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Investigating launching of black hole jets with the combined power of the EVN and the EHT

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Abstract. AGN-launched jets are a crucial element in the study of super-massive black holes (SMBH) and their closest surroundings. The formation of such jets, whether they are launched by magnetic field lines anchored to the accretion disc or directly connected to the black hole's (BH) ergosphere, is the subject of ongoing, extensive research.

3C 84, the compact radio source in the central galaxy NGC 1275 of the Perseus super-cluster, is a prime laboratory for testing such jet launching scenarios, as well as studying the innermost, sub-parsec AGN structure and jet origin. Very long baseline interferometry (VLBI) offers a unique view into the physical processes in action, in the immediate vicinity of BHs, unparalleled by other observational techniques. With VLBI at short wavelengths particular high angular resolutions are obtained.

Utilising such cm and mm-VLBI observations of 3C 84 with the European VLBI Network and the Event Horizon Telescope, we study the magnetic field strength and associated accretion flow around its central SMBH. This is possible, as higher frequency VLBI measurements are capable of peering through the accretion flow surrounding the central engine of 3C 84, which is known to block the line of sight to the sub-parsec counter-jet via free-free absorption. Furthermore, we study the magnetic field's signature in the core region, as manifested in polarised light. As part of this analysis we compare our observations to relativistic magneto-hydrodynamic simulations. Finally, we investigate the effect of instabilities on the shape of the jet's parsec-scale funnel and try to connect them to its historical evolution.

1. Open jet formation questions

Astrophysical jets launched by active galactic nuclei (AGN) are powerful, highly collimated outflows of matter that play a crucial role in shaping the evolution of galaxies and their surrounding environments. They may influence star formation, regulate galaxy growth, and are thought to be able to transport energy over vast cosmic distances, impacting the interstellar, intergalactic, and intracluster media, thus providing insights into the most extreme physical conditions in the universe. The exact mechanisms behind the formation of such astrophysical jets remain elusive. Two leading models, presented in Blandford & Payne 1982 (BP) and Blandford & Znajek 1977 (BZ), offer alternative theories: the former model suggests jets are driven by magnetic fields interacting with accreting material, while the latter model attributes their formation to the extraction of rotational energy from a spinning black hole.

2. A laboratory in space

3C 84 (NGC 1275), the brightest radio source in the Perseus cluster, is a prime laboratory for investigating jet formation due to its proximity and the unique properties of its AGN, thus being a frequent target of monitoring campaigns (e.g. presented in Paraschos et al. 2022). Its jets are relatively young and evolving on observable

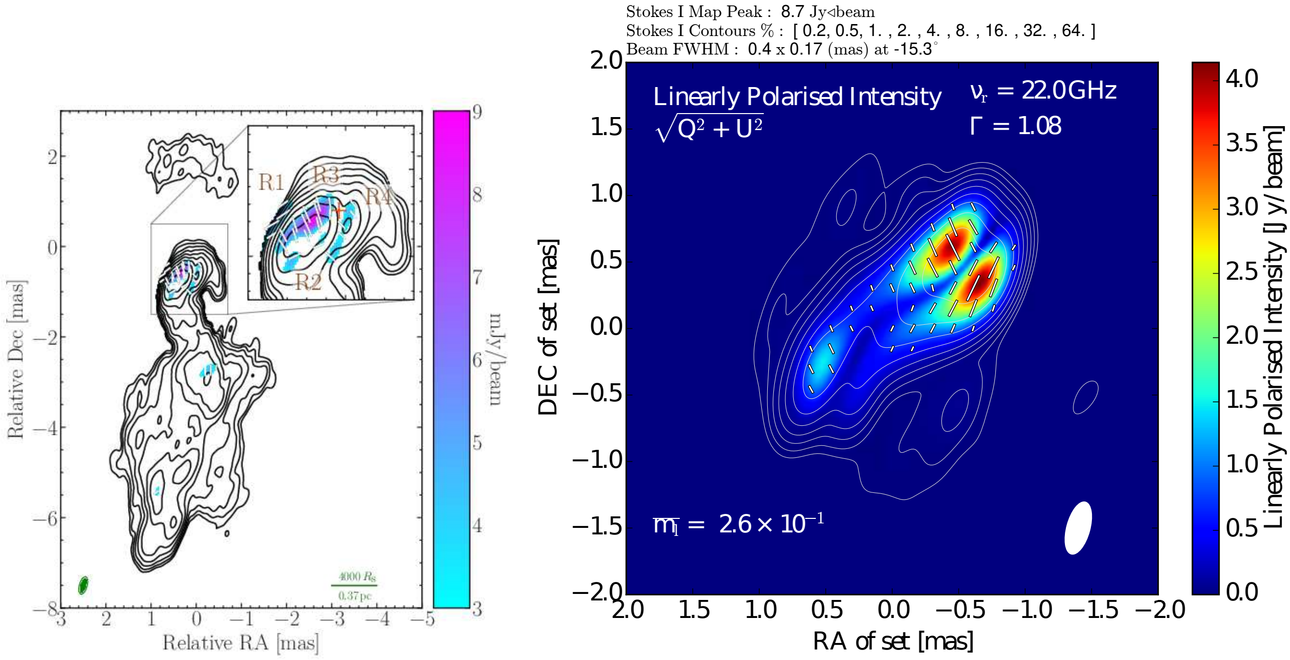

Fig. 1. Observations and simulations of the 3C 84 small-scale jet. Left: EVN image of Stokes I (black contours), polarised intensity (colour scale), and EVPA (white bars) of 3C 84 at 22 GHz. Right: Results from RMHD simulations showing a synthetic intensity map of a ray-traced hybrid fluid-particle jet, moving from north-west to south-east; Stokes I, P, and EVPAs are shown similarly to the observations (as published in Paraschos et al. 2024b).

timescales, facilitating the study of their structure and behaviour. To distinguish between the models describing the launching and collimation of these jets, we rely on very long baseline interferometry (VLBI). VLBI provides the high resolution needed to observe the fine-scale structures in the jet close to the black hole, resolving features that would otherwise be unresolvable. Interestingly, 3C 84 exhibits an elongated structure in the core region, perpendicularly oriented to the bulk jet flow, as revealed by space-VLBI in Giovannini et al. 2018. Attempts have been made to explore this region both spectrally (see, e.g. work by Paraschos et al. 2021) and via magnetic field signatures embedded in polarised light (see, e.g. work by Kim et al. 2019). In the section below we discuss further insights about jet launching, that we gained by using polarised light observations of 3C 84.

3. EVN and EHT synergy

Combining VLBI observations both at centimetre and millimetre wavelengths offers the unique opportunity to study the jet both in the ultimate vicinity of the central engine as well as further downstream in the sub-parsec scales. We achieved this by observing the 3C 84 jet with the European VLBI Network (EVN) at 22 GHz and the Event Horizon Telescope (EHT) at 230 GHz.

3.1. Insights from cm-VLBI and simulations

Our cm-VLBI observations revealed the presence of a double rail structure (also seen in Giovannini et al. 2018) in Stokes I but also in Stokes P deep in the core region (see Fig. 1 left panel). Furthermore, an inner spine is also detected in linear polarisation, at a significance level of 4 σ. Interestingly, this jet stratification is accompanied by distinct electric vector position angles (EVPAs) along the two regions. Specifically, the EVPAs are parallel at the spine to the bulk jet flow and perpendicular to it at the sheath. A fourth region of interest is identified at the north east part of the core, spatially coincident with the area, where the jet is turning downstream. The morphology of the EVPAs there is suggestive of a shock or jet shear.

We also compared our observations with state-of-the-art relativistic magneto-hydrodynamic (RMHD) simulations (see also the work by Kramer & MacDonald 2021, Kramer et al. 2024), which revealed that the observed EVPA pattern is consistent with a helical or toroidal magnetic field configuration (see Fig. 1 right panel). A poloidal field on the other hand did not reproduce the observed geometry. Our RMHD simulations showed that the EVPAs also follow the bulk jet flow at the spine and are orthogonal to it at the limbs when the magnetic field is helical or toroidal. These patterns is also consistent with spine-sheath geometry. A more detailed overview is presented in Paraschos et al. 2024b, on which this subsection is also based on.

3.2. Insights from mm-VLBI

In order to peer even deeper into the core region, we employed mm-VLBI observations of 3C 84, taken quasi-

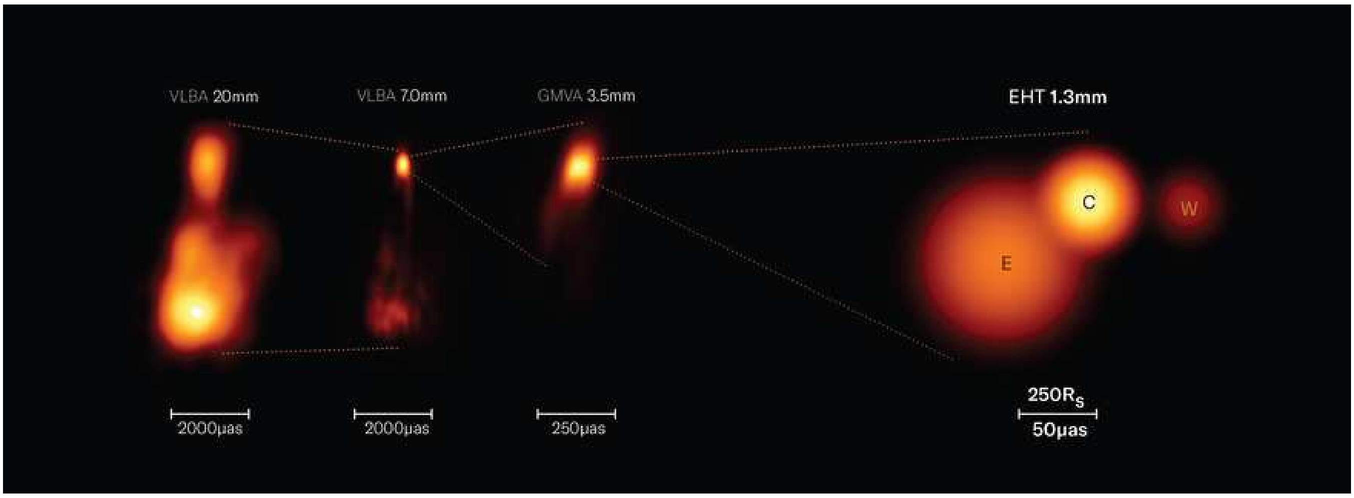

Fig. 2. Jet morphology of 3C 84 shown in total intensity at different wavelengths. From left to right, we show the 15, 43, 86 (images), and 228 GHz (model) measurements (as published in Paraschos et al. 2024a).

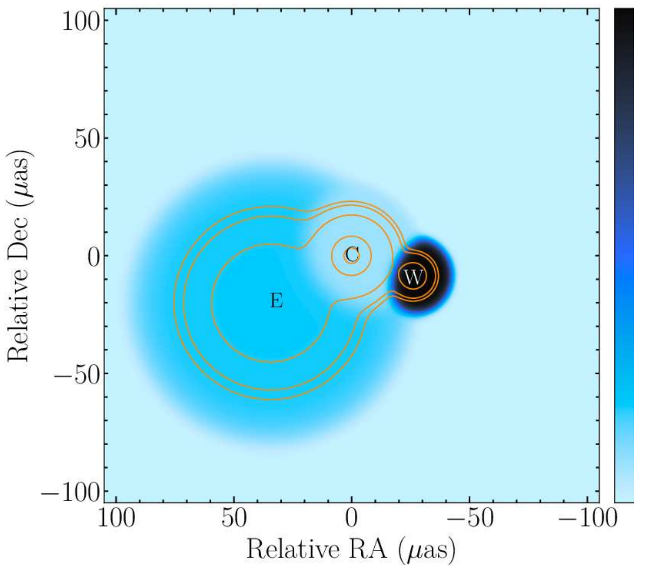

Fig. 3. Fractional polarisation of the EHT data. Shown here is a representation of the best-fit model to the fractional polarisation data in the image plane (as published in Paraschos et al. 2024a).

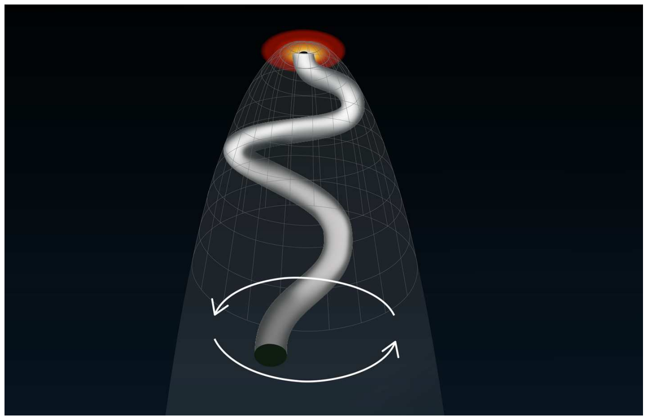

Fig. 4. Sketch of a filamentary flux-tube structure rotating inside a surrounding sheath.

simultaneously with longer wavelength observations (see Fig. 2). At 1.3 mm the core of 3C 84 is best modelled by three components called W, C, and E. As shown in Fig. 3 component C, identified as the core, appears unpolarised. On the other hand, the two components E and W framing it, exhibit high amounts of fractional polarisation (20-80%). Thus, E and W could correspond to the footpoints of the emerging jet.

Additional information can be gathered by leveraging the lower frequency observations to calculate physical quantities such as the Faraday rotation measure, flux density, and mass accretion rate. From these quantities we were able to derive that magnetic field $B \sim 3 - 6$ G and also to show a preference for the spin parameter $\alpha_* = 1$ (corresponding to rapid rotation associated with an advection dominated accretion flow; ADAF), and the dimensionless magnetic flux $\phi \sim 40 - 90$ (indicating a preference for a magnetically arrested disc; MAD). Evidence for the BZ type of jet launching is also found (consistent with Paraschos et al. 2023). A more detailed overview is presented in Paraschos et al. 2024a, on which this subsection is also based on.

3.3. A proposed toy model

A stratified combination of both a BP and BZ jet, consisting of a fast, rotating inner filament and an outer, slower moving sheath could be a potential explanation of the observed phenomenology (see Fig. 4 for a visualisation). This setup could produce the elongated core as a broad jet base associated with accretion disc jet launching, as well as the BZ type characteristics that our polarisation analysis revealed. It would also explain naturally the jet stratification manifested in polarised light in the core of 3C 84 in polarised light. Finally, it could explain the observed moving jet components over the years (see, e.g. Paraschos et al. 2022) and the associated Doppler boosting as elements of the inner spine being aligned to our line of sight during parts of its rotation.

4. Conclusions

Our conclusions can be summarised as follows:

- We found a highly coherent, strong magnetic field around the central SMBH of 3C 84.
- The system indicates a preference for an advection-dominated accretion flow (ADAF) in a magnetically arrested (MAD) state around a rapidly rotating ($\alpha_* \sim 1$) SMBH.
- On a larger scale, we found that the polarised emission in the core region traces the brightened limbs.
- The EVPA orientation suggests a toroidal or helical magnetic field configuration consistent with a spine/sheath geometry.

Our work presented here elucidates the excellent capability of combining cm and mm-VLBI to comprehensively study the jets of nearby AGN at multiple scales in both Stokes I and P.

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