

LETTER TO THE EDITOR

Pinpointing the jet apex of 3C 84

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ABSTRACT

Nearby radio galaxies that contain jets are extensively studied with very long baseline interferometry (VLBI), addressing jet launching and the physical mechanisms at play around massive black holes. 3C 84 is unique in this regard because the combination of its proximity and large super massive black hole mass provides a high spatial resolution to resolve the complex structure at the jet base. For 3C 84, an angular scale of $50 \mu\text{as}$ corresponds to 200–250 Schwarzschild radii (R_s). Recent RadioAstron VLBI imaging at 22 GHz has revealed an east-west elongated feature at the northern end of the VLBI jet, which challenges past interpretations. Here we propose instead that the jet apex is not located within the 22 GHz VLBI core region but more upstream in the jet. We base our arguments on a 2D cross-correlation analysis of quasi-simultaneously obtained VLBI images at 15, 43, and 86 GHz, which measures the opacity shift of the VLBI core in 3C 84. With the assumption of the power-law index (k_r) of the core shift being set to 1, we find the jet apex to be located $83 \pm 7 \mu\text{as}$ north (upstream) of the 86 GHz VLBI core. Depending on the assumptions for k_r and the particle number density power-law index, n , we find a mixed toroidal-poloidal magnetic field configuration, consistent with a region that is offset from the central engine by about 400–1500 R_s . The measured core shift is then used to estimate the magnetic field strength, which amounts to $B = 1.80\text{--}4.0 \text{ G}$ near the 86 GHz VLBI core. We discuss some physical implications of these findings.

Key words. galaxies: individual: 3C 84 (NGC 1275) – galaxies: jets – galaxies: active – techniques: interferometric – techniques: high angular resolution

1. Introduction

3C 84 is a peculiar Seyfert 1.5-type radio galaxy (Véron-Cetty & Véron 2006). It is located relatively nearby, at a distance of 76.9 Mpc ($z = 0.0176$) (Strauss et al. 1992)¹, and harbours a central super massive black hole (SMBH) of $M_{\text{BH}} \sim 9 \times 10^8 M_\odot$ (Scharwächter et al. 2013). This makes 3C 84 a prime target to pinpoint the location of the SMBH and to study the magnetic field in the very inner jet region for this enigmatic radio galaxy. 3C 84 has been studied with centimetre- and millimetre-very long baseline interferometry (VLBI) for decades (e.g. by Walker et al. 1994, 2000; Dhawan et al. 1998; Suzuki et al. 2012; Nagai et al. 2014; Giovannini et al. 2018, and Kim et al. 2019, among others). It features a complex two-sided jet (Vermeulen et al. 1994; Walker et al. 1994; Fujita & Nagai 2017; Wajima et al. 2020), which commonly exhibits moving radio emitting features (blobs) that accelerate with apparent speeds from $\leq 0.1c$ on sub-milliarcsecond (sub-mas) scales to $0.5c$ on milliarcsecond (mas) scales (Krichbaum et al. 1992; Dhawan et al. 1998; Punsly et al. 2021). Bright and fast moving knots have been tracked over the years (Dhawan et al. 1990, 1998), and two components have also been ejected in the southern jet, called C2 and C3 (following the naming convention of Nagai et al. 2014). Recent high-resolution VLBI imaging of 3C 84 with the RadioAstron space telescope has revealed a limb-brightened double-railed jet, possibly anchored in a very wide jet base of $\sim 250 R_s$ diameter (Giovannini et al. 2018). This raises the question of whether

the jet in 3C 84 is launched via magneto-centrifugal acceleration from the accretion disk – the Blandford & Payne (1982) (BP) model – or via energy extraction directly from the ergosphere of the spinning central black hole – the Blandford & Znajek (1977) (BZ) model.

The unknown location of the SMBH in 3C 84 can be estimated by assuming its proximity to the jet apex. The latter can be determined from high-resolution VLBI imaging in the millimetre bands. VLBI imaging at these short wavelengths not only provides a higher angular resolution than in the centimetre bands, but also helps to overcome opacity effects; these effects are caused by the synchrotron self-absorption in the jet and by free-free absorption from the circum-nuclear gas of the accretion flow, which partially obscures the counter-jet and jet base (Walker et al. 1994; Fujita & Nagai 2017; Kim et al. 2019).

Here we present a new study of 3C 84, which measures the VLBI core shift. Such core shifts are also observed in the jets of several other galaxies and blazars (e.g. Lobanov 1998a; Fromm et al. 2013; Hada et al. 2011; Pushkarev et al. 2012; Haga et al. 2013; Park et al. 2021). Active galactic nucleus (AGN) jets emit synchrotron radiation, which is susceptible to synchrotron self-absorption. Synchrotron self-absorption is frequency dependent (Rybicki & Lightman 1979). When the VLBI core is associated with the $\tau = 1$ absorption surface (e.g. Konigl 1981; Lobanov 1998a), its position becomes frequency dependent. The optically thick VLBI core region becomes more transparent at higher frequencies and shifts in the direction of the opacity gradient. For a conical, homogeneous, and straight jet, this opacity gradient points towards the jet apex. With this assumption, the observed

¹ We assume Λ cold dark matter cosmology with $H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_\Lambda = 0.73$, and $\Omega_M = 0.27$.

position shift of the VLBI core can be used to estimate the magnitude and topology of the magnetic field at the jet base (i.e. toroidal vs. poloidal field; see Lobanov 1998b; Hirovani 2005; Vlemmings et al. 2006; O’Sullivan & Gabuzda 2009; Pushkarev et al. 2012; Fromm et al. 2013).

This Letter is organised as follows: in Sect. 2 we briefly summarise the observations and data reduction and then present our spectral and core shift analysis results. We discuss our results in Sect. 3 and present our conclusions in Sect. 4.

2. Data, analysis, and results

In this section we present the 2D cross-correlation analysis used to produce the spectral index maps and core shift. We define the spectral index α as $S \propto \nu^{\alpha}$. The observations were made with the Very Long Baseline Array (VLBA) at 15 and 43 GHz and the Global Millimeter VLBI Array (GMVA) at 86 GHz during the period of 11–18 May, 2015. Total intensity and polarisation imaging results have already been published; for the details we refer to Kim et al. (2019). In this follow-up paper we used the same data but now focus on the spectral properties and opacity shift in the VLBI core region.

Following the analysis presented in Kutkin et al. (2014, and references therein), we computed the core shift and magnetic field strength and estimated the topology of the magnetic field. For the analysis described below, we convolved the maps with a circular beam with a size corresponding to the geometric mean of the major and minor axis of the lower-frequency beam (see Table A.1). After the convolution of each image pair, we selected a region within the optically thin part of the jet for the alignment, for which positions are frequency independent. For the 15–43 GHz pair, we selected region A3, which is around the bright and well-defined component C3 (Nagai et al. 2014), located ~ 2 mas south of the VLBI core (see Fig. 1). For the 43–86 GHz pair, we aligned the maps using region A2, which is located closer to the core (see Fig. 1). A2 is bright enough and well defined, and it also shows a steep spectrum (see e.g. Fig. 1), which justifies our choice.

The next step was to iteratively shift one image against the other in right ascension (RA) and in declination (Dec). For each position shift (i, j) the cross-correlation coefficient was calculated as follows (Lewis 1995):

$$\rho(i, j) = \frac{\sum_{x,y} [f^{\nu_1}(x, y) - \bar{f}_{i,j}^{\nu_1}] [f^{\nu_2}(x - i, y - j) - \bar{f}_{i,j}^{\nu_2}]}{\left\{ \sum_{x,y} [f^{\nu_1}(x, y) - \bar{f}_{i,j}^{\nu_1}]^2 \sum_{x,y} [f^{\nu_2}(x - i, y - j) - \bar{f}_{i,j}^{\nu_2}]^2 \right\}^{0.5}}, \quad (1)$$

where x and y are the pixel indices in the different images, $f^{\nu_1}(x, y)$ is the flux density of the selected feature in the static image at (x, y) , $f^{\nu_2}(x - i, y - j)$ is the flux density of the selected feature in the shifted map (shifted by $x - i$ and $y - j$), and $\bar{f}_{i,j}^{\nu_1,2}$ are the mean fluxes in the selected feature. The maximum $\rho(i, j)$ yields the best shift position. For further details on the method, we refer to Lewis (1995).

We aligned adjacent frequency maps pairwise to avoid artefacts due to the very different beam sizes at 15 and 86 GHz. In order to be as conservative as possible, we used the larger beam size at the longer wavelength (see Table A.1) for the alignment of each frequency pair. At 15–43 GHz, we obtain position shifts of $\Delta\text{RA} = 60 \pm 58 \mu\text{as}$ and $\Delta\text{Dec} = 240 \pm 53 \mu\text{as}$. At 43–86 GHz, we obtain position shifts of $\Delta\text{RA} = 20 \pm 52 \mu\text{as}$ and $\Delta\text{Dec} = 120 \pm 46 \mu\text{as}$. A description of our conservative error

estimation is presented in Appendix A. Table A.2 summarises the results.

We define the core of our images as the brightest and most compact component at the northernmost region of the jet. As a preparatory step for the 2D cross-correlation at 15 and 43 GHz, we fitted circular Gaussian components at 15 GHz to the C3 and core region and determined their relative distance to be 2.24 ± 0.02 mas. We then aligned the 15 GHz and 43 GHz maps by this shift and performed the cross-correlation. At 43 GHz and 86 GHz, the intensity peak is at the northernmost region of the jet and no additional shift is necessary. In this procedure and at all frequencies, we fitted a circular Gaussian to the VLBI core to identify their position shifts from the phase centres, finding $< 16 \mu\text{as}$ offsets at all frequencies (i.e. significantly smaller than the pixel scale and the image shifts). We thus ignore these offsets in the following analysis. The uncertainties of the image alignment for both frequency pairs is further discussed in Appendix A.

Figure 1 (left panel) displays the core shift values as a function of frequency. We used the VLBI core at 86 GHz as a reference, setting its position to zero. The two insets present the distribution of the cross-correlation coefficient for the 15–43 GHz pair (left) and the 43–86 GHz pair (right).

We then used this map alignment to calculate the spectral index distributions. In Fig. 1 (right panel) we show the spectral index maps at 15–43 GHz and at 43–86 GHz. The northern side of the core region exhibits an inverted spectral index of $\alpha_{15-43} = 1.0 \pm 0.3$. The α_{15-43} gradually decreases southwards, with a typical value of $\alpha_{15-43} = -0.5 \pm 0.4$ in the C3 region, consistent with past spectral index measurements at lower frequencies (e.g. Unwin et al. 1982; Bartel et al. 1988; Marr et al. 1989; Vermeulen et al. 1994; Walker et al. 1994; Taylor et al. 2006; Wajima et al. 2020).

For the 43–86 GHz pair, we detect a prominent spectral index gradient between regions A1 and A2 (see Fig. 1), from $\alpha_{43-86} = 2.0 \pm 0.5$ in the north-west to $\alpha_{43-86} = -1.0 \pm 0.6$ in the south-east. Details on the spectral index error estimation are given in Appendix A. Based on this, we conclude that the overall trend of the spectral index gradients from inverted in the northern region (A1) to steeper in the two southern regions (A2 and A3) are significant and real. We also note that the apparent difference between the spectral index in the two southern regions (A2: $\alpha \sim -1.0$; A3: $\alpha \sim -0.5$) may not be significant, due to residual calibration uncertainties. However, due to the nature of C3 (moving shock) and its interactions with the ambient jet, the flatter spectrum in region A3 is not unexpected (e.g. Nagai et al. 2014).

If the size of the emission region increases linearly with the distance, r , from the core, $w \propto r$, the magnetic field strength and particle density decrease with distance as $B \propto r^{-b}$ and $N \propto r^{-n}$, respectively. The distance between the jet apex and the apparent VLBI core, Δr_{core} , relates to the frequency with a power law of the form:

$$\Delta r_{\text{core}} = r_0 \left(\left(\frac{\nu}{86 \text{ GHz}} \right)^{-1/k_r} - 1 \right) [\mu\text{as}], \quad (2)$$

where $k_r = [2n + b(3 - 2\alpha_{\text{thin}}) - 2]/(5 - 2\alpha_{\text{thin}})$ (Lobanov 1998a), n and b are the particle number density and magnetic field strength power-law indices, respectively, and α_{thin} is the optically thin spectral index. According to the definition of Eq. (2), and using the 86 GHz core as the reference point, we can determine $|r_0|$, which is the distance to the jet apex. To obtain the absolute distances of the 15 GHz and the 43 GHz cores from the 86 GHz core, we added the ΔRA and ΔDec shifts listed

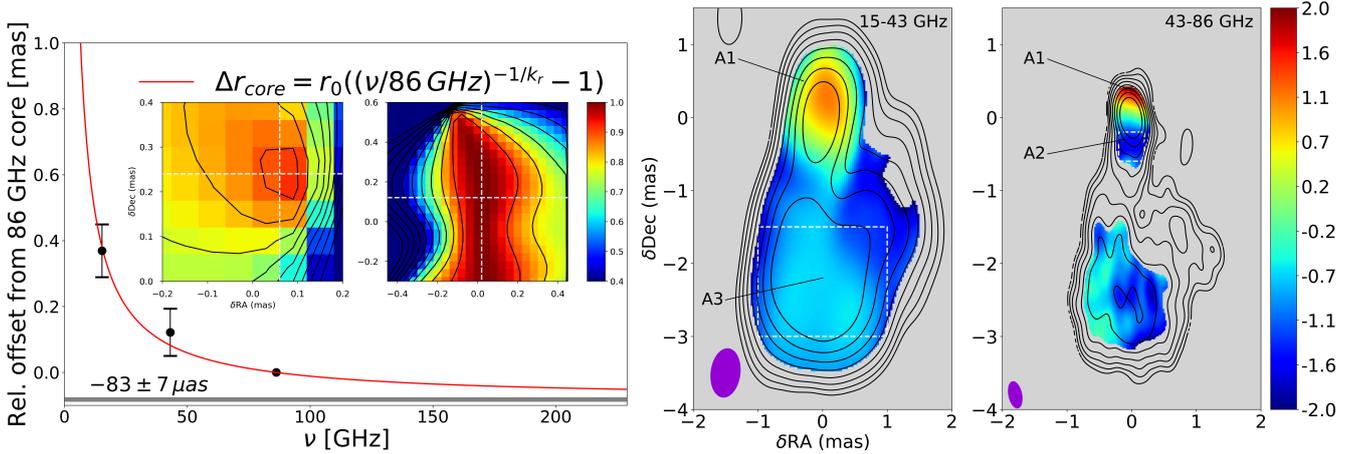


Fig. 1. Core offset position fit and spectral index maps at 15–43 GHz and 43–86 GHz of 3C 84. *Left:* core shift of 3C 84 at frequencies of 15, 43, and 86 GHz. The red line shows a fit of Eq. (2) to the core offset positions (for the numbers, see Table A.3). The shaded grey line denotes the distance from the 86 GHz total intensity peak to the true location of the jet apex. The insets show 2D cross-correlation coefficients of the images at two different frequency pairs. Each axis is in units of mas. The contours start at 1% and increase in steps of 10% relative to the maximum cross-correlation coefficient (0.9975 and 0.9995, respectively). The perpendicular dashed white lines intersect at the maximum of the colour map, which corresponds to the maximum value of $\rho(i, j)$. *Right:* spectral index maps after image alignment. *Left panel:* 15 GHz image in contours and the 15–43 GHz spectral index in colours. The contours start at $4.36 \text{ mJy beam}^{-1}$ and increase by a factor of two. The maps are convolved with a beam of $0.45 \times 0.67 \text{ mas}$, oriented at a PA = -9.44° . *Right panel:* 43–86 GHz spectral index in colours and the contours of the 43 GHz map, which start at $4.26 \text{ mJy beam}^{-1}$ and increase in steps of two. The maps are convolved with a beam of $0.20 \times 0.37 \text{ mas}$, oriented at a PA = 14.1° . We only display regions that have (i) a S/N of at least five for the total intensity contours and (ii) a spectral index in the range -2 to 2 , within 1 rms error (± 0.14 for the 15–43 GHz pair and ± 0.21 for the 43–86 GHz pair), gained from the uncertainty from a region the size of each beam, centred around the core shift location of each frequency (see Appendix A for further details). Boxes marked by dashed white lines correspond to the regions used for the 2D cross-correlation. A1, A2, and A3 are the three characteristic regions where the spectral indices were measured (see Table A.4).

in Table A.2 in quadrature. Table A.3 summarises the resulting positions. The limited frequency range and scarcity of the data points only allow a fit for one free parameter, namely r_0 . We therefore assumed a physically motivated value of $k_r = 1$, as also observed in other VLBI jets (e.g. Lobanov 1998a; Hada et al. 2011; Pushkarev et al. 2012; Fromm et al. 2013). We solved Eq. (2) via the least squares fit method for r_0 . We used the inverse variance of the data for their weighting. From the fit we obtain $r_0 = 83 \pm 7 \mu\text{as}$, which is marked as a grey line in Fig. 1 (left)². This corresponds to a projected distance of $0.030 \pm 0.002 \text{ pc}$, or $413 \pm 34 R_s$ (with the Schwarzschild radius, R_s). Adopting a viewing angle in the range of 20° – 65° (Fujita & Nagai 2017; Abdo et al. 2009), we determine the de-projected distance to be 0.028 – 0.11 pc , or 400 – $1500 R_s$. For the position angle (PA) of the jet apex, we obtain $-20^\circ \pm 14^\circ$ relative to the 86 GHz core position in the image plane. In Fig. 2 we over-plot the core positions at 15, 43, and 86 GHz, as well as the estimated position of the jet apex, on the intensity contours of the 86 GHz map. The estimated position of the jet apex, marked as a filled circle, is located north-west of the VLBI core at 86 GHz.

3. Discussion

3.1. Implications of the jet apex location

Over the years, a variety of interpretations have been proposed to explain the highly complex structure in 3C 84. Based on 22 GHz space-VLBI imaging with $20 \mu\text{as}$ resolution, Giovannini et al. (2018) found an east-west, broadly elongated structure at the

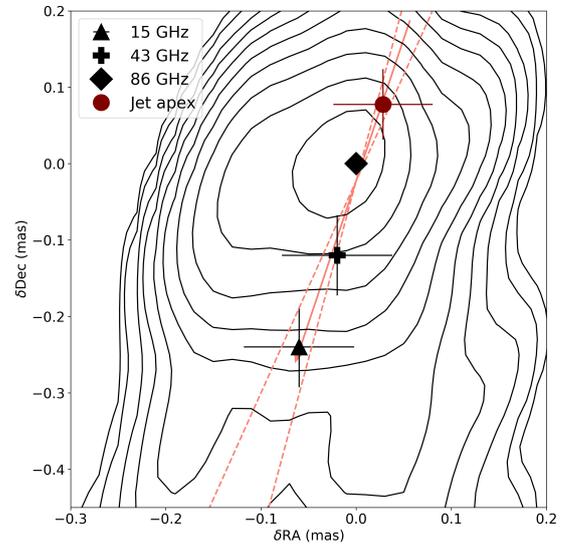


Fig. 2. Core locations at 15, 43, and 86 GHz (black) and extrapolated jet apex location (dark red), plotted over the 86 GHz total intensity map. The contours start at 0.1% of the image peak ($1.82 \text{ Jy beam}^{-1}$) and then increase in steps of two. The solid light red line is obtained from a 2D line fit to the core positions at different frequencies and the jet apex location with respect to the reference point (i.e. 86 GHz core). The broken light red lines show the 99% confidence interval of the fit.

northern end of the jet. The authors suggest that this may correspond to a broad jet apex of $\sim 120 R_s$ width, with some diffuse emission farther to the north, marking the onset of the counter-jet. Our analysis indicates a different scenario, in which the jet apex is located more upstream, at ~ 400 – $1500 R_s$ north-west of

² We note the good agreement with the work of Oh et al. (2021), who find an offset of 54–215 μas from long-term, time-averaged 86 GHz GMVA imaging.

the VLBI core at 86 GHz, as illustrated in Fig. 2. The measured orientation along PA = $-20^\circ \pm 14^\circ$ favours this scenario because it is in line with the direction of the northern counter-jet PA = -25° , as seen on the larger mas scales (Vermeulen et al. 1994).

We point out that on sub-mas scales the northern emission from the counter-jet is not yet unambiguously detected. It is unclear if the emission seen north of the brightest jet components at 43 GHz and 86 GHz belongs to the jet or to the counter-jet. Fujita & Nagai (2017) report the detection of a counter-jet at 15 and 43 GHz in the northern 1–2 mas region. The apparent emission gap between this mas-scale region and the sub-mas-scale region close to the VLBI core (as seen at higher frequencies) may be explained by free-free absorption from optically thick and clumpy gas, for example a torus or accretion flow (e.g. Salomé et al. 2008; Fujita & Nagai 2017; Kim et al. 2019). The highly inverted spectrum ($\alpha_{43-86} \sim 2$ for the core region; see Fig. 1, right panel) could support such a scenario. However, highly inverted spectra (with spectral indices reaching up to $\alpha = +2.5$) are also possible for homogeneous self-absorbed synchrotron emitting components. Depending on homogeneity, the VLBI cores in many AGN jets more typically show inverted spectra with lower indices in the range of 0 to 1.5, though occasional higher values cannot be excluded. Dedicated spectral and Faraday rotation measure-sensitive polarimetric millimetre-VLBI observations in the future could help to clarify the situation.

3.2. Magnetic field strength and topology

Following Lobanov (1998a) and Eqs. (38) and (39) in Fromm et al. (2013), we determined the magnetic field strength in the jet. We assumed a power-law index $k_r = 1$. Details of the procedure and parameter ranges are given in Appendix B. Table B.1 summarises the relevant parameters. For the location of the jet apex with respect to the 86 GHz core ($r_0 = 76\text{--}90 \mu\text{as}$), we computed the magnetic field to be in the range of $B = 1.80\text{--}4.0 \text{ G}$ at the 86 GHz core; this is lower than the magnetic field strength estimate of $21 \pm 14 \text{ G}$ obtained by Kim et al. (2019), where the synchrotron self-absorption formula from Marscher (1983) was used with several assumptions. We followed the literature (Fromm et al. 2013; Kutkin et al. 2014; Lisakov et al. 2017 and references therein) to determine the magnetic field topology and thus assumed a power-law index of $n = 2$ for the radial dependence of the particle number density. From this, we derive $b = 1$ for the power-law index of the magnetic field, which is commonly interpreted as evidence for a toroidal magnetic field configuration.

We note that the above analysis of the magnetic field strength (see also Appendix B) largely relies on the Blandford & Königl (1979) jet model, where the particle number density and the magnetic field strength gradients depend on the shape of the jet (see also Lobanov 1998a). Thus, we can further examine our assumption by adopting a more realistic boundary shape of the jet and checking the dependence of b on n . That is, the radius (or transverse width) of a compact jet, w , depends on the core distance, r . Previous such studies of 3C 84 (Nagai et al. 2014; Giovannini et al. 2018) revealed that, on average, $w \propto r^{0.21}$. Thus, the jet cross-sectional area $A(r) \propto w^2 \propto r^{0.42}$. The total number of particles, N_{tot} , passing through each cross-section is assumed to be conserved. Therefore, assuming a slab of width dr , the total number of particle $N_{\text{tot}} \propto N(r)A(r)dr^3$ needs to be

constant, where $N(r) \propto r^{-n}$. This leads to the number density $N(r) \propto A(r)^{-1}$ or $N(r) \propto r^{-0.42}$, and thus we now have $n = 0.42$. We then obtain $b \approx 1.7$, which comes closer to a poloidal magnetic field configuration ($b = 2$). However, the underlying uncertainty in $b \approx 1.7$ could be large due to the $k_1 = 1$ assumption. Future millimetre-VLBI imaging of the electric vector polarisation angle (EVPA) distributions in the core region would independently and directly measure the b parameter.

We also note that the jet apex and the location of the central engine (the SMBH) may not coincide spatially. That is, the jet apex, which is the upstream end of a luminous flow of relativistic plasma, can only be physically associated with the central engine when the jet base emits synchrotron radiation. Therefore, the conversion of the magnetic or Poynting-flux energy into particle energy at the jet base (e.g. ‘magnetoluminescence’; Blandford et al. 2017) must be efficient enough. If this is not the case, the ‘physical’ origin of the jet (the location of the SMBH) may even be located beyond the position of the jet apex derived above.

Blandford & Payne (1982) and Blandford & Znajek (1977) presented two different jet launching scenarios. In the former the jet is powered by magnetic field lines anchored in the accretion disk, while in the latter the magnetic field lines are directly connected to the ergosphere of the spinning black hole. Depending on the chosen value of n , we conclude that the magnetic field configuration is either a toroidal or is of a mixed toroidal-poloidal nature. Such a scenario is also consistent with observational findings, which indicate the presence of toroidal fields in AGN jets from scales of parsecs to kiloparsecs (Molina et al. 2014; Knuettel et al. 2017). Under the assumption of the validity of the Blandford & Königl (1979) jet model, our data suggest that, at a distance of $\sim 400\text{--}1500 R_s$ from the jet apex, the magnetic field configuration is most likely mixed. We note that the initial magnetic field configuration of the BP model is expected to be toroidal, whereas the BZ model predicts a poloidal geometry (Davis & Tchekhovskoy 2020). Therefore, the observed mixed configuration either points to a stratified combination of both the BP and BZ models or to a jet launching process in which the initial field configuration is altered by some internal physical jet processes acting farther downstream, such as developing shocks and/or instabilities.

To date, the magnetic field strength of only a few other nearby AGN has been studied on scales of a few hundred R_s . Baczkó et al. (2016) determined the magnetic field strength of NGC 1052 to be $\geq 100 \text{ G}$ at $\sim 4 R_s$. Kim et al. (2018) computed the magnetic field of M 87 to be in the range of $\sim 60\text{--}210 \text{ G}$ on $\sim 10 R_s$ scales.

Adopting $b = 1$ and extrapolating to $10 R_s$, the magnetic field of 3C 84 is of the order of $70\text{--}600 \text{ G}$ and thus compares well to those in NGC 1052 and M 87. Furthermore, we can extrapolate the B_0 of 3C 84 to a distance of 1 pc from the jet apex, $B_{1 \text{ pc}}$, in order to compare this value to literature results of additional AGN jets from a time when such high spatial resolution imaging was not yet possible. Using $b = 1$, we obtain $B_{1 \text{ pc}}$ to be $60\text{--}180 \text{ mG}$. Pushkarev et al. (2012) obtain $B_{1 \text{ pc}} \sim 400\text{--}900 \text{ mG}$ for a total of ~ 100 jets in quasars and BL Lac objects based on their core shifts. The B field found in 3C 84 is a factor of four to six lower, which may indicate intrinsic differences between radio galaxies and the more luminous quasars and BL Lac objects.

It is interesting to compare our result to the magnetic field strength expected from the total jet power. Using the following equation (see Eq. (8.35) in Ghisellini 2013 and the listed assumptions),

³ We further assume a constant jet speed over the short distance scales discussed in this Letter.

$$B \leq \sqrt{\frac{8\pi P}{A\Gamma^2\beta c}}, \quad (3)$$

where P is the total jet power, β is the intrinsic speed of the jet, Γ is the associated bulk Lorentz factor, and A is the total cross-section of the jet, we can compute an estimate for the magnetic field strength from the total jet power for 3C 84. We note that the equality holds only if the total energy budget of the jet is solely dominated by the magnetic field. [Abdo et al. \(2009\)](#) and [MAGIC Collaboration \(2018\)](#) report a jet power as high as $\sim 10^{44} - 10^{45} \text{ erg s}^{-1}$, stemming from the observed extreme teraelectronvolt γ -ray variability. Thus, for an emitting region the size of the jet cross-sectional area ($\sim 50 \mu\text{as}$), a magnetic field strength of $\lesssim 30 - 60 \text{ G}$ would be possible without exceeding the jet power. Our finding for the magnetic field strength does not exceed this upper limit. The moderately large magnetic field strength from the core shift, in comparison to the upper limit estimated from the jet power analysis, therefore also supports a scenario in which the magnetic field at the jet base is prominent, which, in turn, is in support of magnetic jet launching (e.g. [Narayan et al. 2003](#); [Tchekhovskoy et al. 2011](#)).

4. Conclusions

In this Letter we have studied the spectral index and core shift of 3C 84. Our major findings and conclusions can be summarised as follows.

1. We performed a 2D cross-correlation of the 15–43 GHz and 43–86 GHz image pairs, using quasi-simultaneous VLBI observations from May 2015. The analysis of the core shift reveals that the jet apex is located north-west of the VLBI core at 86 GHz, displaced by 76–90 μas , with the distance from the core as a function of the frequency, following Eq. (2).
2. With the detected core shift and the possible location of the jet apex north of the 86 GHz VLBI core, the east-west oriented VLBI core structure (which is also seen in the 22 GHz RadioAstron map) appears less likely to be the physical origin of the jet. We further note that a location of the true jet apex north of this east-west oriented feature and north of the 86 GHz $\tau \sim 1$ surface would also lead to a smaller initial jet-opening angle (as opposed to the 130° angle that has been suggested by [Giovannini et al. 2018](#)).
3. The new spectral index images at 15–43 GHz and, especially, 43–86 GHz reveal the presence of a strong spectral index gradient in the northwest-southeast direction, with an inverted spectrum of the millimetre-VLBI core ($\alpha_{43-86} \sim +2$). With a synchrotron turnover frequency of $\nu_m \geq 86 \text{ GHz}$, 3C 84 will be a suitable target for VLBI studies at higher frequencies (e.g. with the Event Horizon Telescope, EHT; [Event Horizon Telescope Collaboration 2019](#)).
4. At a de-projected distance of 400–1500 R_s (76–90 μas) from the jet apex, the magnetic field topology is not purely poloidal; a mixed poloidal-toroidal configuration is suggested. This points towards a stratified combination of the BP and BZ models (acting in parallel) or towards an alteration to the initial magnetic field configuration due to some internal physical jet processes acting farther downstream (e.g. developing shocks and/or instabilities).
5. We measure the magnetic field to be in the range $B_0 = 1.80 - 4.0 \text{ G}$ at the jet apex. This value is lower compared to the maximum possible magnetic field strength derived from the total jet power, which is $\lesssim 30 - 60 \text{ G}$. The magnetic

field also compares well with the magnetic field measured in some other nearby AGN, such as M 87 and NGC 1052, and suggests magnetic jet launching.

Overall, our study suggests that the complex nature of 3C 84 can be partially explained by the location of the jet apex being upstream from the VLBI core at 86 GHz. Questions about the nature of the east-west oriented elongated VLBI core, including whether it is a stationary or oblique shock or part of a curved filament in a wider jet channel, still remain open. A broader frequency coverage from quasi-simultaneous observations may be necessary to achieve an improved estimate of the power-law index (k_r) of the core shift. We plan to further investigate, and constrain our results, by employing millimetre-VLBI monitoring observations with the highest possible resolution (EHT, GMVA, Global-EVN) in the near future.

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Appendix A: Error estimation

The total error budget of our cross-correlation analysis depends on the cross-correlation image alignment error (σ_{ccf}), the image parameters, the correlation region, and the rms error (σ_{core}) of the core shift (Lisakov et al. 2017). The image size, convolving beam size, and pixel scale should be varied with frequency. Before we performed a cross-correlation of two images, these three parameters needed to be set to a common value. To consolidate the image parameter differences, we chose the beam size and map size of the lower-frequency map and the pixel scale of the higher-frequency map. We found minor offsets, which were taken as the uncertainties for the image alignment, as described in the next paragraph. The error of the core position (σ_{core}) depends primarily on the maximum resolution, d_{lim} , that can be achieved for a given map, which is given by Eq. (A.1) and taken from Lobanov (2005):

$$d_{\text{lim}} = \left[\frac{16}{\pi} \Theta^2 \ln 2 \ln \left(\frac{S/N}{S/N - 1} \right) \right]^{1/2} \text{ [mas]}. \quad (\text{A.1})$$

Here, Θ is the radius of the circular beam and S/N is the signal-to-noise ratio. For the 15–43 GHz pair, we calculated the S/N from the ratio of the image peak and rms error to be ~ 500 by averaging the S/Ns from the 15 and 43 GHz images. We followed the same procedure for the 43–86 GHz pair and determined the S/N to be ~ 375 . We followed Schinzel et al. (2012) and used Eq. (7) therein:

$$\sigma_{\text{core}} = \frac{\mathfrak{D}}{S/N}, \quad (\text{A.2})$$

where \mathfrak{D} is either equal to d_{lim} or to the central component size, d , if $d_{\text{lim}} < d$. In our case $d_{\text{lim}} > d$, so the first case applied. The final values for the error budget due to the uncertainty of the core position, σ_{core} , are $\sigma_{\text{core}}^{15-43} = 19 \mu\text{s}$ and $\sigma_{\text{core}}^{43-86} = 15 \mu\text{s}$.

Subsequently, we adhered to the following procedure to calculate the cross-correlation image alignment error, σ_{ccf} . First, two of the authors did independent imaging of the three available frequency maps to produce different sets of images. We then aligned them using the similar, though not identical, optically thin regions and observed the difference in the alignment. Then, we used half of the shift differences as the image alignment uncertainty. The resulting uncertainties are $\sigma_{\text{ccf}}^{\text{RA}} = 30 \mu\text{s}$ and $\sigma_{\text{ccf}}^{\text{Dec}} = 30 \mu\text{s}$ in the RA and Dec directions for the 15–43 GHz pair and $\sigma_{\text{ccf}}^{\text{RA}} = 40 \mu\text{s}$ and $\sigma_{\text{ccf}}^{\text{Dec}} = 20 \mu\text{s}$ for the 43–86 GHz pair, respectively. For the final values for each image, we added σ_{core} to σ_{ccf} in quadrature, thus $\sigma_{\text{tot}} = \sqrt{\sigma_{\text{core}}^2 + \sigma_{\text{ccf}}^2}$, and used σ_{tot} to calculate the errors shown in Table A.3.

We also estimated an error budget for our spectral index map by creating spectral index error maps. We used a combination of the image noise uncertainty and systematic amplitude calibration error to derive the error budget, as presented in Eq. (3) of Kim & Trippie (2014). The image alignment uncertainty, as described in the previous paragraph, yields uncertainties of ~ 0.3 for the 15–43 GHz pair and ~ 0.5 for the 43–86 GHz pair. For the 15–43 GHz pair, we find a systematic amplitude calibration error of 0.30 and for the 43–86 GHz pair 0.35; both these values refer to the entire region of emission. Adding these in quadrature produces total error estimates of $\Delta\alpha_{15-43}^{\text{entire}} = 0.4$ and $\Delta\alpha_{43-86}^{\text{entire}} = 0.6$. We also focused on the region around the core, this time examining only an area of the beam size for each pair, centred on the location of the core shift, where we found the spectral index gradient. The 15–43 GHz pair yields a systematic amplitude calibration error of 0.14, and the 43–86 GHz pair 0.21. Adding again

Table A.1. Summary of the image parameters.

Image	Beam [mas, deg]	Pixel scale [$\mu\text{s}/\text{pixel}$]
Figure 1, left	$0.45 \times 0.67 (-9.44)$	30
Figure 1, right	$0.20 \times 0.37 (14.1)$	20
Figure A.1, left	$0.55 \times 0.55 (0)$	30
Figure A.1, right	$0.27 \times 0.27 (0)$	20

Table A.2. Relative core shifts for the low- and high-frequency alignment pairs.

ν_{pair} [GHz]	ΔRA [μs]	ΔDec [μs]
15–43	60 ± 58	240 ± 53
43–86	20 ± 52	120 ± 46

Table A.3. Absolute distances from the extrapolated jet apex.

ν [GHz]	Δr [μs]
15	369 ± 80
43	122 ± 72
86	83 ± 7

Table A.4. Spectral index measurements per region.

Region	α_{15-43}	α_{43-86}
A1	1.0 ± 0.3	2.0 ± 0.5
A2	–	-1.0 ± 0.6
A3	-0.5 ± 0.4	–

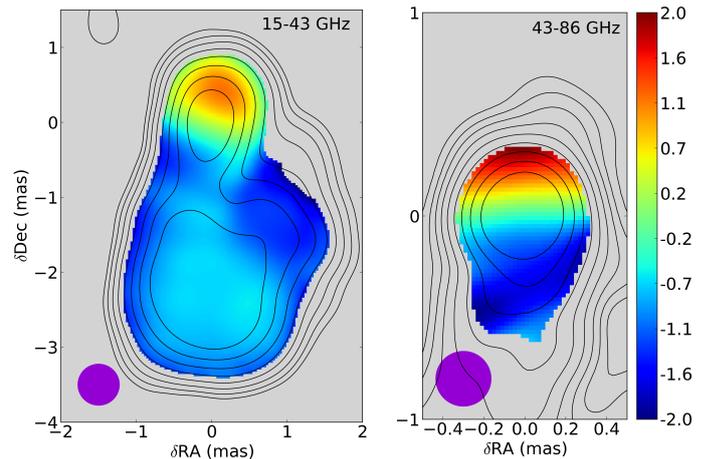


Fig. A.1. Spectral index maps after image alignment, convolved with a beam of a radius equal to the geometric mean of the lower-frequency image map beam (see Table A.1). *Left panel:* 15 GHz image in contours and the 15–43 GHz spectral index in colours. The contours start at $4.41 \text{ mJy beam}^{-1}$ and increase with a factor of two. The spectral index map is convolved with a circular beam of 0.55 mas . *Right panel:* we zoomed in on the nuclear region of the 43–86 GHz spectral index image, shown in colour to better illustrate the spectral index gradient. The contours start at $4.38 \text{ mJy beam}^{-1}$, corresponding to the 43 GHz image, and increase in steps of two. The spectral index map is convolved with a circular beam of 0.27 mas . We apply the same cutoffs as in Fig. 1.

the error from the alignment in quadrature to these values yields total error estimates of $\Delta\alpha_{15-43}^{\text{core}} = 0.3$ and $\Delta\alpha_{43-86}^{\text{core}} = 0.5$. For the three regions, the spectral indices and their errors are summarised in Table A.4.

Appendix B: Magnetic field strength estimation

Table B.1. Fit parameters that appear in the text.

Parameter	Value
k_r	1
r_0	83 ± 7 [$\mu\text{as GHz}$]
b	1
Δr_{core}	$76-90$ [μas]
α_{thin}	-0.77
γ_{max}	10^3-10^5
PA	$-20^\circ \pm 14^\circ$
β_{app}	$0.1-0.2c$
θ	$20^\circ-65^\circ$
ϕ	$2.8^\circ-20^\circ$
Ω_r^y	$1.93-3.95$ [pc GHz]
B_0	$1.80-4.0$ [G]

Following Lobanov (1998a), the core shift (in mas) between two frequencies, ν_1 and ν_2 (in GHz), with $\nu_1 < \nu_2$, can be expressed in terms of the parameter Ω_r^y :

$$\Omega_r^y = 4.85 \times 10^{-9} \frac{\Delta r_{\text{core}} D_L}{(1+z)^2} \left(\frac{\nu_1^{1/k_r} \nu_2^{1/k_r}}{\nu_2^{1/k_r} - \nu_1^{1/k_r}} \right) [\text{pc GHz}^{1/k_r}], \quad (\text{B.1})$$

where Δr_{core} is the core shift in mas, D_L is the luminosity distance in pc, and z is the redshift. We find that $\Omega_r^{15-43} = 2.08 \pm 0.15$ [pc GHz] and $\Omega_r^{43-86} = 3.69 \pm 0.26$ [pc GHz]. For our subsequent analysis, we used a weighted mean of the two, yielding $\Omega_r = 3.10 \pm 0.13$ [pc GHz]. Equation (39) in Fromm et al. (2013), in turn, relates the magnetic field strength at a specified distance (in pc) from the jet base:

$$B_0 \approx \frac{2\pi m_e^2 c^4}{e^3} \left[\frac{e^2}{m_e c^3} \left(\frac{\Omega_r^y}{r_0 \sin \theta} \right)^{k_r} \right]^{\frac{5-2\alpha_0}{7-2\alpha_0}} \left[\pi C(\alpha_0) \frac{r_0 m_e c^2}{e^2} \frac{-2\alpha_0}{\gamma_{\text{min}}^{2\alpha_0+1}} \right. \\ \left. \times \frac{\varphi}{\sin \theta} K(\gamma, \alpha_0) \left(\frac{\delta}{1+z} \right)^{\frac{3}{2}-\alpha_0} \right]^{\frac{-2}{7-2\alpha_0}} [\text{G}], \quad (\text{B.2})$$

with

$$K(\gamma, \alpha_0) = \frac{2\alpha_0 + 1}{2\alpha_0} \frac{[(\gamma_{\text{max}}/\gamma_{\text{min}})^{2\alpha_0} - 1]}{[(\gamma_{\text{max}}/\gamma_{\text{min}})^{2\alpha_0+1} - 1]} \quad (\text{B.3})$$

and $C(\alpha_0)$ being tabulated in Hirotani (2005) and r_0 a fixed distance so that $B = B_0(r_0/r)^b$. We set r_0 to be $76-90 \mu\text{as}$, which is the distance from the 86 GHz VLBI core to the jet apex. Furthermore, γ_{min} and γ_{max} are the minimum and maximum Lorentz factors for emitting electrons, θ is again the jet viewing angle, $\delta \equiv [\Gamma(1 - \beta \cos(\theta))]^{-1}$ is the Doppler factor, $\Gamma = (1 - \beta^2)^{-\frac{1}{2}}$ is the bulk Lorentz factor, and ϕ is the jet half opening angle. For γ_{max} we used the range $\gamma_{\text{max}} = 10^3-10^5$, reported by Abdo et al. (2009), and for γ_{min} we used a low value of 1. The jet speed and apparent jet speed are connected through Eq. (3.37) in Ghisellini (2013). For the jet half opening angle we used the formula $\phi = \arctan(\sin(\theta) \tan(\phi_{\text{app}}/2))$ from Pushkarev et al. (2017), having adopted the apparent opening angle range of $\phi_{\text{app}} = 3^\circ-20^\circ$. For the jet speed near the VLBI core, a typical value range of $\beta_{\text{app}} = 0.1-0.2c$ for 3C 84 (Krichbaum et al. 1992; Dhawan et al. 1998; Punsly et al. 2021) was adopted, with viewing angles in the range $\theta = 20^\circ-65^\circ$, as discussed in Sect. 2. For these parameters we computed the Doppler factor and obtain $\delta \sim 1.18-1.25$. For the optical thin spectral index we estimated α_{thin} based on the flux densities in the radio (Laing & Peacock 1980) and ultraviolet (Bai et al. 2015) bands in the time-averaged spectral energy distribution (SED), obtaining $\alpha_{\text{thin}} \sim -0.77$. This value agrees well with other spectral index measurements of the more extended jet emission in 3C 84 seen at longer wavelengths (e.g. Walker et al. 2000), as well as with our own results for the optically thin jet region on ~ 0.5 mas scales (Fig. 1).

⁴ We set as an upper limit the angle created by the upper and lower limit of the PA of the core shift, as displayed in Fig. 2. For the lower limit we used the full width at half maximum (FWHM) value of the bright component at a distance of ~ 2 mas from the VLBI core, as seen, for example, in Fig. 1.