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Imaging strong blazars with space VLBI

J. Anton Zensus [a], Laura Vega-García [a], Eduardo Ros [a,*], Andrei P. Lobanov [a]
Manel Perucho [b], Gabriele Bruni [c], Yuri Y. Kovalev [d,e,a]

[a] *Max-Planck-Institut für RadioAstronomie, Bonn, Germany*
[b] *Dep. Astron. i Astrofísica & Obs. Astronòmic, Universitat de València, Spain*
[c] *INAF – Istituto di Astrofisica e Planetologia Spaziali, Rome, Italy*
[d] *Astro Space Center, Lebedev Institute, RAS, Moscow, Russia*
[e] *Moscow Institute of Physics and Technology, Russia*

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Abstract

The *RadioAstron* mission has obtained a series of detailed multi-frequency images of the brightest blazars of the radio sky concentrated in three key science programs. We present here results of the program on powerful jets in blazars. In the first two years of the mission, observations of compact relativistic jets in 0836+710, 3C 345, 3C 273, and 4C+69.21 were made at $\lambda\lambda$ 18, 6, and 1.3 cm. The resulting images have revealed compact emitting regions with brightness temperature in excess of 10^{13} K and a complex jet structure that can be explained by plasma instability developing in a relativistic outflow.

We present here some highlights of these space-VLBI observations, designed to resolve the innermost regions in these powerful targets and address some of the still unanswered questions on their physical nature.

Keywords: Techniques: radio interferometry; Active galactic nuclei; Quasars: individual: 0836+714 (4C+71.28); Quasars: individual: 3C 345; Quasars: individual: 3C 273; Quasars: individual: 4C+69.21

1. Introduction

Detailed imaging of the innermost regions of extragalactic jets is needed in order to understand the physical mechanisms governing acceleration and collimation of relativistic outflows powered by super-massive black holes residing in the centers of active galactic nuclei (AGN). Achieving this goal requires high fidelity imaging to be made on linear scales of $\leqslant 10^5$ gravitational radii (R_s), which is presently only possible with very long baseline interferometry (VLBI).

VLBI observations have uniquely addressed such compact scales in AGN since the advent of the technique in the early 1970s (see e.g., Zensus, 1997). Angular resolution of VLBI observations can be improved either by increasing the baseline length or by observing at progressively shorter wavelengths (higher frequencies). Record angular resolution of ~ 50 microarcseconds (μas) can be achieved in VLBI observations at millimetre wavelengths. At this frequency range, jet self-synchrotron absorption and scattering effects get mitigated and the central regions of AGN can be probed. In extreme cases, it is possible to reach the event-horizon scales at a wavelength of λ 1.3 cm for at least two relatively nearby sources, M 87 and Sgr A$^{☆}$ (see Boccardi et al., 2017, for a review on millimetre VLBI

* Corresponding author.
E-mail addresses: azensus@mpifr-bonn.mpg.de (J.A. Zensus), lauvegar@mpifr-bonn.mpg.de (L. Vega-García), ros@mpifr-bonn.mpg.de (E. Ros), alobanov@mpifr-bonn.mpg.de (A.P. Lobanov), perucho@uv.es (M. Perucho), gabriele.bruni@inaf.it (G. Bruni), yyk@asc.rssi.ru (Y.Y. Kovalev).

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including the Global mm-VLBI Array (GMVA) and the Event Horizon Telescope (EHT) networks). The other option, pursued since the late 1970s, has led to the advent of *space VLBI* which combines ground-based telescopes with an antenna on board of a satellite in orbit around the Earth. After pioneering space VLBI experiments performed in the 1980s, regular space-VLBI observations were realized with the Japanese VLBI Space Observatory Program (VSOP) (Hirabayashi et al., 1998; Hirabayashi et al., 2000) which provided baselines of about three Earth diameters, $\mathbf{D}_{\oplus}$ with an angular resolution roughly equivalent to global mm-VLBI. At present, baselines of up to $\sim 30\,D_{\rm E}$, can be reached with the Russian *RadioAstron* mission (Kardashev et al., 2013) operating since 2011 and employing a 10-m space radio telescope (SRT) on board the satellite *Spektr-R*.

The highly elliptical orbit and a long (8–10 days) orbital period of *Spektr-R* impose strong restrictions performing on VLBI imaging observations. Such observations are generally only feasible either during perigee passages of the SRT or for a limited number of objects momentarily located near the orbital plane of the satellite. Both of these approaches imply specific and restrictive time constrains. The particular logistical challenge comes from the necessity to split a given observing run for into a $\sim$ 12–18 h-long perigee imaging segment (with a full track of visibilities on baselines of $1 - 10\,D_{\rm E}$), and multiple $\sim$ 1 h-long visibility tracking segments scheduled over subsequent (or preceding) 3–4 days and covering baselines of at $10 - 20\,D_{\rm E}$ in length. The latter segments typically use one large and three small ground radio telescopes, an example of which can be found in the *RadioAstron* survey of AGN cores with extreme angular resolution, see Kovalev (2015).

Perigee imaging is being performed with *RadioAstron* during the early science program (ESP), for three imaging key science programs (KSP) and in several general observing time (GOT) programs addressing AGN, at 22 GHz, 5 GHz, and 1.6 GHz (K, C, and L-bands, respectively). Concurrent observations at other frequency bands have often been scheduled at the ground arrays during the time gaps when the SRT is required for cooling. The AGN imaging experiments made with *RadioAstron* have been largely concentrated within three *imaging* KSP efforts. The first program (see Savolainen, 2018) has specifically targeted the nearby sources M 87, 3C 84, Cen A, and Cyg A, whilst also performing simultaneous observations of M 87 at 230 GHz with the Event Horizon Telescope (EHT), in 2017. First results from these observations have been reported on the innermost jet in 3C 84 Giovannini et al. (2018). The second imaging KSP program (see Bruni et al., 2020) has focused on studying polarisation properties in a larger set of sources. Results on sources such as 0642 +449 (Lobanov et al., 2015), BL Lac (Gómez et al., 2016), 3C 273 (Bruni et al., 2017), and 3C 345 (Pötzl et al., 2018) have been reported so far.

Here we report the progress on the third imaging KSP program addressing the physics and evolution of powerful outflows in bright active galactic nuclei. Most of the results presented here were obtained by L. Vega-García for her PhD Thesis project carried out at the Max-Planck-Institut für Radioastronomie (Vega-García, 2018).

2. *RadioAstron* KSP on strong jets: initial results

This program was initiated immediately after the Early Science Program, addressing the opportunity to use imaging of AGN jets for understanding the dominant physical regime (Poynting flux-dominated or kinetic-flux dominated flow) on parsec scales. Such observations probe the main production site of variable non-thermal continuum in radio-loud AGN, and study the development of shocks and plasma instabilities in powerful jets.

Four sources were observed in first years of the mission (see Table 1). All the targets were selected by their ground-based VLBI images on the criteria that they should All targets should be transversally resolved with *RadioAstron*, providing information about morphology and spectral properties of the compact emission.

Here we briefly report on the progress of the processing, analysis, and interpretation of the data resulting from these observations.

2.1. 3C345

This source is a gamma-loud, low-spectral peaked, highly polarised quasar (see e.g., Ros et al., 2000). The *RadioAstron* observation made on April 21, 2014 at 5 GHz yielded space fringes only in one scan, resulting in

Table 1
Journal of observations of the Strong AGN KSP.

IAU (1950.0)	ID	z	Scale [pc/mas]	Code	Bands	Obs. date
0836+710	4C+71.28	2.218	8.37	GL038A	L[a]	24oct2013
				GL038B/C	C/K	10jan2014
1641+399	3C 345	0.593	6.63	GL038D/E	C/K[a]	21apr2014
1226+023	3C 273	0.158	2.70	GL038F	C/K	30apr2014
1642+690	4C+69.21	0.751	7.35	GL042A	C/K[a]	26dec2014
				GL042B/C	L	20jan2015

[a] Results from these data sets will be presented elsewhere.

a modest improvement of image resolution compared to the respective ground array image.

Fig. 1 shows the preliminary ground- and space-array images obtained from this observation. A more detailed description of the results will be given in Vega-García et al. (submitted for publication). Note that this source is also being observed in the polarisation KSP (e.g., Pötzl et al., 2018), thus providing further basis for comparison and analysis of the fine structure in this object.

2.2. 4C+69.21

This source is a gamma-quiet, low-spectral peaked, highly polarised quasar. Kinematic observations from the MOJAVE program report apparent speeds of $(14.5 \pm 0.3)c$ in the jet. Observed with *RadioAstron* on December 26, 2014 in C-band and on January 20, 2015 in L-band, the jet base in 4C+69.21 is found to be still transversally unresolved, as presented in Fig. 2. Estimates of the brightness

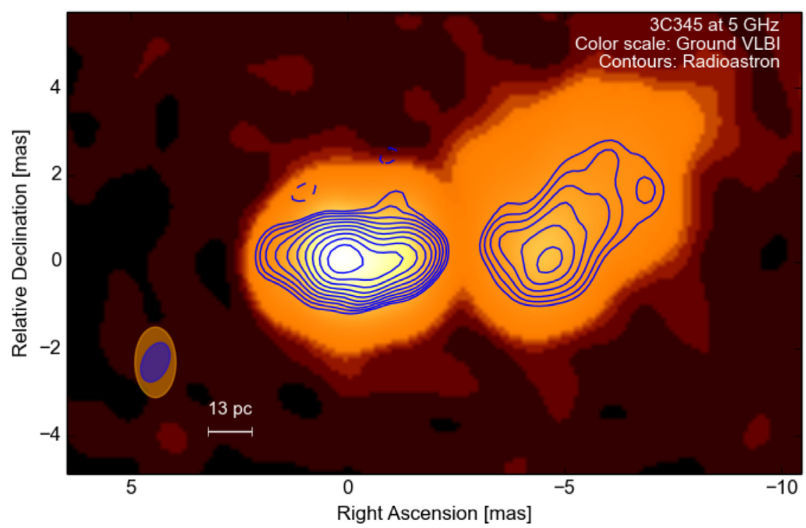

Fig. 1. Image of the inner jet 3C 345 at 5 GHz obtained from *RadioAstron* observation made on April 21, 2014. The observing beam (bottom left) follow the same scale as the images: ground array in orange, space-ground in blue. The space beam is (959×598) µas, -25° and the ground beam is (1625×944) µas, 0°. Only one scan was detected for ground-space baselines. At the distance and with the black hole mass of 3C 345, a resolution of 600 µas corresponds to about 43 000 Schwarzschild radii. See Vega-García (2018) for more details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

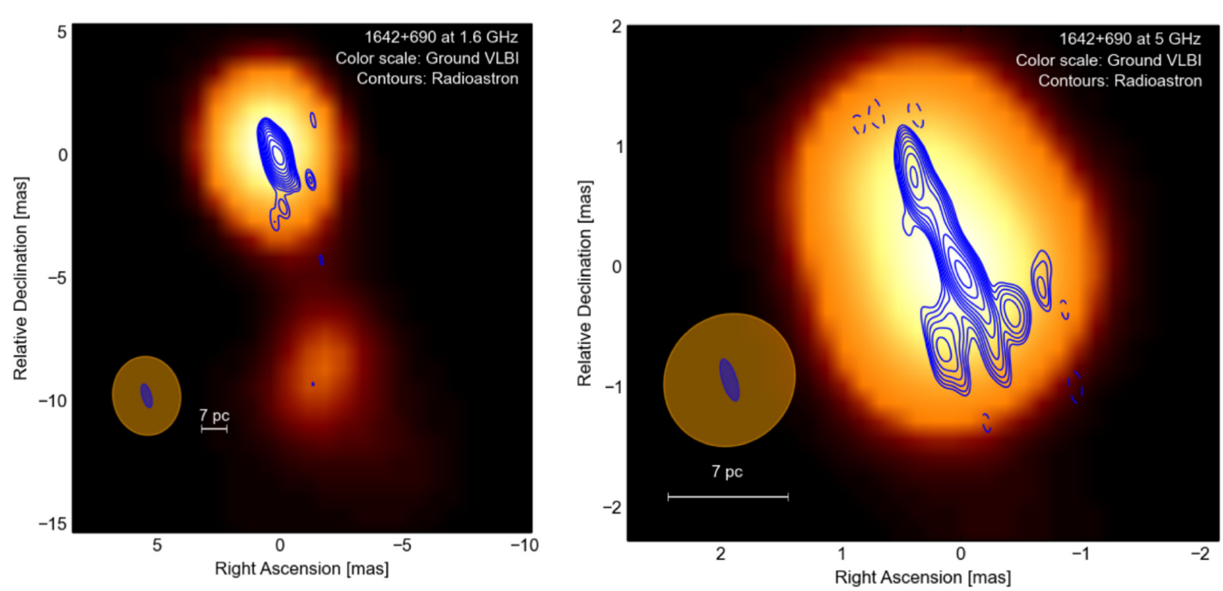

Fig. 2. *RadioAstron* observing results on 4C+69.21: Left January 20, 2015 in L-band. The space beam is (993×373) µas, 16° and the ground beam is (3220×2760) µas, 7°. Right December 26, 2014 in C-band. The space beam is (585×227) µas, 19° and the ground beam is (1140×1060) µas, -41°. The structure revealed by the space-VLBI observations shows a straight, unresolved jet in the same position angle as the results reported, e.g., by the MOJAVE survey. Note the different angular scales covered by the two images. See Vega-García (2018) for more details. At the distance and with the black hole mass of 4C+69.21, a resolution of, say 300 µas, corresponds to about 23 000 Schwarzschild radii.

temperature in the image yield a value between $10^{12.7}$ K and 10^{13} K. The east-west structure at the end of the jet in the C-band image is real. Any attempts to remove the features in the imaging process resulted in an excess in the residual map. A comparison with a ground-array image in K-band reveals a similar morphology.

2.3. 3C273

The gamma-loud, low spectral-peaked, low-polarisation quasar 3C 273 is one of the most prominent radio sources in the sky and was the first quasar ever reported (Schmidt, 1963). The MOJAVE program has reported maximum apparent speeds in its jet of up to $(14.85 \pm 0.17)\,c$ (see Lister et al., 2013).

The images presented in Fig. 3 show a clear presence of intricate and filamentary structure in the jet, similar to that observed earlier with the VSOP (Lobanov and Zensus, 2001). This has also been studied by *RadioAstron* at other epochs, as reported in Kovalev et al. (2016), Johnson et al. (2016) and Bruni et al. (2017). An estimate of the brightness temperature provides similar values to the ones published in Bruni et al. (2017).

2.4. 0836+710

The source 0836+710 (4C+71.28) is a gamma-loud, low spectral-peaked, low-polarised blazar. The MOJAVE program reports apparent speeds reaching $(21.1 \pm 0.8)\,c$ (Lister et al., 2013).

0836+710 was already observed with space-VLBI in the VSOP era (Lobanov et al., 1998), the curved jet ridge line revealed Kelvin-Helmholtz instability developing in a relativistic outflow with a Mach number of about 6, and a confined outflow with a Lorentz factor of about 11. Subsequent studies of the intrinsic structure and plasma instability (Perucho and Lobanov, 2007; Perucho et al., 2012,) have addressed the full range of spatial scales from milliarcseconds to arcseconds.

The imaging results obtained for this source count among the best imaging data sets achieved by the *RadioAstron* mission so far. The results at C and K-band are shown in Fig. 4. The L-band image is presented, together with the other two, by Vega-García et al. (submitted for publication). The K-band image reveals structures at record-breaking structures at scales down to 15 µas, similar to the ones reached by the EHT (although it should be noted that this source is not visible by ALMA and therefore not accessible for the full EHT).

The multi-band observations of this source, presented in Vega-García et al. (submitted for publication), reveal the fine structure down to 15 µas resolution. The source was detected on baselines as long as $10\,D_\oplus$ at L-band, and $12\,D_\oplus$ at C and K-band. The full-resolution images show a much richer structural detail that any ground-array image earlier, and at C- and K-band the jet is transversely resolved revealing a bent and asymmetric pattern embedded into the flow. Additional ground observations with subsets of the array were performed also at 15 GHz (U-band) and 43 GHz (Q-band). The analysis of these data

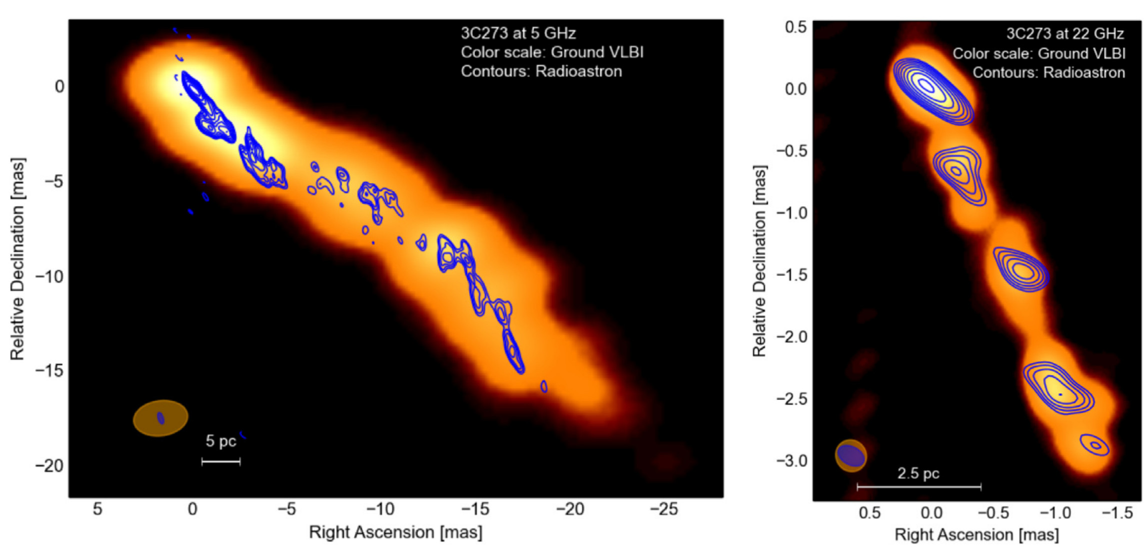

Fig. 3. *RadioAstron* observing results on 3C 273: **Left** April 30, 2014 in C-band. Space-fringes were only obtained for the second half of the observations. The space beam is (632 × 270) µas, 18° and the ground beam is (2880 × 1860) µas, −82°. **Right** April 30, 2014 in K-band. Space-detections are only obtained for one scan. The space beam is (226 × 147) µas, 62° and the ground beam is (260 × 246) µas, 32°. See Vega-García (2018) for more details. The observing beam (bottom left in both panels) follow the same scale as the images: ground array in orange, space-ground in blue. At the distance and with the black hole mass of 3C 273, a resolution of 150 µas corresponds to about 5400 Schwarzschild radii. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

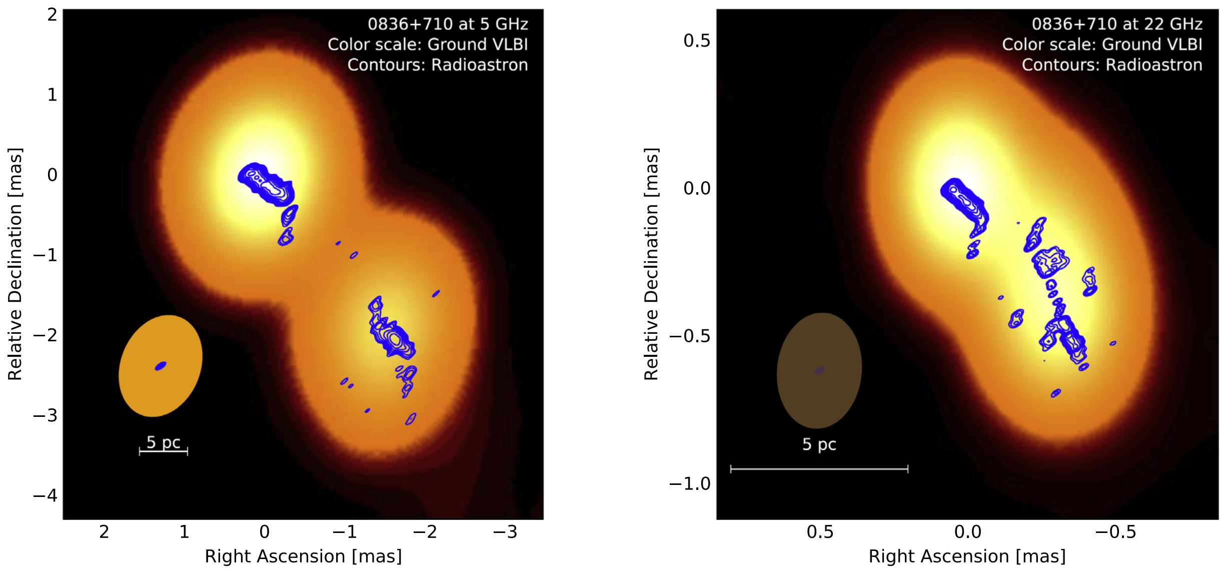

Fig. 4. *RadioAstron* observing results of 0836+710 (4C+71.28): **Left** C-band on January 10, 2014. The space beam is (146 × 56) μas, −54° and the ground beam is (1290 × 975), −22°. **Right** K-band on January 10, 2014. The space beam is (35 × 16) μas, 77° and the ground beam is (388 × 282) μas, −6°. Note the different angular scales covered by the two images. The observing beam (bottom left in both panels) follow the same scale as the images: ground array in orange, space-ground in blue. At the distance and with the black hole mass of 0836+710, a resolution of 15 μas corresponds to about 1 300 Schwarzschild radii. See Vega-García (2018, submitted for publication) and Vega García et al. (in press) for more details. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

is presented in detail in Vega-García et al. (submitted for publication).

Estimates of the brightness temperature of the core yield values of $10^{12.6}$ K, $10^{13.8}$ K, and $10^{12.9}$ K at L, C, and K-bands, respectively. A detailed analysis of the ridge-line of the jet, to be presented in Vega-García et al. (submitted for publication) and a forthcoming publication, show that this can be represented by multiple oscillatory modes which can be understood and modelled in the framework of Kelvin-Helmholtz instability developing in the flow (Lobanov and Zensus, 2001; Perucho and Lobanov, 2007; Perucho et al., 2012,). Using this model, a Mach number of ∼12 as well as a jet-to-ambient density ratio of ∼0.33 are estimated.

3. Discussion and summary

The *RadioAstron* KSP targeting jets in strong (bright) AGN has so far focused on observations of the radio jets in 0836+710, 3C 273, 3C 345 and 4C+69.21, with three of these sources also integrated in the target list of the polarisation AGN KSP (Gómez et al., 2018; Bruni et al., 2020). In all of the cases, the *RadioAstron* observations have revealed synchrotron emission with extremely high brightness temperature of the order of 10^{13} K, which would require further detailed investigations of a physical mechanism responsible for such extreme energy release in relativistic jets.

Imaging with *RadioAstron* helps to better model the structure of sources. Concerning 4C+69.21, the spectral index maps and kinematics showed the possible presence of a recollimation shock, which was better located with *RadioAstron*. The source was also checked to verify the findings on high brightness temperature shown by the AGN survey of the mission, being the source with the largest estimated value. 4C+71.28 was observed to continue the instability studies on the source being performed earlier, and to transversally resolve the jet, which was not possible with the VSOP mission; the 22 GHz image provides hints of an asymmetric jet or a bright spine. Concerning 3C 273, the motivation for the observations was to confirm the double-helix structure known since the VSOP mission, this will be confirmed in a coming study based on L-band observations. To conclude, 3C 345 was not successful due to the limited ground-space detections.

The *RadioAstron* observations of 3C 273 and 0836+710 have provided the largest improvement of image resolution and quality in comparison to ground array observations made at the same frequencies. For both objects, the space images show intricate, filamentary structure resolved across the jet on scales at which ground arrays could only see broad features filling the jet. In contrast, the imaging results on 4C+69.21 reveal the inner structure, but without any remarkable features. 3C 345, for which only one space-baseline scan had detections, is being further studied within the polarisation program, with promising prospects of better resolving the innermost jet structure (Pötzl et al., 2018).

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