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An extensive analysis of the sub-parsec region of 3C 84

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The study of jet launching in AGN is an important research method to better understand supermassive black holes (SMBHs) and their immediate surroundings. The main theoretical jet launching scenarios invoke either magnetic field lines anchored to the black holes's (BH) accretion disc [1] or a magnetic field, which is directly connected to its rotating ergosphere [2].

The nearby and bright radio galaxy 3C 84 (NGC 1275) is a very suitable target for testing different jet launching mechanisms, as well as for the study of the innermost, sub-parsec scale AGN structure and the jet origin.

Very long baseline interferometry (VLBI) – specifically at millimetre wavelengths – offers an unparalleled view into the physical processes in action, in the close vicinity of SMBHs. Utilising such mm-VLBI observations of 3C 84, we study the jet kinematics of the VLBI core region of 3C 84 by employing all available, high sensitivity 3 mm-VLBI data sets of this source. As part of this analysis we associate the component ejection events with the variability light-curves at different radio frequencies and in the γ-rays. Furthermore, by cross-correlating these light-curves, we determine their time-lags and draw conclusions regarding the location of the high energy emission close to the jet base.

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1. Kinematics in the radio source 3C 84

The radio source 3C 84 (NGC 1275; z=0.0176 [3], see Fig. 1) is one of the brightest radio galaxies in the northern sky and a TeV emitter [4]. The relatively large viewing angle (estimated to be $11^\circ - 35^\circ$ [5, 6] in the nuclear region) at which its jet is moving with regard to our line of sight, combined with the subluminal flow speed of its jet features [7–10], allows us to effectively study its jet kinematics, as the Doppler-beaming effect is thus not strong.

In the work, presented in [10], we used over 20 years worth of Global mm-VLBI Array (GMVA) data for 3C 84 at 86 GHz, and, in combination with 43 GHz data [11, 12], we were able to cross-identify at both frequencies and track inside the nuclear region, five jet features, named $F_1 - F_5$. We fitted a linear regression to the VLBI component trajectories, to calculate their velocity and also back-extrapolate their time of ejection. Our work reveals that the features move with velocities up to $\sim 0.1c$ in the nuclear region, that newer components (after 2016) seem to move faster, and that at 86 GHz, the features move at approximately twice the speed as at 43 GHz.

2. Total flux density variability and feature ejection association

Oftentimes, the emergence of VLBI features in AGN-jets can be associated with flares in the radio-bands and in the γ-rays [13, 14]. To test if this is also the case in 3C 84, we compared the temporal point of ejection of the features $F_1 - F_5$ with available radio- and γ-ray light curves (see also Fig. 4 in [10]). In our cross-correlation analysis we employed radio light curves at 4.8, 8.0, and 14.8 GHz, obtained at University of Michigan Radio Observatory (UMRAO), at 15 GHz obtained at the Owen's Valley Radio Observatory (OVRO; [15]), at 37 GHz obtained at the Metsähovi Radio Observatory (MRO), at 230 and 345 GHz obtained with the Submillimeter Array (SMA), and the γ-ray light curve of NGC 1275 (3C 84) at MeV-GeV energies [16, 17]. For a more detailed description refer to [10].

We do not find a clear relation between the ejection times of jet features and flaring activity in both radio- and γ-ray light curves. F_1 and F_2 do not seem to be associated with any activity in the available centimetre radio flux [10]. F_3, F_4, and F_5 on the other hand seem to be associated with radio- and γ-ray flares but it is not always clear if the radio flux is preceding or trailing the γ-ray flux (see top of Fig. 2). Our work is presented in more detail in [18].

3. Light curve cross-correlation analysis

3.1 Core shift

In VLBI images of jets, a compact, non-expanding, bright region, which exhibits a flat spectrum is called the core. The core is thought to be characterised by an optically thick surface [19] and the position of it is thus dependent on the observing frequency (assuming a conical, homogeneous jet, as, for example, described in [20, 21]). This opacity effect, which shifts the apparent location of the core in the sky, is called the core shift [22]. The core shift can be estimated using total variability light curves, as explained, for example in [14, 19, 23] (see also Fig. 2). For our analysis we used the

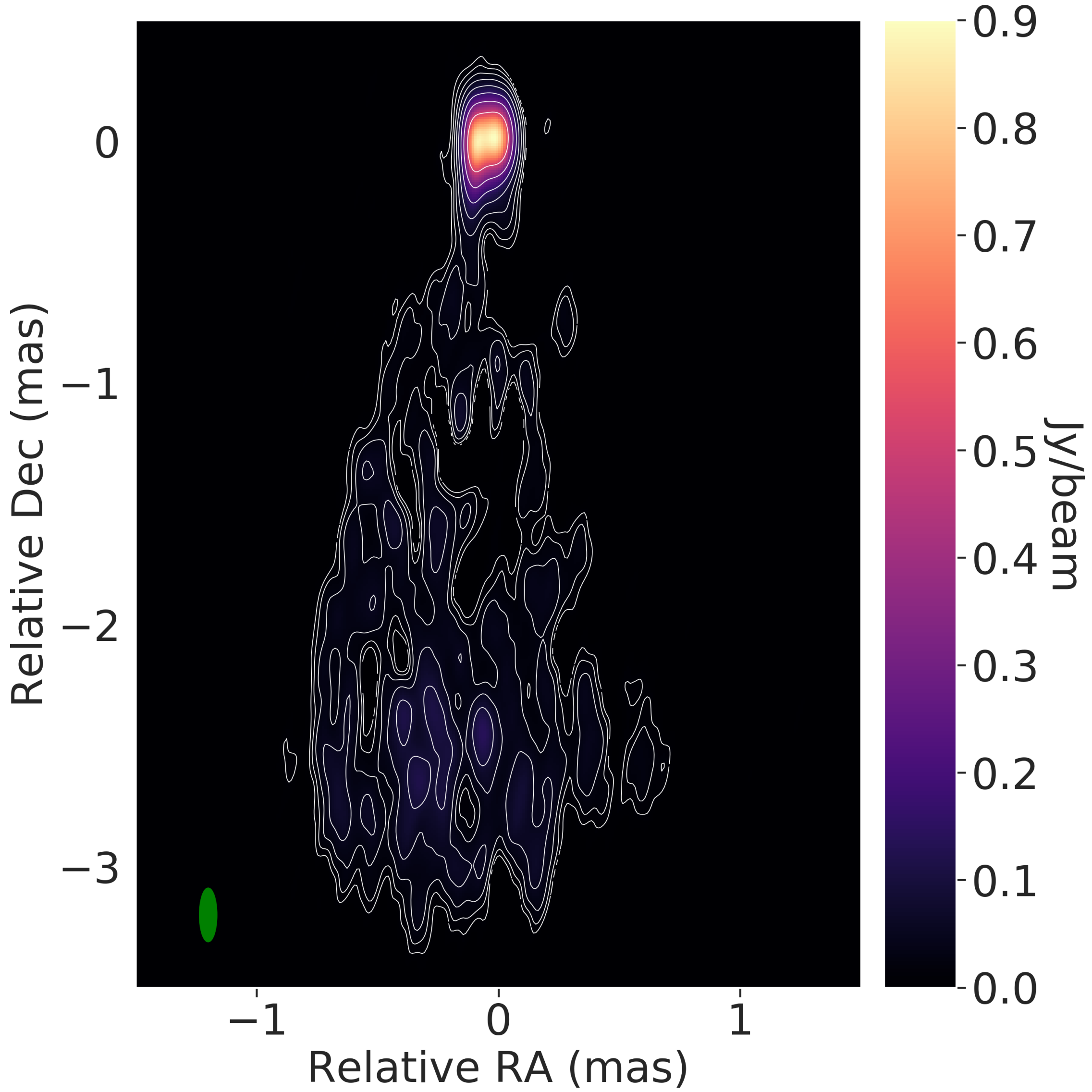

Figure 1: *Stokes I image of* 3C 84 *observed with the GMVA at* 3 *mm in September* 2014. *The core exhibits an elongated region, which is perpendicularly oriented to the bulk jet flow. The contour levels correspond to* (0.005, 0.009, 0.02, 0.03, 0.05, 0.09, 0.16, 0.28, 0.49, 0.88) *Jy/beam. The beam size* (0.22×0.07 *mas*) *is denoted as a green ellipse in the bottom left corner.*

light curves described in Sect. 2 and also added a 91.5 GHz light curve obtained by the Atacama Large Millimeter Array (ALMA)[1].

We used two approaches to cross-correlate the available light curves: 1) the discrete cross-correlation function (DCF) [24], which is a procedure used to measure correlations between data sets with known measurement errors, which can even be unevenly sampled (see also [25–29]); and the so-called 2) Gaussian process regression (GPR) [30], which is a machine learning procedure that utilises a non-parametric approach to data fitting, without prerequisite assumptions about the

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[1] Details regarding the estimation of the flux are presented in the Flux Service of the ALMA Source Catalogue manual.

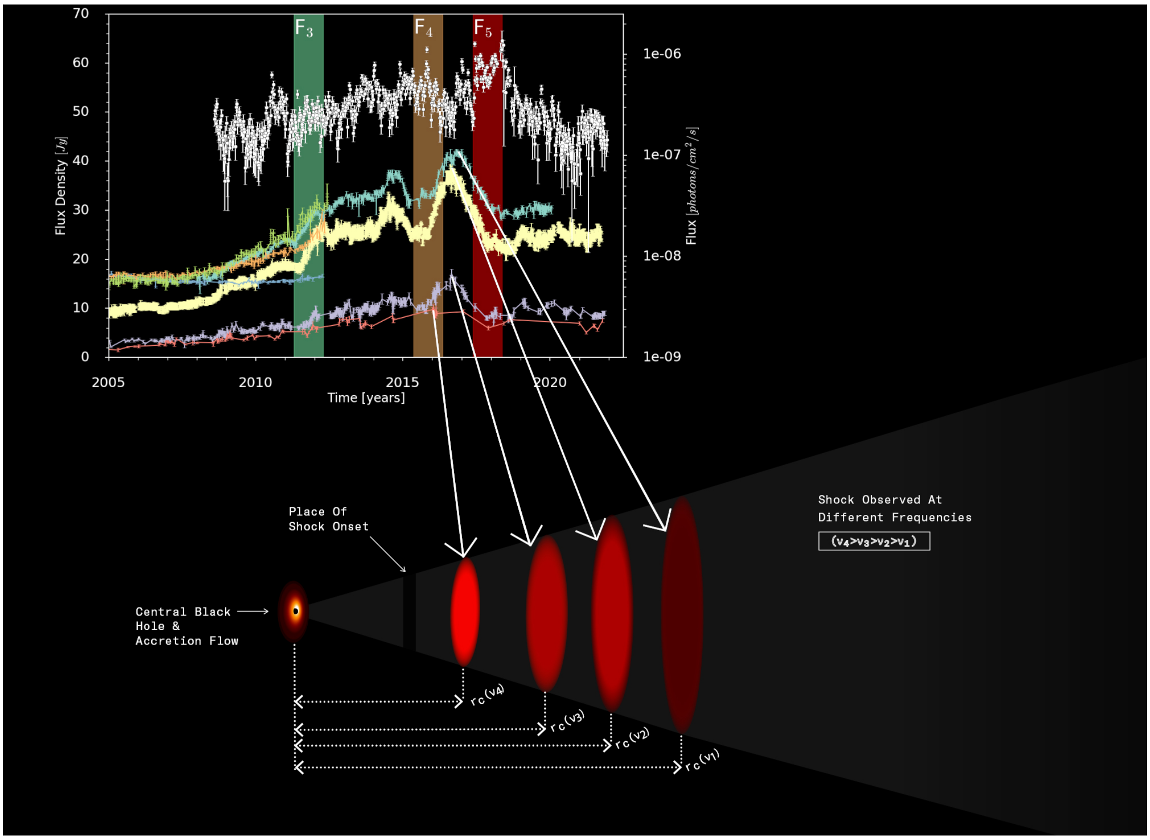

Figure 2: *Illustration of the appearance of shocks in a conical and homogeneous jet* [20] *depending on the observing frequency* $(\nu_1 - \nu_4)$*. The top panel displays (from top to bottom) the light curves at* γ*-rays (white), 15 GHz (light blue), 37 GHz (yellow) 14.8 GHz (green), 8.0 GHz (orange), 4.8 GHz (dark blue), 230 GHz (purple), and 345 GHz (red). The 2016 flare is first visible in the millimetre radio flux and starts getting visible later on downstream in the centimetre radio flux. Arrows are used to guide the eye. The shaded regions denote the temporal points of ejection of the features* F_3*,* F_4*, and* F_5*. The apparent distance of the shock onset* $(r_\mathrm{c}(\nu))$ *from the black hole is denoted with the orange ellipses in the bottom panel. Figure inspired by Fig. 1 in* [19].

fitting function (see also [14, 23, 31, 32]). A detailed discussion about both methods is presented in [18].

We utilised both, the GPR and the DCF method to cross-correlate the radio light curves at each frequency, to its neighbouring frequency (for example 4.8 GHz with 8.0 GHz, 8.0 GHz with 15 GHz, etc.) and from this we calculated the time lags, that is, the time it takes for a flare at frequency ν_2 to appear at frequency ν_1 ($\nu_2 > \nu_1$). We then fitted a power law of the form $\Delta t \propto \nu^{1/k_\mathrm{r}}$ to the averaged time lags acquired with both methods. The fit yielded $k_\mathrm{r} = 1.08 \pm 0.18$. In order to then transform the core shift (see [22, 33] for a detailed description) in physical units of distance, we adopted average component velocities in the nuclear region, in the range of $\beta_\mathrm{app} = 0.03 - 0.12$c. This computation yields distances in the range of $z_{3\,\mathrm{mm}} = 22 - 645$ Schwarzschild radii (R_s) between the jet base and the 3 mm VLBI core. This range is also in agreement with another core shift estimate presented in [6, 34]. The interested reader is referred to [18] for a more in-depth presentation of the analysis.

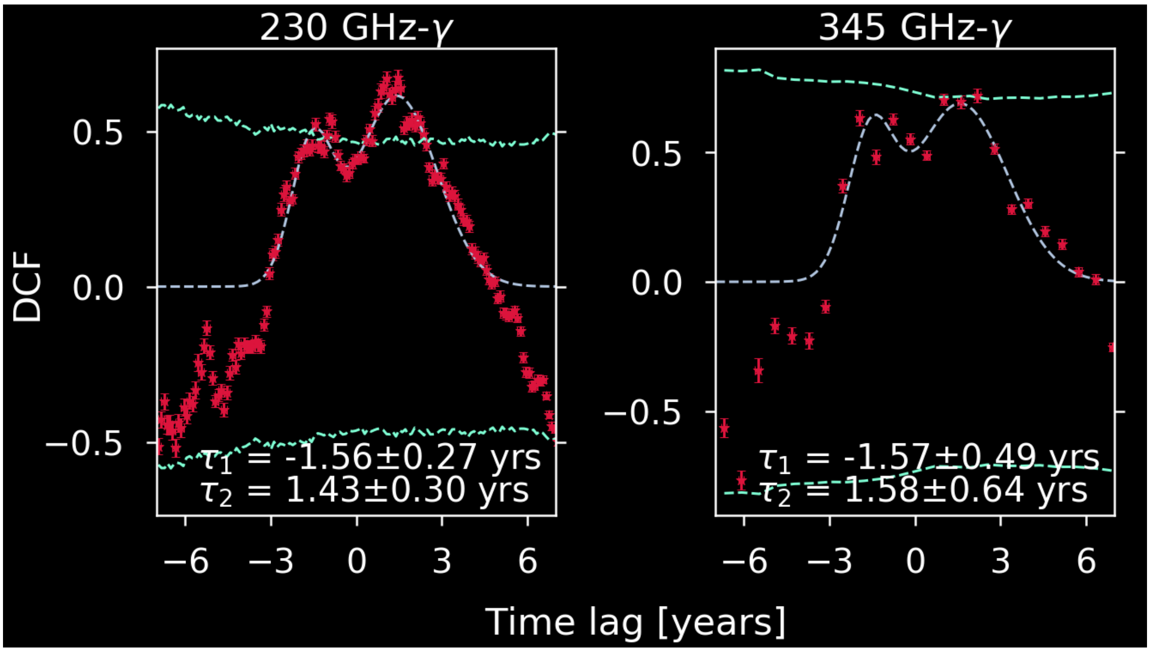

Figure 3: *DCF analysis of γ-ray light curve. Left: DCF of γ-rays versus* 230 *GHz for* 3C 84*. A double Gaussian function (dashed light-blue line) was fit to the DCF, to estimate more accurately the two peak positions (using the means τ_1 and τ_2). The dashed green curve denotes the* 99.7% *confidence band. Right: Same for* 345 *GHz versus γ-rays.*

3.2 Location of γ-ray emission

An open question regarding the jet in 3C 84 is the location of the γ-ray emission within the jet (see, e.g. [35]). Both an upstream [36] and a downstream location [29, 37] of the γ-ray emission site, with regard to the radio emission site, have been suggested.

Using the DCF approach (see Fig. 3), we find that the γ-rays may either precede the 230 GHz flux by $\tau_{\gamma-230\,\mathrm{GHz}} = 1.56 \pm 0.27$ years or trail the 230 GHz flux by $\tau_{230\,\mathrm{GHz}-\gamma} = 1.43 \pm 0.30$ years Since we find positive and negative time lags between the radio emission and the γ-rays (see [18] for a detailed presentation and discussion of the results), this might indicate multiple locations of emission of the γ-rays, both upstream and downstream of the radio emission, depending on individual flares. At 345 GHz we see a similar effect. However, the sparse time sampling of the 345 GHz light curve formally limits the significance of the cross-correlation. Ideas to explain the γ-ray emission invoke an origin in the parsec-scale jet and multi-zone emission [29, 38], or 'mini-jets' [9, 39].

4. Conclusions

We have presented a high-resolution kinematics study of the jet of 3C 84, using millimetre-VLBI observations, and a search for possible correlations with flux density variability in the radio- and γ-ray bands. We find:

1. Jet features move subluminally in the nuclear region of 3C 84 (with apparent speeds up to 0.1c), with newer ejected features moving faster. We find evidence of faster motion (by a factor of two) at 86 GHz when compared to 43 GHz.
2. A clear association between VLBI component ejection and flaring activity is not found. We note that jet component F_4 was ejected at the onset of a radio flare, but component F_5 during a phase of declining radio flux.
3. The jet apex of 3C 84 is located at $z_{3\,\mathrm{mm}} = 22 - 645\,R_\mathrm{s}$ upstream of 3 mm VLBI core, which compares well to previous work [6, 34].
4. The presence of two correlation peaks in the DCF plot of the radio- and γ-ray flux suggests multiple locations of the γ-ray emission region further downstream in the bulk jet flow.

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