Jet kinematics in the core of 3C 84

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Abstract

3C 84, the core of the radio galaxy NGC 1275, displays a unique blend of brightness, large BH mass and proximity. Its jet exhibits intermittent activity, offering a distinctive opportunity to study the inner jet and core region with high spatial resolution; down to a ∼200 Schwarzschild radii for the GMVA beam. Recently, a new jet component appeared in the northern core region, which is oriented perpendicularly to the bulk jet flow and is hypothesised to correspond to the physical jet base. Presently, it is unclear if the jet base of 3C 84 is as large as a recent *RadioAstron* image suggested. Our imaging analysis of all recent GMVA/VLBA 3mm/7mm epochs of 3C 84 reveals the same E-W elongation, hinting at a new component ejection. Two are the main interpretations: either the bright components follow a winding path (helical magnetic field lines), or they accelerate along the outer jet sheath (spine-sheath model). Here we explore how this dichotomy ties into the true location of 3C 84's BH.

Introduction

3C 84 is a peculiar Seyfert 1.5-type radio-galaxy (Véron-Cetty et al. 2006), located relatively nearby, at a distance of 76.9 Mpc (z=0.0176) (Strauss et al. 1992). It harbours a central super massive black hole (SMBH) of $M_{BH} \sim 9 \times 10^8 M_\odot$ (Scharwächter et al. 2013), making it a prime laboratory to study the jet kinematics in the ultimate proximity of the central black hole (BH).

3C 84 furthermore features a complex two-sided jet (Vermeulen et al.1994; Walker et al. 1994; Fujita et al. 2017; Wajima et al. 2020), which commonly exhibits moving radio emitting features/blobs that accelerate with apparent speeds from $\lesssim$0.1c on sub-milliarcsecond (sub-mas) scales to 0.5c on 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 an east-west (E-W) elongated structure connecting to a limb-brightened double-railed jet (see Fig. 1 (a)), possibly anchored in a very wide jet base of $\sim 250 R_s$ in diameter (Giovannini et al. 2018). These findings cast doubt on the exact location of the BH. A possible location within/slightly upstream of the E-W elongated structure could perhaps point to a spine/sheath jet scenario (e.g., Pelletier et al. 1989; Komissarov 1990, Pushkarev, 2005), where the jet flow does not display any significant kinks. The competing scenario places the BH on W side of the elongated core, signalling that the jet flow follows an inverted "S" shape, consistent with a bent, helical magnetic field (Gabuzda 2017 and references therein). Fortunately, the unknown location of the SMBH in 3C 84 can be estimated assuming its proximity to the jet apex and then utilising high resolution VLBI imaging in the mm-bands. By following the trajectories of the recently ejected bright components, we illustrate here the two possible scenarios.

Methods

The most recent 86 GHz observations we present here were made with the Global Millimeter VLBI Array (GMVA) at 86 GHz spanning a period between April 2017 and April 2020. The corresponding 43 GHz observations were made with the Very Long Baseline Array (VLBA), spanning a period between April 2017 and October 2020 (Jorstad et al. 2017). We fit circular Gaussian model components (using the task MODELFIT in Difmap) to the total intensity maps to study the kinematics of the jet base. Further details about the total intensity maps and Gaussian model fitting will be presented in Paraschos et al. in prep.

Results

RA map of 3C 84, 43 & 86 GHz contour maps of the VLBI core/jet apex, modelled with circular Gaussian components & illustrations of the possible physical processes

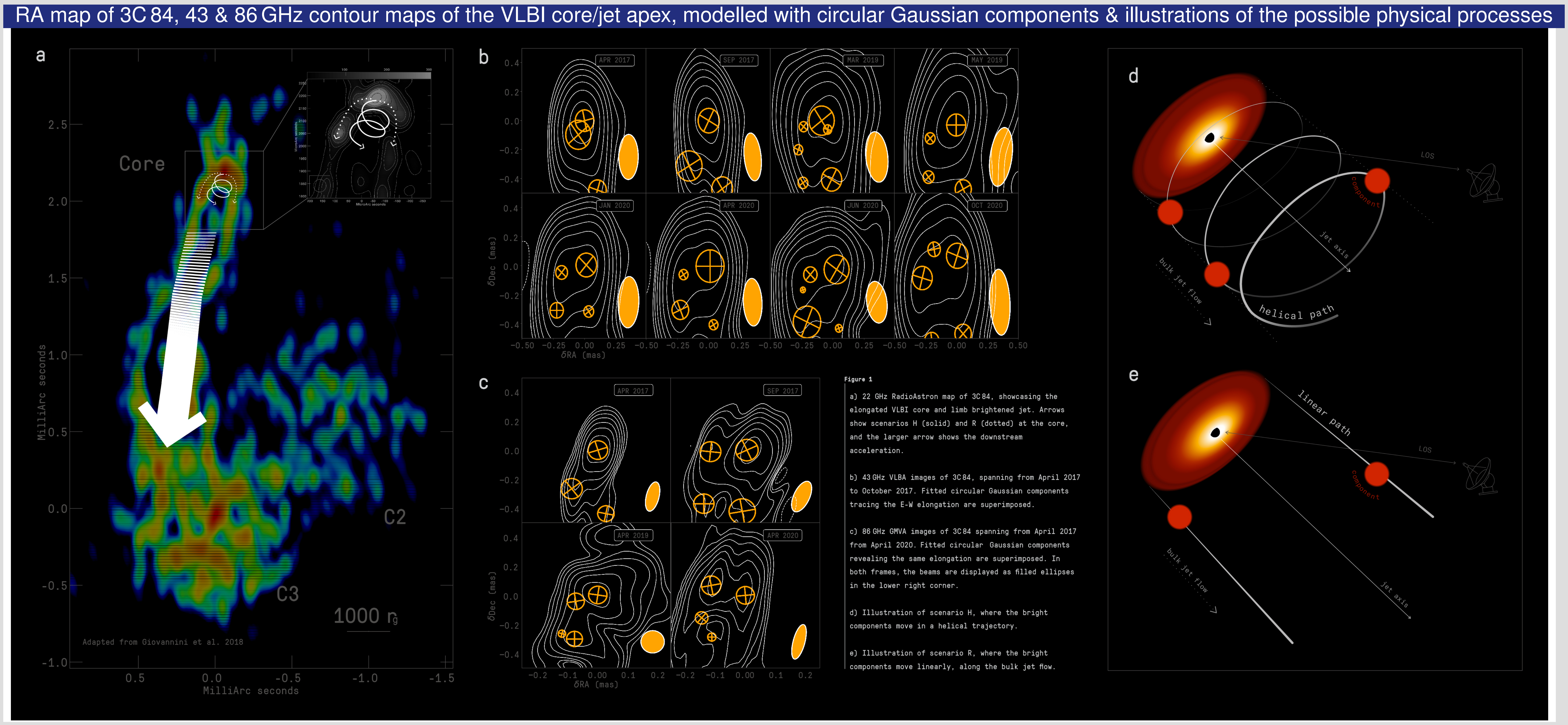

Figure 1

a) 22 GHz RadioAstron map of 3C 84, showcasing the elongated VLBI core and limb brightened jet. Arrows show scenarios H (solid) and R (dotted) at the core, and the larger arrow shows the downstream acceleration.

b) 43 GHz VLBA images of 3C 84, spanning from April 2017 to October 2017. Fitted circular Gaussian components tracing the E-W elongation are superimposed.

c) 86 GHz GMVA images of 3C 84 spanning from April 2017 from April 2020. Fitted circular Gaussian components revealing the same elongation are superimposed. In both frames, the beams are displayed as filled ellipses in the lower right corner.

d) Illustration of scenario H, where the bright components move in a helical trajectory.

e) Illustration of scenario R, where the bright components move linearly, along the bulk jet flow.

Figure 1 (b), (c) displays our analysis of the 43 and 86 GHz observations. Displayed are the contours of the total intensity maps and superimposed are the fitted circular Gaussian components. The most remarkable feature is the emergence and persistence of multiple components in the core regions, in both frequency images, consistent with the analysis of Punsly et al. 2021 (43 GHz), who cover the time range between 2018 and April 2020 and Oh et al. 2021 (submitted, 86 GHz), who cover the time range between 2008 and 2015. The 43 GHz observations, which feature a more complete time coverage, allow for a tracking of the bright components as they move downstream. The four available 86 GHz epochs on the other hand reveal the same E-W elongation and apparent component ejection. Even though the gap between the 2017 and 2019 observations does not allow for a robust cross-identification of the the ejected components, the velocity of the ejected component can be determined. Specifically, the VLBI core ejects components in the E-W direction at (0.03-0.1)c.

Discussion

The two main scenarios for the apparent motion of the bright components, mostly visible in the 43 GHz maps but also detectable in the 86 GHz maps, are summarised in Fig. 1 (d), (e). The apparent motion of the components can be explained as a helical motion tracing the magnetic field lines of the cosmic battery model (e.g., Gabuzda 2017, Contopoulos et al. 2009, Christodoulou et al. 2016). We call this the H model, and the motion of the components is illustrated in Fig. 1 (d). In the H model, the components would follow a mirrored "S" shaped bulk path, with the BH being located in the NW of the VLBI core. The helicity of the path would result in a "zig-zag" projection on the sky plane, which would potentially explain the observations. The observed elongated structure in the RA maps would then possibly be the jet base, but oriented perpendicularly to the bulk jet flow further downstream. The second interpretation (Fig. 1 (e)) is the R model, in which the BH is situated slightly upstream (as shown by the spectral index analysis of the VLBI core by Paraschos et al. submitted) of the E-W elongated structure of the VLBI core. The R model would suggest that this structure is a stationary shock, very close to the jet base of 3C 84, and the bright components move almost entirely downstream, without any kinks or bends in their path. The double railed (limb brightened) structure observed in the recent RA map (Giovannini et al. 2018) would then alternatively be interpreted as a spine/sheath jet (e.g., Pelletier et al. 1989; Komissarov et al. 1990, Pushkarev et al. 2005). In this case the highly relativistic spine is invisible due to extreme Doppler boosting, leaving only the mildly relativistic jet sheath and boundary layer visible to us.

Conclusions

The exact trajectory of motion of the continuously created components in 3C 84's jet base is still unclear and is tied to the true location of the SMBH. Two are the main competing scenarios: the H (helical path) model and the R (spine/sheath) model. In the former the BH is located NW of the apparent VLBI elongated core, revealed in the recent RA map. In this scenario the bulk jet flow follows a mirrored "S" shape, bending southwards within the central 0.1 mas. The components follow a helical trajectory reflected as a "zig-zag" motion in the sky plane. In the latter model, the BH is located purely to the N of the elongated core and the components move in a linear trajectory, free of any major bends, which we observe as the bright jet sheath.

References: • Christodoulou et al. 2016, A&A, 591, A61 • Contopoulos et al. 2009, ApJ, 702, L148 • Dhawan et al. 1990, ApJ, 360L, 43D • Dhawan et al. 1998, ApJ, 498L, 111D • Fujita et al. 2017, MNRAS, 465, L94 • Gabuzda 2017, Galax, 5, 11G • Giovannini et al. 2018, NatAst, 33 • Jorstad et al. 2017, ApJ, 846, 98 • Komissarov 1990, SvAL, 16, 284K • Krichbaum et al. 1992, A&A, 260, 33K • Nagai et al. 2014, ApJ, 785, 53N • Pelletier et al. 1989, A&A, 224, 24P • Punsly et al. 2021, ApJ, 911, 19P • Pushkarev et al. 2005, MNRAS, 356, 859P • Scharwächter et al. 2013, MNRAS, 429, 2315 • Strauss et al. 1992, ApJS, 83, 29 • Vermeulen et al. 1994, ApJ, 430L, 41V • Véron-Cetty et al. 2006, A&A, 455, 773V • Wajima et al. 2020, ApJ, 895, 35W • Walker et al. 1994, ApJ, 430L, 45W

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