Proceedings of the 16th European VLBI Network Symposium
Ros, E., Benke, P., Dzib, S., Rottmann, I., & Zensus, J.A. (eds.)
September 2nd-6th 2024, Bonn, Germany

Probing the polarized innermost structure of the relativistic jet of 4C +01.28

L. Ricci[1,2], A. Alberdi[3], E. Ros[2], M. Kadler[1], J. Röder[2], F. Rösch[1], F. Eppel[1], M. Janßen[4,2], J. A. Kramer[2], C. M. Fromm[1], and S. D. von Fellenberg[2]

[1] Julius-Maximilians-Universität Würzburg, Fakultät für Physik und Astronomie, Institut für Theoretische Physik und Astrophysik, Lehrstuhl für Astronomie, Emil-Fischer-Str. 31, D-97074 Würzburg, Germany
[2] Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
[3] Instituto de Astrofísica de Andalucía-CSIC, Glorieta de la Astronomía s/n, E-18008 Granada, Spain
[4] Department of Astrophysics, Institute for Mathematics, Astrophysics and Particle Physics, Radboud University, PO Box 9010, NL-6500 GL Nijmegen, The Netherlands

Abstract. The formation of relativistic jets from active galactic nuclei remains a subject of intense debate, despite significant advances. Here, we outline our work on 4C +01.28 (B1055+018), a blazar that shows a relevant correlation between emission at radio and gamma-ray wavelengths, and whose previous very long baseline interferometry (VLBI) observations highlight the presence of a remarkable jet stratification. The latter consists of an inner spine with a transverse magnetic field and a distinct boundary layer - the sheath - with a longitudinal magnetic field. Exploring the properties of this unique jet stratification, alongside the jet magnetization on sub-parsec and parsec scales, is key to unlocking the secrets of the jet launching mechanisms in such a source. The VLBI images of 4C +01.28 at various frequencies, including new 86 GHz GMVA and 230 GHz EHT observations, in combination with relativistic magnetohydrodynamic numerical simulations, offer an excellent opportunity for testing state-of-the-art models of jet formation.

1. Introduction

The formation of relativistic jets from active galactic nuclei (AGN) is a topic that has driven intense scientific effort for several decades. While many secrets of these exotic and powerful objects have been unveiled, many questions remain. The state of the art describes two possible channels to launch the relativistic jets: i) via the Blandford & Znajek (1977) mechanism, in which the outflows are launched by extracting rotational energy from the central supermassive black hole; ii) via the Blandford & Payne (1982) mechanism, in which the jets are launched in the form of winds from the surrounding accretion disk. The fine details of how the two mechanisms act and their interplay are currently under investigation. A common feature of both these models is the relevant role played by the magnetic fields permeating the region. The latter are the means that convey and accelerate the particles outside the central engine. In recent years, many steps forward have been taken in the investigation of the magnetic field properties in jets, both theoretically and in terms of observational aspects. However, a comprehensive and general view of their role is lacking. In particular, it is currently unclear which magnetic field configuration is preferred for sustaining the launching and propagation of relativistic jets. Understanding the strengths of the fields at the jet anchor and the magnetic field geometry, namely toroidal, poloidal, or helical, at the compact jet scales, is crucial to understanding how the Blandford & Znajek (1977) and Blandford & Payne (1982) mechanisms work. To pursue this goal, the theoretical studies need to be compared with the observational results obtained through very long baseline interferometry (VLBI) observations, ideally employing the highest observing frequencies possible to dig as close as possible inside the central engine.

In this context, we are studying 4C +01.28 (B1055+018) a blazar at redshift 0.89 (Jorstad et al. 2017) and optically classified as a flat-spectrum radio quasar (see, e.g., Lister & Homan 2005, Véron-Cetty & Véron 2010)). The source is a highly relevant target for studying the formation of relativistic jets, with a particular focus on their magnetization. Indeed, 4C +01.28 shows a particularly high fractional linear polarization[1], and previous studies highlighted a remarkably interesting polarization structure. From 5 GHz VLBA (plus one VLA antenna) observations, Attridge et al. (1999), constrained a polarization structure which suggests the magnetic fields to be oriented perpendicular to the jet direction along the central spine, and parallel to the jet axis along the external sheath. Such a unique magnetic field structure was later confirmed by Pushkarev et al. (2005), in which a helical or toroidal magnetic field configuration is suggested to be responsible for the observed polarization structure. Our study aims to test the previously described results in a region much further upstream, closer to the jet launching site. We use Global mm-VLBI

[1] See: `https://www.bu.edu/blazars/VLBA_GLAST/1055.html`

array (GMVA) 86 GHz observations to which data from the Event Horizon Telescope (EHT) at 230 GHz will be added in the future. The observational results will be contextualized with the ones from numerical simulations. The BEAM-ME and VLBA-BU-BLAZAR programs provide complementary data at 43 GHz, which are crucial for validating the results from our higher-frequency observations and performing spectral studies, alongside four epochs at 86 GHz.

This manuscript is organized as follows. In Sect. 2 we describe the data sets and the methods we use for the data analysis; in Sect. 3 we present our preliminary results; in Sect. 4 we highlight the conclusions and the future prospects of this work.

2. Observational data

As mentioned before, to explore the jet magnetization on small scales, we aim at utilizing the EHT 230 GHz and GMVA 86 GHz observations summarized in Table 1. In several of the available GMVA epochs, 4C +01.28 is used as a calibrator for the main experiment target, OJ 287.

Table 1: VLBI data used in this project

ν [GHz]	Project code	Obs date
86	MA002B	29 Sept 2014
86	MA002C	14 May 2015
86	MM007A	02 Oct 2016
86	MG002	02 Apr 2017
86	MM012	01 Oct 2017
86	MG004	15 Apr 2018
86	MG005A	05 Apr 2019
86	MG006B	25 Apr 2021
230	Multiple	05, 10, 11 Apr 2017
230	E18G27	25–26 Apr 2018

Notes. Summary of the VLBI data considered in this project. The upper lines report the GMVA 86 GHz data while the bottom two lines include the 230 GHz EHT observations. Column 1: observing freq. in GHz; Column 2: project code; Column 3: observation date

Concerning the EHT results, the Gaussian modelfitting from 2017 data will be presented elsewhere, while the analysis of the 2018 EHT observations is in progress. In this regard, particularly important are the quasi-simultaneous GMVA observations (see Table 1), which allow us to compare the jet structure at the two different frequencies and to perform spectral studies. Additionally, the observing epochs of April 2017, 2018, and 2021 are particularly important. Indeed, in such observations, ALMA participated alongside the standard GMVA array. The inclusion of ALMA boosts the sensitivity of such observations and greatly influences the final resolution of the radio images. Given that 4C +01.28 is an equatorial source, the absence of ALMA results in a lack of North-South baselines, leading to a high-elliptical beam with poor North-South resolution. On the contrary, the inclusion of ALMA enhances the North-South coverage, resulting in a quasi-circular beam. Examples of the two different uv-coverages are reported in Figures 1 left and right panels, for the case without and with ALMA, respectively. In this manuscript, we present the 86 GHz total intensity source structure from April 2018 (see next Section).

Moreover, as shown in Rösch et al. (2023), in recent years 4C +01.28 underwent two flaring episodes, in the late 2016 and early 2017. From the analysis of the 43 GHz BEAM-ME observations, Rösch et al. (in prep.) have linked these flares to the ejection of two new components from the radio core following each flare. With the time sampling of the GMVA data, we can explore whether such new components are detected at 86 GHz as well.

2.1. Data reduction

The GMVA data are calibrated using two different approaches. On the one hand, we follow the standard procedure for VLBI data in AIPS (Greisen 1990). On the other hand, we use the CASA-based pipeline rPicard (Janssen et al. 2019). Given that 4C +01.28 serves as a calibrator in many analyzed observations, running rPicard requires some additional steps with respect to the standard procedure. For the complete and detailed overview, we refer to Appendix A in Kim et al. (2023). Among the two sets of calibrated data, we select the one of higher quality for imaging in DIFMAP (Shepherd 1997)). Various factors were considered to determine the best-calibrated dataset for each observation, including the number of flagged data points, the ratio of successful to failed solutions in the global fringe fitting, and the overall phase stability. For the observation reported in Sect. 3, we imaged the dataset obtained with rPicard. Finally, to derive the linear fractional polarization and the electric-vector position angles (EVPAs), we correct for the D-terms using the CASA-based Polsolve pipeline (Martí-Vidal et al. 2021) by using the self-calibrated data. In both the BEAM-ME data and the observations presented in Table 1, the flux density of 4C +01.28 at 86 GHz is notably low, around $\sim (1-2)$Jy. In this proceeding, to reconcile the low fluxes to the higher ones detected in single-dish monitoring [2], we apply a scaling factor to the flux density of the final images. A more refined analysis to reconcile the fluxes is currently under investigation.

To calculate the brightness temperature of the 86 GHz cores (see next Section), we fit the visibilities with circular Gaussian components using the *modelfit* task in DIFMAP. As error, we assume a very conservative value 30% on the flux density, to include the uncertainty arising from the data calibration, imaging, and flux scaling aforementioned, while we assume 20% on the component size. We filter out the core components whose full width at half

[2] https://almascience.eso.org/sc/

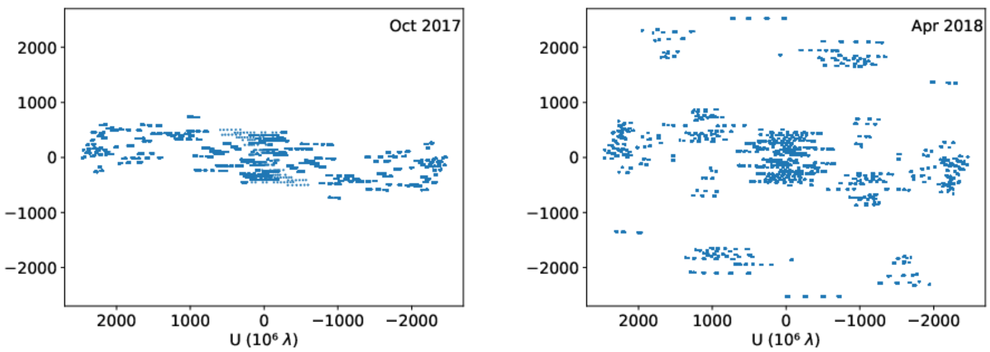

Fig. 1: (u, v)-coverages of two GMVA observations of 4C +01.28. Left panel: Oct 2017 observations, ALMA did not observe; Right panel: Apr 2018 observations with ALMA which highly improves the North-South coverage.

maximum is lower than 20% the minor beam axis since we consider them unresolved.

3. Preliminary results from VLBI observations

In Fig. 2 we show a preliminary total-intensity image of 4C +01.28 obtained from the Oct 2018 86 GHz observational data. As reported in the correlation log, the atmospheric corrections have been applied twice to the ALMA data in this epoch. The correction of this is still going on. Therefore, we only show an image with the ALMA data flagged here. The jet structure seen in Fig. 2 is in remarkable agreement with the 43 GHz simultaneous counterpart observed from the BEAM-ME project. Indeed, the jet points toward West, with an emission gap around ~ -0.7 mas and with a component close to –1.0 mas, which hints at the jet changing direction towards North-West, following the position angle observed at lower frequencies.

To explore the physical properties of the outflows, including magnetization, a powerful indicator is the brightness temperature. The latter is calculated following (see, for example, Kadler et al. 2004)

$$T_{\rm b} = 1.22 \times 10^{12}(1+z)\left(\frac{S_\nu}{\rm Jy}\right)\left(\frac{\nu}{\rm GHz}\right)^{-2}\left(\frac{d}{\rm mas}\right)^{-2} {\rm K} \quad (1)$$

in which z is the redshift, S_ν the flux density, ν the frequency, and d the component full width at half maximum. To calculate the core brightness temperature at the different epochs, we employ the parameters reported in Table 2 extrapolated from the image shown in Fig. 2 and from the 86 GHz observations available in the BEAM-ME program. Consequently, we extrapolate the intrinsic brightness temperature as $T_{\rm b}^{\rm int} = T_{\rm b}^{\rm obs}/\delta$ in which $\delta = \sqrt{(1-\beta^2)}/(1-\beta\cos\theta)$ is the Doppler factor. As viewing angle θ, we use the upper limit of 4 degrees constrained in Rösch et al. (in prep.). In Fig. 3, the orange data points represent the apparent brightness temperature, the blue continuous line the average apparent brightness temperature of the four points shown, and the blue dashed lines show the intrinsic average brightness temperature at increasing jet speed, from $\beta = 0.5$ to $\beta = 0.9$. The dashed horizontal lines highlight the expected values for a jet region in an equipartition state (magnetic vs. particle's energy). From statistical studies, the equipartition brightness temperature is expected to lay around 5×10^{10} K (Readhead 1994), with 10^{11} K as the upper limit (Singal 2009)). The apparent brightness temperature of the 86 GHz core remains relatively constant in the range $(5-10)\times10^{10}$ K, matching the value of the 230 GHz core, $T_{\rm b} = 4.3\times10^{10}$ K , extrapolated from the 2017 EHT observations (Röder 2024). Figure 3 demonstrates that, with a sufficiently high jet speed, the intrinsic core brightness temperatures decrease to values below the expected range for a jet in equipartition, suggesting a magnetically dominated jet. Constraining the jet speed at these scales is, therefore, essential for understanding its properties. In future work, we aim to expand the brightness-temperature profile by incorporating additional 86 GHz observations, along with 43 GHz and 15 GHz data, to provide a comprehensive view of the jet properties on parsec scales.

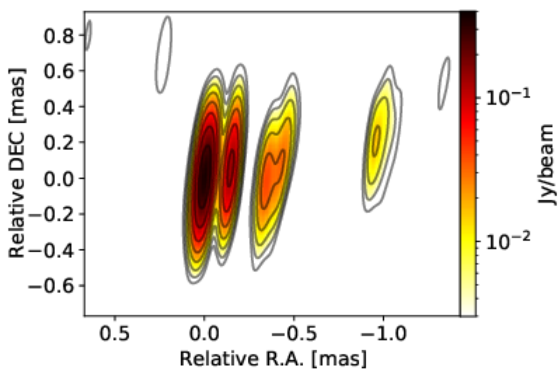

Fig. 2: Stokes I image of 4C +01.28 at 86 GHz from the Apr 2018 observations with the GMVA (ALMA flagged). The contours start at 3σ.

4. Overview and future prospects

In this proceeding, we have highlighted the key points of our project on 4C +01.28, along with some preliminary results. To summarize:

– 4C +01.28, thanks to its exceptional properties, namely high linear polarization and stratified polarized

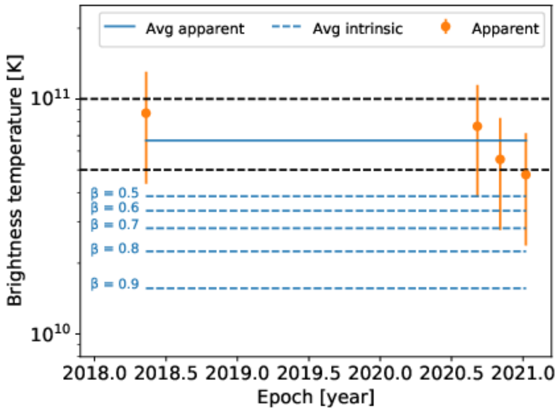

Fig. 3: 86 GHz T_b at different epochs. The horizontal dashed black lines show the expected range of brightness-temperature values for a jet in the equipartition state. The blue continuous horizontal line is the average apparent brightness temperature calculated using the data points shown. The dashed blue lines show the average intrinsic brightness temperature at increasing jet speeds.

Table 2: Parameters of the modelfit components of the cores at 86 GHz

Obs date	S_ν [Jy]	d [mas]
15 Apr 2018	0.6	1.09×10^{-1}
06 Sept 2020	0.8	8.916×10^{-2}
01 Nov 2020	2.1	1.27×10^{-1}
08 Jan 2021	2.2	1.38×10^{-1}
22 Jan 2021	1.1	3.45×10^{-2}

Notes. Column 1: observing date; Column 2: flux density of the core components; Column 3: full width at half-maximum of the core components.

structure, is an excellent laboratory to test the state-of-the-art models concerning jet production in AGN, with a focus on the jet's magnetization.
- To pursue this goal, we employ the large variety of VLBI datasets available for 4C +01.28, with a focus on the 86 GHz GMVA and 230 GHz observations reported in Table 1. 4C +01.28 has been the target of 2018 EHT observations, whose analysis is under way, and was a calibrator source during the 2017 EHT campaign, allowing us to explore the jet structure of such a source at the highest resolution up to date.
- To explore the jet magnetization on compact scales, one of our primary goals is to extrapolate polarization information for our high-frequency data. The jet properties will be constrained by studying the brightness temperature and the spectrum of the radio emission.
- Finally, we aim to compare our observational results with synthetic polarized images obtained by means of 3D relativistic magnetohydrodynamic simulations with different initial conditions, mostly different magnetic field configurations.

Acknowledgements. LR is funded by the Deutsche Forschungsgemeinschaft (DFG, German Research Foundation) – project number 443220636. We thank Dr. J. L. Gómez and collaborators, PIs of multiple GMVA projects in which 4C +01.28 is a calibrator source. This research has made use of data obtained using the Global Millimetre VLBI Array (GMVA), which consists of telescopes operated by the Max-Planck-Institut für Radioastronomie (MPIfR), IRAM, Onsala, Metsähovi Radio Observatory, Yebes, the Korean VLBI Network, the Greenland Telescope, the Green Bank Observatory (GBT) and the Very Long Baseline Array (VLBA). ALMA is a partnership of ESO (representing its member states), NSF (USA) and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan) and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NRAO and NAOJ. This study makes use of VLBA data from the VLBA-BU Blazar Monitoring Program (BEAM-ME and VLBA-BU-BLAZAR; http://www.bu.edu/blazars/BEAM-ME.html), funded by NASA through the Fermi Guest Investigator Program. J.R. received financial support for this research from the International Max Planck Research School (IMPRS) for Astronomy and Astrophysics at the Universities of Bonn and Cologne. This research is supported by the European Research Council advanced grant "M2FINDERS – Mapping Magnetic Fields with INterferometry Down to Event hoRizon Scales" (Grant No. 101018682).

References

Attridge, J. M., Roberts, D. H., & Wardle, J. F. C. 1999, ApJ, 518, L87
Blandford, R. D., & Znajek, R. L. 1977, MNRAS, 179, 433
Blandford, R. D., & Payne, D. G. 1982, MNRAS, 199, 883
Greisen, E. W. 1990, in Acquisition, Processing and Archiving of Astronomical Images, 125–142
Janssen, M., Goddi, C., van Bemmel, I. M., et al. 2019, A&A, 626, A75
Jorstad, S. G., Marscher, A. P., Morozova, D. A., et al. 2017, ApJ, 846, 98
Kadler, M., Ros, E., Lobanov, A. P., et al. 2004, A&A, 426, 481
Kim, D.-W., Lee, S.-S., Hodgson, J. A., et al. 2023, A&A, 680, L3
Lister, M. L., & Homan, D. C. 2005, AJ, 130, 1389
Martí-Vidal, I., Vlemmings, W., & Muller, S. 2021, A&A, 646, A52
Pushkarev, A. B., Gabuzda, D. C., Vetukhnovskaya, Y. N., & Yakimov, V. E. 2005, MNRAS, 356, 859
Readhead, A. C. S. 1994, ApJ, 426, 51
Röder, J. 2024, Doctoral Thesis, Universität zu Köln, `https://kups.ub.uni-koeln.de/73675/`
Rösch, F., Kadler, M., Müller, C., et al. 2022, European VLBI Network Mini-Symposium and Users' Meeting, 2021
Shepherd, M. C. 1997, in Astronomical Society of the Pacific Conference Series, Vol. 125, Astronomical Data Analysis Software and Systems VI, ed. G. Hunt & H. Payne, 77
Singal, A. K. 2009, ApJ, 703, L109
Véron-Cetty, M.-P., & Véron, P. 2010, A&A, 518, A10