PROCEEDINGS OF SCIENCE

Rotation Measure studies of the quasar 3C 345 with *RadioAstron*

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A fraction of about 10 % of supermassive black holes in the centres of active galactic nuclei (AGN) produce powerful jets emitting across the electromagnetic spectrum. The formation of jets and what collimates them on parsec scales is still poorly understood and debated to date. Many jet launching scenarios predict the existence of helical magnetic fields in the jet, potentially being one of the jet collimation mechanisms and manifesting themselves in polarisation structure and transverse Faraday rotation gradients. Therefore, studying the magnetic fields on the smallest possible scales in AGN jets can give crucial insight into the physics of jet launching, acceleration and collimation.

This is one of the main aims of the *RadioAstron* mission, which operated from 2011 to 2019. The 10-m antenna onboard the *Spektr-R* spacecraft in a highly elliptical orbit with major axis of 350,000 km was complemented by a ground-array of telescopes, including the EVN, at observing frequencies of 0.32, 1.6, and 22 GHz with full polarisation capabilities.

The powerful flat-spectrum radio quasar (FSRQ) 3C 345 is one of those archetypical AGN that underwent several flaring episodes in the optical, γ-rays and at radio wavelengths. Observed with VLBI over several decades, it shows a compact jet closely aligned with the line of sight, with components exhibiting apparent superluminal motion.

We observed 3C 345 with *RadioAstron* at 1.6 GHz on March 30, 2016, resulting in the highest-resolution image of this source at this frequency to date (see [1]) with a resolution along the jet direction of $\sim$300 μas. In addition to the published results we present studies of the spectral index and the rotation measure in the source. These were obtained with the *RadioAstron* data in conjunction with ground-VLBI data from the same epoch. We test for possible Faraday rotation gradients and study the change of the electric vector position angles.

15th EVN Symposium & User's Meeting,
11-15 July 2022
University College Cork, Cork, Ireland

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1. Background

1.1 The RadioAstron project

Supermassive black holes in the centres of radio-loud active galactic nuclei (AGN) produce collimated relativistic outflows (jets). Very-Long-Baseline Interferometry (VLBI) is a powerful tool to study these objects on milliarcsecond-scales. Space-VLBI observations (including the *Spektr-R* spacecraft) of these objects within the *RadioAstron* ([2]) key science program on AGN polarization provide images at an unprecedented resolution, which enables us to study the magnetic field strength and morphology in the innermost regions of AGN jets. Eleven of the brightest and highly polarised AGN were observed with *RadioAstron* between July 2013 and April 2018 ([1, 3–9]); operations of the spacecraft ceased in 2019.

1.2 Magnetic fields in AGN jets

Many theoretical models of jet launching predict a helical magnetic field (B-field) (e.g., [10], [11]), where an initially poloidal field is wound up by rotation of the accretion flow around the SMBH and/or the SMBH itself. Testing the 3D-structure of the B-field in AGN jets thus sheds light on the nature of jet launching and collimation. While the B-field component projected onto the source plane can be studied by examining the electric vector position angles (EVPAs) of the linearly polarised synchrotron radiation, the line-of-sight component $B_{\parallel}$ can be studied with Faraday rotation, where the EVPAs are rotated by an amount $\Delta\chi$ as a function of wavelength λ, with the Rotation Measure (RM) defined by

$$\Delta\chi = RM \times \lambda^2 = \frac{e^3}{8\pi^2\epsilon_0 m^2 c^3}\lambda^2 \int B_{\parallel} n_e \mathrm{d}s\,,$$

where the integral is over the distance along the line of sight s. Recent studies on a large sample of AGN have shown a tendency for EVPAs to be aligned with the jet in BL Lac objects, with quasars having less of that tendency ([12]). In addition, temporal changes in the EVPAs over time have been observed at both radio and optical wavelengths, as well as tight correlations between the two bands (see, e.g., [13] for a review). EVPAs parallel (i.e., for the optically thin case, B-field orthogonal) to the jet are expected for plane shock waves, where the B-field is compressed along the jet. In addition, interaction with the surrounding medium can cause longitudinal structures of the B-field at the jet edges. This kind of polarisation pattern could also be expected for a helical field that is projected onto the plane of the sky with a relatively small viewing angle in the observer's frame. This scenario can be further tested by looking for Faraday rotation gradients perpendicular to the local jet direction, which has been shown to exists in a number of AGN (e.g., [14–16]). For helical fields, e.g., an EVPA distribution around a centroid is expected as well ([5]).

2. Multi-frequency polarisation observations of the FSRQ 3C 345

RadioAstron observations of the quasar 3C 345 (e.g., [17, 18]) (z = 0.59) at λ = 18 cm took place on March 30th & March 31st 2016, with a ground array of eighteen antennas (VLBA + EVN). We detected ground-space fringes on baselines with lengths up to 9 earth diameters. For details about the calibration and imaging, see [1]). Here, we also use complementary VLBA data at 4.8, 8.4

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from the same epoch and 15.3 GHz data taken within the MOJAVE survey ([21]) 25 days before our observations. For the VLBA data, as for the *RadioAstron* data, we have done the EVPA calibration using single-dish observations close in time with the Effelsberg telescope, and used the AIPS Task `LPCAL` to correct the instrumental polarisation, which has been within 10 %.

3. Results & Discussion

3.1 Spectrum

3C 345 is known to show a shift of the VLBI core with frequency (core-shift; see [19, 20]). Thus, we aligned the obtained images at the different frequencies by convolving them with the 8.4 GHz restoring beam (slightly over-resolving the 4.8 GHz map, but still within reasonable limits of over-resolution, see [22, 23]) and then using a 2D-cross correlation algorithm ([24]) to find the optimal positional shift aligning optically thin regions in the jet. Fig. 1 shows the obtained spectral index map ($S_\nu \propto \nu^\alpha$) between 1.6 and 15 GHz, where the very similar beam sizes allowed us to use almost the same, original beam. This yields the highest-resolution spectral index map of this source at these frequencies to date. It clearly shows the expected partially optically thick core, with the spectral index decreasing along the jet. However, we see a local increase of α at the position of the bright polarisation peak at the map centre. This indicates local re-acceleration of particles, possibly by a shock travelling down the jet. The significance of this local enhancement in α still has to be tested by computing the error map, which includes a proper treatment of the map alignment errors and is deferred to future work. The shock scenario is supported by the EVPAs being parallel to the local jet direction, as depicted in Fig. 2 (left). However, there we have not yet taken into account the apparent Faraday rotation, which is especially significant at the low radio frequencies.

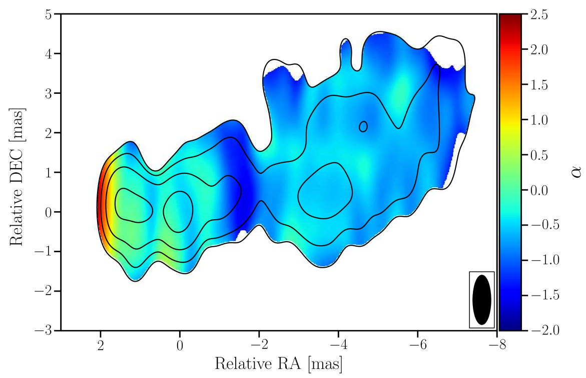

Figure 1: Spectral index map ($S_\nu \propto \nu^\alpha$) between the 1.6 GHz *RadioAstron* and 15 GHz MOJAVE ([21]) image. The optically thick core is clearly visible, and there is a hint of a region of increased opacity close to the emission peak, possibly indicating a shock travelling down the jet.

3.2 Rotation measure and magnetic field structure

After subtracting galactic foreground RM ($18 \pm 0.3\,\mathrm{rad\,m^{-2}}$, [25]), we attempted to fit all four frequencies for RM, using the procedures and error analysis presented in [14], and allowing for several $n\pi$-rotations. However, the regions in the maps with significant polarised intensity differ

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dramatically over the studied frequency range, yielding poor fits. Hence, we just fitted between 1.6, 4.8 and 8.4 GHz, and obtained good results. The resulting RM map can be seen in Fig. 3. Overall, the rotation of the EVPAs is dominated by the foreground RM, resulting in an apparent rotation of the EVPAs closer to perpendicular rather than parallel to the jet. This can be seen by comparing the jet ridgeline with the EVPAs in Fig. 2. The ridgeline has been computed by taking the maxima of Gaussian profiles fitted to the jet emission in vertical slices along the jet axis in x-direction.

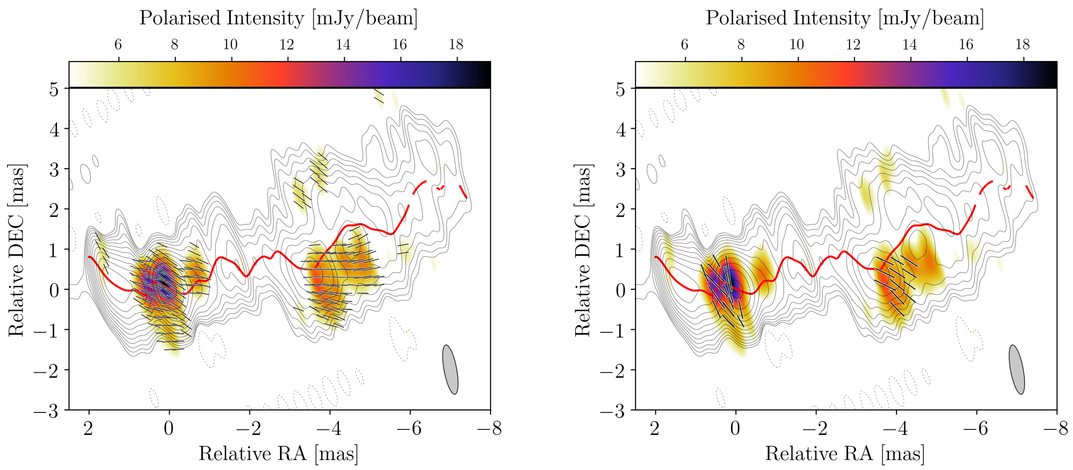

Figure 2: *Left*: 1.6 GHz linear polarisation maps with EVPAs seemingly aligned with the local jet direction (indicated by the jet ridge line in red), uncorrected for RM. The fractional polarisation at the peak brightness location (map centre) is about 5 %. *Right*: Same map with EVPAs corrected, where significant RM fits have been calculated.

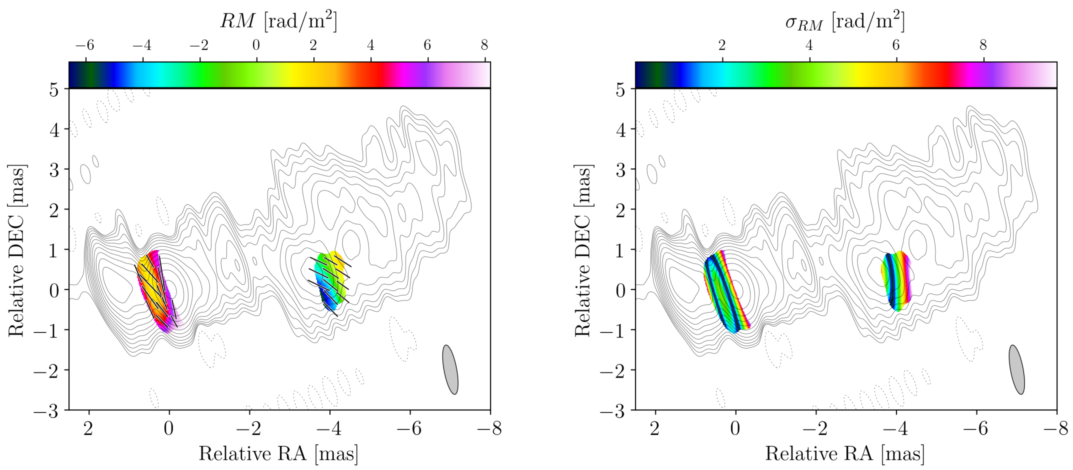

Figure 3: RM (error) map on the left (right) obtained from the 1.6, 4.8 and 8.4 GHz polarisation map, overlaid onto the original 1.6 GHz *RadioAstron* map. There is an indication of a transverse RM gradient, hinting at a toroidal B-field, but it is not yet detected with clear significance.

The interpretation of such a B-field structure is not straightforward. In [26], they found a

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conical recollimation shock in 3C 120, where the EVPAs were oriented perpendicular along the conical shock front. For a plane shock wave travelling down the jet, parallel EVPAs are expected. The connection with shocks in the jet plasma may still be valid here, in the sense that the B-field uniformity is enhanced by compression. A likely explanation for our observations would be severe projection effects on a plane shock wave that is travelling on a helical path along the jet. A helical jet structure would be expected for a precessing accretion disk or a binary black hole system, which has been suggested for 3C 345 ([27]). However, this remains speculative and needs further investigation.

We see indications of a transverse gradient in RM in the jet, close to the location of peak brightness. The significance is calculated as $(RM_1 - RM_2)/(\sigma^2_{RM_1} + \sigma^2_{RM_2})^{0.5}$, where the indices 1 and 2 denote the two edges of the transverse RM slice. We estimate that the gradient could be significant within ~2.5 σ, but this needs further scrutiny dedicated to future work. The potential RM gradient indicates also a toroidal B-field, that might be part of a helical one, as has already been shown to exist in many AGN jets at lower resolution (e.g., [16]). The sample in [16] also includes 3C 345, where a RM gradient was found with a significance of 2.2 σ at ~20 mas from the jet base between 1.4 and 1.6 GHz, notably in the same direction as in this study.

4. Conclusions & Outlook

RadioAstron allows us to study the polarisation properties of AGN at unprecedented resolution, even at low radio frequencies. Combined with ground-array observations at higher frequencies, it even allows the study of RM at ultra-high resolution. Our findings for the quasar 3C 345 suggest that Faraday rotation may significantly change the orientation of EVPAs with respect to the direction of the parsec-scale jet, indicating more a poloidal than a toroidal B-field along the parsec-scale jet.

In order to better understand the results presented here, for the future, we are looking to study more epochs with ground arrays to investigate the evolution of EVPAs and RM with time. If the presumably helical magnetic field traced by the Faraday Rotation is situated in a sheath around the jet or in the jet itself, is another open question for AGN jets. In can in part be answered by studying the degree of depolarisation in dependence of the wavelength and observed RM. This will be studied in a future publication, along with a test of the significance of the tentative RM gradient observed here.

Acknowledgements

The *RadioAstron* project is led by the Astro Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences and the Lavochkin Scientific and Production Association under a contract with the State Space Corporation ROSCOSMOS, in collaboration with partner organizations in Russia and other countries. Partly based on observations performed with radio telescopes of IAA RAS (Federal State Budget Scientific Organization Institute of Applied Astronomy of Russian Academy of Sciences). The European VLBI Network is a joint facility of independent European, African, Asian, and North American radio astronomy institutes. Scientific results from data presented in this publication are derived from the following EVN project code(s): GG079A. Results of optical positioning measurements of the *Spektr-R* spacecraft by the global MASTER Robotic Net ([28]), ISON collaboration, and Kourovka observatory were used for spacecraft orbit determination in addition to mission facilities. The National Radio Astronomy Observatory and the Green Bank Observatory are facilities of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This research has made use of data from the MOJAVE database that is maintained by the MOJAVE team ([21]). Partly based on observations with the 100-m telescope of the MPIfR (Max-Planck-Institut für Radioastronomie) at Effelsberg. The data were correlated at the DiFX correlator ([29]) of the MPIfR at Bonn. FP acknowledges support by the European Research Council (ERC) under the HORIZON ERC Grants 2021 programme under grant agreement No. 101040021. This research has made use of NASA's Astrophysics Data System. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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