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Rapid e-EVN studies of newly discovered γ-ray blazars

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Blazars are powerful active galactic nuclei radiating prominently in the whole electromagnetic spectrum, from the radio to the X-ray and γ-ray bands. New candidate blazars are often discovered by their high-energy radiation, but their identification with low-energy counterparts could be challenging. Due to their compact radio emission, these sources are good targets for Very Long Baseline Interferometry (VLBI) observations. VLBI can help to confirm the blazar nature of the sources while providing accurate astrometric positions down to the milliarcsecond level. Here we report on the results of two short exploratory experiments with the European VLBI Network using the e-VLBI mode. The target sources, RX J0648.7+1516 and IGR J12319−0749, were observed in 2012.

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1. Introduction

Blazars, active galactic nuclei (AGN) with powerful, variable non-thermal emission across the whole electromagnetic spectrum, come in two basic varieties: BL Lacertae (BL Lac) objects and flat-spectrum radio quasars (FSRQs). The former objects show practically no emission lines in their optical spectrum. On the other hand, FSRQs are characterised by strong, broad emission lines. For a recent review of multi-band blazar properties, see e.g. [1, 10] and references therein. In the radio, blazars in general have flat or inverted power-law spectrum (spectral index $\alpha \geq -0.5$; $S \propto \nu^{\alpha}$, where S is the flux density and ν the frequency). When observed with milliarcsecond (mas) scale angular resolution, using the technique of Very Long Baseline Interferometry (VLBI), blazars are compact sources with typical one-sided jet structures, dominated by an often unresolved or slightly resolved "core". According to the unified scheme of AGN [17], the approaching one of the symmetric pair of AGN jets points close to our line of sight, causing the synchrotron radio emission of the plasma to be relativistically beamed. VLBI imaging and model-fitting are useful to directly verify the blazar nature of an AGN by detecting high apparent brightness temperature indicative of Doppler-boosted emission. With multi-epoch VLBI monitoring, apparent superluminal motion of jet features could possibly be also measured.

The dominant fraction of the high-energy (hard X-ray and γ-ray) emission of blazars is intimately related to the synchrotron radiation, as it is attributed to the inverse-Compton process, where the photons are upscattered by interacting with the relativistic charged particles in the jet. New candidate blazars are often discovered nowadays by their high-energy radiation. In fact, blazars are becoming the most common type of AGN found at γ-ray energies [10]. However, their identification with low-energy counterparts could be challenging due to the large positional uncertainties in the high-energy observations. Their compact radio emission makes these sources ideal targets for VLBI which can help to confirm their blazar nature while providing accurate astrometric positions down to the mas level. Electronic VLBI (e-VLBI) is of special value because of the rapid turnaround from the experiment planning through the observation to the data analysis [16]. This makes the technique a valuable tool to quickly follow up transient events (outbursts) in blazars as well. In e-VLBI, the signals are not recorded at the telescope sites on magnetic media, and played back and correlated later to achieve the interference, but transmitted to the correlator via wide-band optical fibre networks in real time.

Here we report on the results of two short 2-hour exploratory experiments with the European VLBI Network (EVN) using the e-VLBI mode. The targets of these e-EVN observations were two recently identified blazar candidates: RX J0648.7+1516, a very-high-energy (VHE) γ-ray source at low redshift (z = 0.179), and IGR J12319−0749, a high-redshift (z = 3.12) soft gamma-ray source. Apart from a promise of quickly confirming the presence of a compact radio source, these observations are potentially valuable for identifying new phase-reference calibrator objects, for the benefit of future VLBI projects. Both exploratory e-EVN experiments were conducted in 2012. The correlation of the data took place at the EVN Data Processor at the Joint Institute for VLBI in Europe, Dwingeloo, The Netherlands.

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2. The target sources and their e-EVN observations

2.1 RX J0648.7+1516

RX J0648.7+1516 is a VHE γ-ray source, optically identified only recently with a blazar at the redshift of z = 0.179, based on absorption lines originating from its host galaxy [2]. The γ-ray source was discovered with the Large Area Telescope of the *Fermi* spacecraft and was followed up with the VERITAS atmospheric Cherenkov telescopes as a promising candidate. The 5.2σ detection in the VHE band (0.1–30 TeV) also suggested that the source is a blazar since the majority of the VHE-detected AGN belongs to this class [8]. Variability has not been detected, neither with *Fermi* during 2.3 years, nor with VERITAS over a period of nearly 1 month [2]. The source is seen very close to the Galactic plane (within 6.3°), where there is an interest to find more VLBI reference sources suitable for studying the structure and dynamics of the Milky Way via maser parallaxes determined with accurate relative astrometry [12, 14]. Observations in the γ-rays can be useful to identify blazars seen in directions close to the Galactic plane where classical radio and optical surveys are less effective due to source confusion and extinction [8].

RX J0648.7+1516 was known previously as a flat-spectrum radio source from the measurements in the NRAO VLA Sky Survey (NVSS) at 1.4 GHz ($S_{1.4} = 64.2$ mJy [5]) and the 6 cm Green Bank survey (GB6) at 4.85 GHz ($S_{4.85} = 60$ mJy [11]). We observed it with the e-EVN at $\nu = 5$ GHz on 2012 Jan 10 (project code: RSF05). The longest baselines were provided by Hartebeesthoek (South Africa) to the European antennas (Effelsberg, Jodrell Bank Mk2, Medicina, Onsala, Toruń, Westerbork). RX J0648.7+1516 was observed in phase-reference mode, using the calibrator J0637+1458. The maximum data recording rate was 1024 Mbit/s. The NRAO Astronomical Image Processing System was used for data calibration and fringe-fitting in a standard way. The imaging, self-calibration, and model-fitting were done with the Caltech DIFMAP package.

We found that the source has a prominent jet pointing to the north (Fig. 1). Its radio emission is resolved, even with the European-only VLBI baselines: the components account for 39 mJy while the total (GB6) flux density is 60 mJy. A circular Gaussian brightness distribution model fitted to the visibility data of the "core" component has $\vartheta = 0.74$ mas diameter (full width at half maximum, FWHM) and $S = 25$ mJy flux density, with the inclusion of Hartebeesthoek data. Following [13], we estimated the minimum resolvable angular size in our experiment, 0.8 mas $\times$ 0.1 mas, calculated from the restoring beam size (Fig. 1, right) and the signal-to-noise ratio. The minimum resolvable size in the direction of the restoring beam major axis (0.8 mas) is comparable to our fitted value (0.74 mas); we used $\vartheta = 0.8$ mas for the following calculations. Note that because of the low Galactic latitude, we may expect relatively large scatter-broadening of a point-like radio source in this direction. However, the value of 0.17 mas taken from the [7] model is much smaller than our fitted core size, therefore this does not change our conclusions.

Considering the absorption-line redshift (z = 0.179) and our upper limit to the core size, we can estimate a lower limit to the brightness temperature [4], $T_{\rm b} = 1.22 \times 10^{12}(1+{\rm z})S\vartheta^{-2}\nu^{-2} = 2.2 \times 10^{9}$ K. This is significantly lower than the equipartition value, $T_{\rm eq} \simeq 5 \times 10^{10}$ K [15], providing no evidence for Doppler boosting in the jet of RX J0648.7+1516. The core seems not as bright and compact as would be consistent with the assumption by [2] for their model of the high-energy emission: the jet viewing angle $\theta = 3^{\circ}$ and the bulk Lorentz factor $\Gamma = 20$ assumed by [2]would imply $\delta = (\Gamma - \cos\theta\sqrt{\Gamma^{2}-1})^{-1} \approx 19$ (see e.g. [17] for the relevant formulae). In this case, the expected apparent brightness temperature $\delta T_{\rm eq}$ [15] would be nearly 10^{12} K. To reliably detect a core as small as $\vartheta \approx 0.04$ mas required for such a high apparent brightness temperature in RX J0648.7+1516, one would need a much smaller restoring beam (by increasing the length of the interferometer baselines), and a higher imaging sensitivity. In our case, close to the Galactic plane, scatter-broadening would however prevent directly measuring such a small angular size. High-quality VLBI imaging in the future, at more epochs could provide useful measurements of jet kinematics and the physical parameters. Phase-referencing to the nearby (2.66°) calibrator J0637+1458 gave accurate coordinates for our target: right ascension $06^{\rm h}\ 48^{\rm m}\ 47.64861^{\rm s}$ and declination $15^{\circ}\ 16'\ 24.7988''$, with an uncertainty of 1 mas in each.

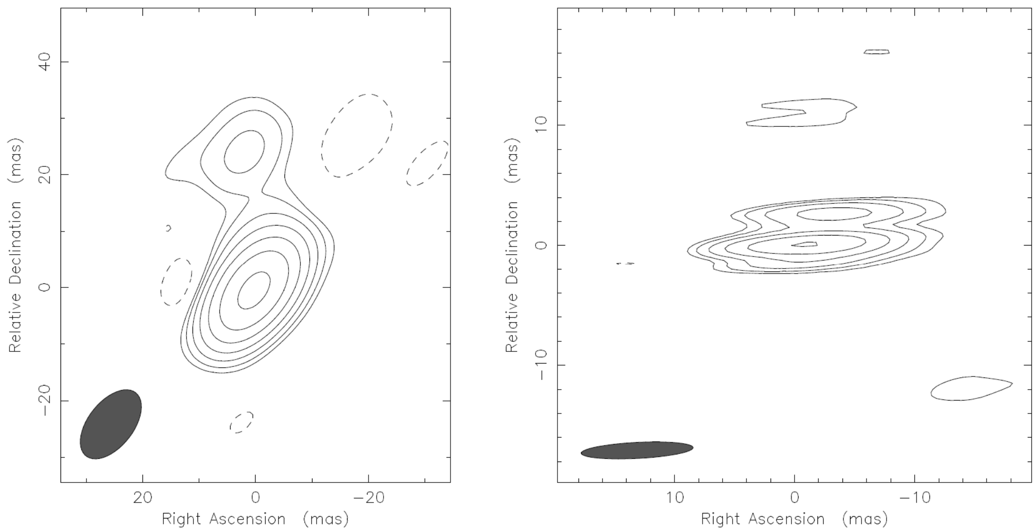

Figure 1: Naturally-weighted 5 GHz e-EVN images of RX J0648.7+1516, with the European antennas only *(left)* and with full resolution including data observed on baselines to Hartebeesthoek *(right)*. The extended jet structure can be traced up to ~ 30 mas from the core towards the north in the lower-resolution image, where the lowest contours are drawn at ± 0.45 mJy/beam, corresponding to $\sim 3\sigma$ image noise. The peak brightness is 35 mJy/beam. The Gaussian restoring beam is 14.2 mas $\times$ 8.0 mas with major axis position angle $-38°$. With significantly longer north-south baselines, and a tenfold increase in the weight of the Hartebeesthoek data, the inner part of the jet is further resolved *(right)*. Here the lowest contours are at ± 0.5 mJy/beam, the peak brightness is 16.6 mJy/beam, and the Gaussian restoring beam is 9.3 mas $\times$ 1.3 mas with major axis position angle $-87°$. The positive contour levels increase by a factor of 2, and the restoring beams (FWHM) are indicated with ellipses in the lower-left corners in both images.

After completing our experiment, we found that RX J0648.7+1516 has independently been observed with the NRAO Very Long Baseline Array (VLBA) at 8.4 GHz, just a month before the 5 GHz e-EVN observation, on 2011 Dec 7 and Dec 11, as part of a large systematic search for off-nuclear supermassive black holes in radio-emitting 2MASS infrared galaxies [6]. The preliminary images from the two ~ 5 min snapshot observations made available on the project web site[1] do show a mas-scale extension to the north, coincidently with the jet direction seen in Fig. 1. The VLBA position estimates are also consistent with ours.

[1] `http://astrogeo.org/v2m/`

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2.2 IGR J12319−0749

Our second target, IGR J12319−0749, is a high-redshift ($z = 3.12$) soft gamma-ray source [3]. It was found with INTEGRAL as the second most distant blazar detected with the satellite so far. From its broad optical emission lines, the mass of the central black hole is estimated to be 2.8×10^9 $M_\odot$. There are several other pieces of evidence suggesting that the source is an extreme blazar, a FSRQ with powerful jets. One piece however, a VLBI detection of the compact radio emission, was missing. Our 5 GHz exploratory e-EVN observation, much similar to that of RX J0648.7+1516, took place on 2012 Jun 19 (experiment code: RSF06). This time the Noto radio telescope was also included in the network. The details of the data analysis are given in [9].

Although IGR J12319−0749 has a similar total flux density as RX J0648.7+1516 (60.4 mJy in the NVSS [5] and 62.9 mJy in the VLA FIRST survey [18], both at 1.4 GHz), we found a much more compact, practically unresolved radio emission (Fig. 2). Since the 5 GHz flux density of the "core" (84.6 mJy) is higher than the 1.4-GHz value, the source is either strongly variable or has an inverted radio spectrum. The brightness temperature estimated from the component size ($\vartheta < 0.29$ mas) and the flux density clearly indicates relativistically beamed emission with a Doppler-boosting factor of at least 4. Phase-referencing to J1233–1025 (separated by 2.65° in the sky) was applied to obtain an accurate position for IGR J12319−0749: right ascension 12^h 31^m 57.68547^s and declination -7° $47'$ $18.0901''$, with uncertainties of 0.7 mas and 1 mas, respectively. It turned out that the target source itself is sufficiently bright and compact to serve as a calibrator for any future phase-referencing observation of nearby weak sources.

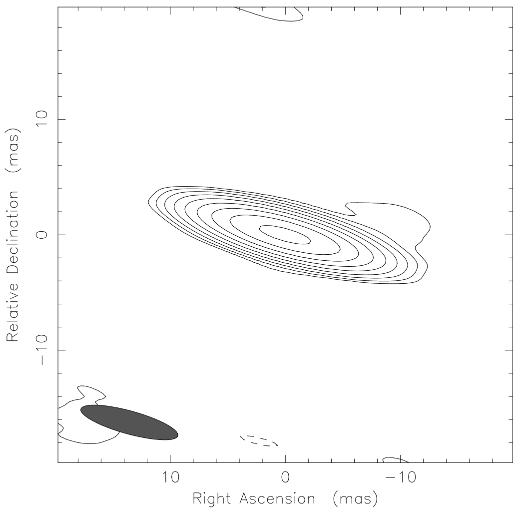

Figure 2: Naturally-weighted 5 GHz e-EVN image of IGR J12319−0749. The lowest contours are drawn at ±0.27 mJy/beam, corresponding to $\sim 3\sigma$ image noise. The positive contour levels increase by a factor of 2. The peak brightness is 84.1 mJy/beam. The Gaussian restoring beam is 8.8 mas × 2.0 mas with major axis position angle 75°.

3. Summary

We observed with the e-EVN the radio counterparts of two suspected blazars recently identified by their high-energy emission. Compact radio sources were detected on intercontinental baselines at 5 GHz frequency during these short 2-hour exploratory experiments conducted in 2012. RX J0648.7+1516, a low-redshift ($z = 0.179$) VHE γ-ray source, has a prominent jet structure out to ~ 30 mas, with a core resolved on the longest EVN baselines. The core is probably not as bright and compact as assumed for the model of its spectral energy distribution [2]. Further high-quality (full-track) VLBI imaging observations would be required to better constrain the core brightness temperature, and to map the complex jet structure. Multi-epoch monitoring would supply data for studying the jet kinematics to determine its physical and geometric parameters. According to our e-EVN results, the other target blazar, IGR J12319−0749, a high-redshift ($z = 3.12$) soft gamma-ray source identified as a FSRQ [3], is a truly compact, essentially unresolved radio source. The Doppler factor of the approaching radio jet is at least 4. This is a strong additional support to its blazar identification. The size of the radio source could be better constrained with higher-resolution VLBI imaging observations, in particular with long intercontinental baselines in the east-west direction that were missing in our exploratory e-EVN experiment.

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