The jet of S5 0716+71 at μas scales with RadioAstron

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Abstract

Ground-space interferometer RadioAstron provides unique opportunity to probe detail structure of the distant active galactic nuclei at μas scales. Here we report on RadioAstron observations of the BL Lac object S5 0716+71, performed in a framework of the AGN Polarization and Survey Key Science Programs at 22 GHz during 2012–2018. We obtained the highest angular resolution image of the source to date, at 57 μas. It reveals complex structure of the blazar jet in the inner 100 μas, with emission regions that can be responsible for the blazar variability at timescales of a few days to week. Linear polarization is detected in the core and jet areas at the projected base-lines up to about 5.6 Earth diameters. The observed core brightness temperature in the source frame of ≥ 2.2 × 10^{13} K is in excess of theoretical limits, suggesting the physical conditions are far from the equipartition between relativistic particles and magnetic field.

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1. Introduction

The international space VLBI mission RadioAstron (Kardashev et al., 2017) features a 10-m radio telescope (SRT) onboard of SPEKTR-R spacecraft, delivering the highest angular resolution to date ( ~7 μas at 1.3 cm, see Kovalev et al. these proceedings). One of the RadioAstron Key Science Programs (KSP) focuses on polarimetric studies of the most active and highly polarized active galactic nuclei (AGN) in the sky. The instrumental polarization of the SRT is less then 9% (Lobanov et al., 2015; Gómez et al., 2016), confirming the RadioAstron capabilities for polarization imaging. During more than five years, the polarization KSP has already delivered the most detailed study of a number of AGN, e.g. TXS 0642+449 (Lobanov et al., 2015), BL Lacertae (Gómez et al., 2016) and 3C 273 (Bruni et al., 2017). Another one of the most relevant RadioAstron Key Science Program is the Survey and Monitoring of AGNs, which aims at investigating the extremely high brightness temperature of AGNs with baselines reaching ~ 28 Earth diameters (ED) (see Kovalev et al. these proceedings for further details on the program).

BL Lacertae object S5 0716+71 (hereafter blazar 0716+714), is a key target for both of these KSPs. 0716+714 is famous for its extreme variability across the electromagnetic spectrum, including intraday variability (IDV). The IDV phenomenon, after its discovery in the middle of 80s (Witzel et al., 1986; Heeschen et al., 1987), still remains a matter of debate. IDV has been commonly

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observed in compact flat-spectrum radio sources (e.g. Lovell et al., 2003) and appears to be correlated with the compactness of the VLBI core (e.g. Kedziora-Chudczer et al., 1997). Considerable evidence has accumulated that interstellar scintillation is the principal mechanism responsible for IDV at cm and shorter wavelengths (ISS; e.g. Koay et al., 2018, and references therein).

On the other hand, there are evidence that IDV is being produced by processes intrinsic to the relativistic jet, like frequency dependence of the IDV amplitude, highly polarized micro-flares, multi-frequency correlation and others.

Blazar 0716+714 is considered as one of the best candidates for having an intrinsic origin of the observed IDV, since there are some properties that cannot be explained by ISS: the correlation between optical brightness and radio spectral index, as well as simultaneous change in variability time-scale during observations in 1990 (Wagner et al., 1990; Quirrenbach et al., 1991; Wagner et al., 1996), observed increase in variability amplitude with frequency (Fuhrmann et al., 2008), rapid variability at millimeter wavelengths (Ostorerò et al., 2006), quasi-periodic intrahour oscillations at optical band (Rani et al., 2010), and highly polarized optical micro flares (Bhatta et al., 2015). However, the observed annual modulation (Liu et al., 2012) implies that some of the 0716+714 variability is indeed produced by interstellar scintillation, at least at 6 cm and 11 cm (Gupta et al., 2012). The motivation of this study was to probe the jet structure at the finest angular resolution and to investigate the origin of its IDV. Further details and other results of this work will be presented in Kravchenko et al. (ApJ in prep.) and Kravchenko et al. (A&A in prep.).

3. Results and discussion

The polarization space VLBI image of the blazar is shown in Fig. 1, using uniform weighting at an angular resolution of ~61 μas. Giving more weights to the RadioAstron data, thus assuming super uniform weighting scheme with a binning size of 2 (υυ)-grid pixels and no weighting of the visibilities by the errors, the maximum angular resolution of the imaging experiment then reaches ~24 μas. Zooming in at this highest angular resolution, 0716+714 image shows a complex bent structure in the central ~100 μas core region, consisting on an unresolved core and nearby components C1 and C2, located at ~41 μas and ~58 μas from the core, respectively. The jet initially extends towards the south-east (C1), at a position angle of 153°, followed by a sharp bending of about 95° towards the north-east (C2), maintaining that direction for about 1 mas until another sharp bend towards the north-west is observed. Such extreme orientation of the central 100–200 μas region relative to the position angle of the jet at larger scales in the blazar is not surprising: Rani et al. (2015, 2014) and Jorstad et al. (2017) have already observed nearly 90° offset in the orientation between these two jet regions.

We estimate the size of the core to be ≤12 × 5 μas, while the sizes of components C1 and C2 are ~32 μas and ~19 μas, respectively. Using model fitted parameters and following Kovalev et al. (2005), we obtain the observed brightness temperatures in the rest frame of the source of (6.99 ± 0.18) × 10^{11} K for C1, (1.20 ± 0.06) × 10^{12} K for C2, and T_b ≥ 2.2 × 10^{13} K for the core.

The limited (υυ)-coverage of an individual RadioAstron snapshot-mode observations taken within AGN Survey KSP does not allow for imaging and model fitting the brightness distribution. Whereas blazar has been targeting 18 times at 22 GHz during 2012–2017 within the program, we combine these epochs and consider them together. (υυ)-coverage for these observations is given in Fig. 2, along with visibility distribution versus (υυ)-distance.

Assuming that interferometric visibility at space-ground baselines is determined by the most compact component (see Lobanov, 2015 for discussion), its size can be estimated. We represent its contribution V by a circular Gaussian function considering only space-ground baselines l in a form V = \text{A} \exp(-l^2/(2C^2)), where A and C are the fitted parameters. The size \( \theta \) of the corresponding emitting region is then derived as \( \theta = \sqrt{2\ln 2} \times 206264.806/(\pi C) \) arcseconds which results in ~15 μas, and the brightness temperature of ~10^{13} K. One need to assume, that these values are a subject of extreme blazar variability and a more complex structure of the jet in the central region, rather than a single compact component. How large is the contribution of these factors is the matter of future studies, meanwhile the values of \( \theta \) and \( T_b \), obtained from the AGN Survey KSP, are close to the corresponding values, coming from the RadioAstron imaging experiment.

2. Observations

Observations of the blazar as part of the Polarization KSP has been performed on 2015 January 3–4 during 12-h global space VLBI session at 22 GHz. The signal has been recorded in two circular polarizations (right- and left-hand) in a bandwidth of 32 MHz for the space and 64 MHz for the ground antennas. An array of 11 ground antennas and SRT tracked the source: Brewster, Effelsberg, Ford Davis, Green Bank, Hancock, Los Alamos, Noto, Owens Valley, Pie Town, Shangai and Torun. Fringes between ground antennas and space telescope has been found at the maximum projected baseline of 5.25 GHz (5.56 ED or 70,833 km).

The AGN Survey KSP consists on snapshot-mode (≤1 h long) observations of the sources with a number of antennas, depending on the availability at the time. 0716+714 has been observed 68 times within this program between 2012 and 2018 at 1.7, 4.8 and 22 GHz. The maximum projected baseline in these observations reached about 25.5 ED (324,900 km), during the segment taken on 2013 November 7 at 1.7 GHz, when blazar was successfully detected.
In the case of inverse Compton losses for incoherent synchrotron sources, it is expected that the intrinsic brightness temperature does not exceed $10^{11.5}$ K (Kellermann and Pauliny-Toth, 1969). In case of equipartition between the energies of the magnetic field and radiating particles, an upper limit of $T_{b,\text{int}} \lesssim 5 \times 10^{10}$ K (Readhead, 1994) is expected. The intrinsic and observed brightness temperatures are connected through the Doppler boosting factor as $T_{b,\text{int}} = T_{b,\text{obs}} / \delta$. Considering a Doppler factor of $\delta \sim 24$, the maximum observed in the blazar (e.g. Rani et al., 2015; Jorstad et al., 2017; Liodakis et al., 2018), the intrinsic brightness temperature of the core results in $\gtrsim 9 \times 10^{11}$ K and is in excess of Compton limit and equipartition brightness temperature value. This result supplements recent RadioAstron studies of a quasar 3C 273 (Kovalev et al., 2016) and a blazar BL Lac (Gómez et al., 2016), where authors also found that $T_{b,\text{int}}$ breaks the abovementioned limits. Excess of $T_{b,\text{int}}$ over the synchrotron limit could indicate that some other mechanisms are at work, such as coherent radiation mechanism (Benford, 1992), quasi-monoenergetic electron population (Tsang and Kirk, 2007) or proton synchrotron radiation (Kardashev, 2000).

The radio polarimetric structure of the blazar at the highest resolution is characterized by 15%-linearly polarized compact component, located $\sim 58$ μas down stream the core (see Fig. 1). The position of this polarized feature coincides with the location of model fitted component at 58 μas. Considering that Doppler-adjusted light-crossing time across jet component governs the observed timescale, the variability timescale can be estimated as $\tau(\text{yr}) = [25.3(R/\text{mas})(D_{L}/\text{Gpc})]/[\delta(1+z)]$ (Jorstad et al.,...
where $D_L$ is the luminosity distance, which equals to $1612.6$ Mpc (assuming flat ΛCDM cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$Mpc$^{-1}$) at the redshift of 0.31 (Danforth et al., 2013; Nilsson et al., 2008), and $R$ is the angular size of the model fitted component.

For the polarized component C2, with an angular size of 19$\mu$as, $\tau$ is about 9 days, meanwhile for the unresolved core it is of $\sim 2.5$ days. Thus, intrinsic processes in the blazar jet can explain its variability on the time scales of a days to a week. To explain five-hour-long, $\lesssim 60\%$ optical polarized micro flare observed in the blazar (Bhatta et al., 2015), even smaller regions with a highly ordered magnetic field are required.

Linear polarization structure of 0716+714 jet, given in Fig. 1, is dominated by two features, associated with the core region and with the jet emission. Uncorrected for the Faraday rotation, electric vector position angle (EVPA) follows the orientation of the jet for both these polarized regions. Lee et al. (2016) in their study measured RM follows the orientation of the jet for both these polarized regions. Lee et al. (2016) in their study measured RM between 22 GHz and 43 GHz ranging between $9200$ to $6300$ rad/m$^2$, and $-71000$ to $-7300$ rad/m$^2$ between 43 GHz and 86 GHz. Assuming that the rotation measure value in the central core region is negative and of a few thousands, then the orientation of the EVPA will be better aligned with the core-C1 component, indicating dominance of the toroidal component of the ordered magnetic field in the blazar jet.

Our results confirm the powerful capabilities of the RadioAstron mission to probe relativistic jets in vicinity of the central black hole, including high angular resolution polarization imaging. Our imaging results from 2015 January 3–4 gave an angular resolution of 24 $\mu$as, a factor of two higher than was achieved with ground VLBI arrays to date (e.g. Rani et al., 2016).

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