at about 1.6 mas a bump appears in the apparent brightness.

3 RADIO BRIGHTNESS AND STRUCTURE OF TXS 0506+056

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This feature suggest we do not see the classical globally outward-moving motion of the jet components, rather see them as lantern-regions, highly Doppler-boosted parts of the jet. In our earlier work we explained the quasi-stationary of the components of S5 1803+784 with the alternation of the plasma flowing through the lantern regions: the plasma reaches the region, it lights up, then moving out form the region it fading below the sensitivity of the interferometer.

In Fig. 2 we plot the $xy$ position of the peak-flux of the jet components relative to the position of the VLBI core. A jet curve appears in the region roughly between 0.5 - 2 mas measured from the core. In Fig. 3 we plot the integrated flux density of the jet components as function of their core separation. It seems first there is a sudden decrease of the apparent brightness starting $\sim 0.5$ mas from the core. After reaching a minimum between 1 and 1.5 mas, it increases up to 1.7 mas, then descends again and the apparent brightness of jet ridge line fades away at about 4 mas. These two plots together suggest the existence of a jet curve between 1.5 and 2 mas, that has larger inclination, consequently experiences weaker Doppler boost then the neighbouring part of the ridge line. The appearance of the so-called lantern regions [Kun et al. 2018] is a consequence of the small inclination: at high jet velocities the apparent brightness is a sharp function of the inclination, so several degrees difference in the inclination may result order of magnitude differences in the apparent brightness.

## 4 APPARENT BRIGHTNESS OF THE CORE

A consequence of the Doppler boosting is that the apparent brightness temperature $T_b$ can exceed the limiting intrinsic brightness temperature $T_{int}$. The Doppler factor $\delta$ connects them as $T_b = \delta T_{int}$. In case of VLBI components the brightness temperature is calculated as (e.g. Condon et al. 1982):

$$T_{b, VLBI} = 1.22 \cdot 10^{12} \times (1 + z) \frac{S_v}{d^2 \nu^2} \text{ (K)},$$(1)

where $S_v$ is the flux density (in Jy), $d$ is the FWHM of the component (in mas), $\nu$ is the observing frequency (in GHz) and $z$ is the red-shift of the source. We calculated the apparent brightness temperature of the core from the integrated flux density and diameter of the respective Gaussian component at each of the 16 epochs of MOJAVE data. Assuming the equipartition brightness temperature $T_{int} \approx 5 \times 10^{10}$ K as the intrinsic brightness temperature (Readhead 1994), we obtained $\delta \approx 9$ for the core.

Often the VLBI jets of AGN show apparent superluminal motion because of the small inclination and their high speed. To calculate the proper motion of the jet components their core separation have to be plotted against time, and then a linear fit yields their apparent velocity $\beta_{app}$. However, as the jet components of TXS 0506+056 presumably indicate different parts of the jet ridge line maintaining quasi-stationary core separations, the proper velocity for them cannot be calculated as they are not manifestation of self-consistent bunches of plasma.

In Fig. 4 we plot the dependence of the Doppler factor $\delta$ from the apparent velocity $\beta_{app}$ in case of different jet velocities $\beta$ and inclination angle $\iota$. The average Doppler factor of the VLBI core of TXS 0506+056 at 15 GHz is marked by a horizontal solid line.

## 5 CONCLUDING REMARKS

Up to date the IceCube Collaboration has published the parameters of 56 cosmic HE neutrino detections [Aartsen et al. 2014; IceCube Collaboration et al. 2014; Schoenen & Raedel 2015; IceCube Collaboration et al. 2015], from which 16 events were track-type, induced by muon neutrinos. For this type of HE neutrino events the average median angular error is smaller than $\sim 1.2^\circ$.

In our earlier work we have investigated the origin of the track-type HE neutrinos detected by the Antarctic IceCube Neutrino Observatory [Kun, Biermann & Gergely 2017, Kun et al. 2018]. We have proposed a qualitative scenario of binary SMBH evolution leading to the observed HE neutrino emission predicting the a sequence of events:

(i) the dominant black hole spin-flips (presumably million years before the merger, Gergely & Biermann 2009),
(ii) a new jet-channel plows through the surrounding material capturing seed particles, also feeding from the accretion disk,
(iii) the dominant jet accelerates ultrahigh-energy cosmic ray particles (UHECRs), and energetic hadronic collisions produce pions that decay further creating neutrinos,
(iv) the SMBH merger occurs with accompanying emission of low-frequency gravitational waves.

Doppler boosting from the underlying jet pointing to the Earth makes it possible to identify the origin of the neutrinos.
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and such the extended flat-spectrum radio emission is a key selection criterion to find traces of this complex process. The dominant jet reoriented after the spin-flip is responsible for the observable consequences of the merger:
(i) enhanced radiation in all EM frequencies due to the high Lorentz factor of the freshly made jet,
(ii) flat spectrum up to THz frequencies due to the energetic synchrotron-radiating electrons,
(iii) increasing radio flux due to enhanced synchrotron radiation,
(iv) emission of HE particles (neutrinos, UHECRs, γ-rays).

The above presented scenario provides a consistent physical picture explaining the multi-messenger observations of the blazar TXS 0506+056 with an ongoing merger at its centre. The radio-brightening coincident with the high-energy neutrino detection reported for the blazar PKS 0723-008 and IceCube event ID5 (Kun, Biermann & Gergely 2017) is consistent with this scenario.

In this paper we presented another such coincident radio-brightening, of the blazar TXS 0506+056 with the IC-170922A high-energy neutrino detection by the IceCube Neutrino Observatory. We analysed the VLBI jet of the blazar, finding that its radio structure, beyond the brightening, exhibits a prominent jet curve at 15 GHz, also that its components maintain quasi-stationary core separations. Such a property was already identified in the jet of the BL Lac object S5 1803+784 (Kun et al. 2018) and interpreted as lantern-regions in a helical jet, indicative of small inclination angles with respect to the line-of-sight. The average Doppler factor of the core limits the inclination angle as being smaller than 7°. The radio jet pointing towards the Earth is the key property enabling the emission of HE neutrinos (IceCube Collaboration 2018) in coincidence with the observed gamma-ray flare (IceCube Collaboration et al. 2018) and the recent substantial increase in the radio brightness of the blazar TXS 0506+056.

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REFERENCES

Aartsen M. G. et al., 2014, Physical Review Letters, 113, 101101
Britzen S. et al., 2010, A&A, 511, 57
Condon J. J., Condon M. A., Gisler G., Puschell J. J., 1982, ApJ, 252, 102
Gergely L. Á., Biermann P. L., 2009, ApJ, 697, 1621
IceCube Collaboration, 2018, Science, 361, eaat1378
IceCube Collaboration et al., 2015, ArXiv e-prints
IceCube Collaboration et al., 2018, Science, 361, 147
Kadler M. et al., 2016, Nature Physics
Kun E., 2017, PhD thesis, University of Szeged
Kun E., Biermann P. L., Gergely L. Á., 2017, MNRAS Lett., 466, L34
Kun E., Gabányi K. É., Karouzos M., Britzen S., Gergely L. Á., 2014, MNRAS, 445, 1370
Kun E., Karouzos M., Gabányi K. É., Britzen S., Kurtanidze O. M., Gergely L. Á., 2018, MNRAS, 478, 359
Lister M. L., Aller M. F., Aller H. D., Hodge M. A., Homan D. C., Kovalev Y. Y., Pushkarev A. B., Savolainen T., 2018, ApJS, 234, 12
Lister M. L. et al., 2013, AJ, 146, 120
Lister M. L. et al., 2009, AJ, 138, 1874
Paiano S., Falomo R., Treves A., Scarpa R., 2018, ApJL, 854, L32
Planck Collaboration et al., 2016, A&A, 594, A13
Readhead A. C. S., 1994, ApJ, 426, 51
Schoenen S., Raedel L., 2015, The Astronomer’s Telegram, 7856
Shepherd M. C., Pearson T. J., Taylor G. B., 1994, in BAAS, Vol. 26, Bulletin of the American Astronomical Society, pp. 987–989
Stecker F. W., Done C., Salamon M. H., Sommers P., 1991, Physical Review Letters, 66, 2697
Urry C. M., Padovani P., 1995, PASP, 107, 803