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Tracing the peculiar jet kinematics of 3C 454.3

Thalia Traianou[a] [*], Thomas P. Krichbaum[a], Svetlana G. Jorstad[b,c], Alan P. Marscher[b], Carolina Casadio[a], Jae-Young Kim[a], Víctor M. Patiño Álvarez[a], Ivan Agudo[d], J. Anton Zensus[a]

[a] : *Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany*

[b] : *Institute for Astrophysical Research, Boston University, 725 Commonwealth Avenue, Boston, MA 022, USA*

[c] : *Astronomical Institute, St. Petersburg State University, Universitetskij Pr. 28, Petrodvorets, 198504 St. Petersburg, Russia*

[d] : *Instituto de Astrofísica de Andalucía (IAA), CSIC, Apartado 3004, 18080, Granada, Spain*

E-mail: etraianou@mpifr.de

In this work, we employed high angular resolution very-long-baseline interferometry (VLBI) observations in order to study the physical conditions in the jet regions near the central engine for the blazar 3C 454.3. We present preliminary results of the jet kinematics from multi-epoch observations at 43 and 86 GHz (with the VLBA and GMVA, respectively) during the period 2013–2017. We trace a new VLBI component (N) that emerged in Spring 2014. The component shows an untypical behaviour in its velocity pattern with a transition from fast to slow motion. Additionally, the radio flux density light curves at 86 and 229 GHz indicate variability, which is likely related to the appearance and propagation of the new feature in the jet. Polarimetric images at 43 GHz (VLBA) and 86 GHz (GMVA) reveal the polarized sub-structure on sub-pc scales, which can be used to trace the local magnetic field topology and rotation measure.

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1. Introduction

The radio source 3C 454.3 (z=0.859) [5] is a prominent and highly variable flat-spectrum radio quasar (FSRQ). Over the last decade, pronounced correlated multi-wavelength flares over the entire electromagnetic spectrum have been observed. In AGN, such flares are often linked to the appearance and propagation of relativistic shocks along the jet [14, 6]. During the period May-June 2014, the source showed some new flaring, which is seen in the mm-radio and also in the gamma-ray bands (Fig. 1). Millimeter VLBI data in combination with broad-band variability measurements allow us to study such activity in more detail, which should provide further insight into initial jet acceleration and production of gamma-rays. The mm-VLBI data at 43 and 86 GHz enable us to look deeper into the core region and trace the jet closer to its origin. This can help to better locate the gamma-ray emission region and determine its distance from the central engine. Properties of the magnetic field, such as its strength, order and topology, are also imprinted in polarization. VLBI polarimetric observations in the mm-regime therefore provide an opportunity to trace these parameters closer to the region where the jet is launched.
We adopt the following cosmological parameters and the luminosity distance of the source D_L: $\Omega_M = 0.27$, $\Omega_\Lambda = 0.23$, $H_o = 71$ km s^{-1}Mpc^{-1}, and $D_L = 5.489$ Gpc [11].

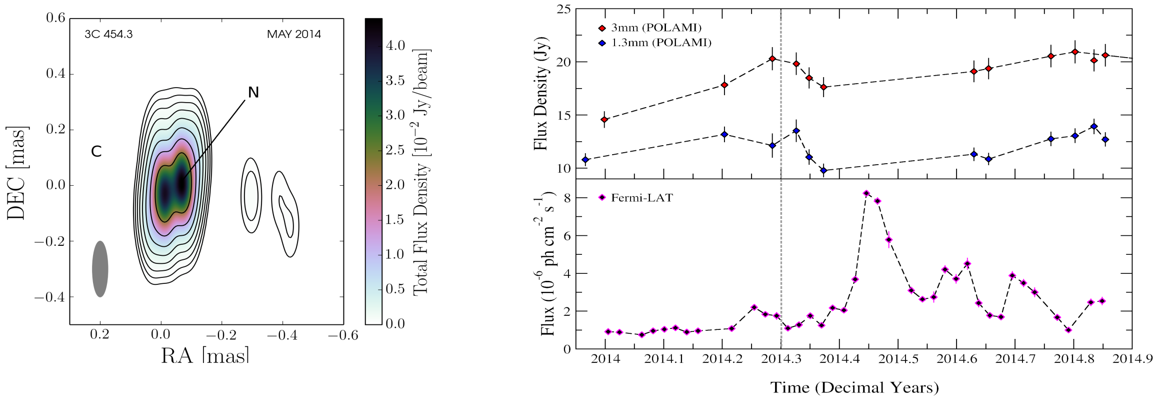

Figure 1: Left panel: Total intensity GMVA image of 3C 454.3 at 86 GHz on May 24, 2014. The restoring beam is 0.27×0.05 mas and the contour levels are 0.25, 0.5, 1, 2, 4, 8, 16, 32, 64 % of the peak (4.28 Jy/beam). Near the bright and unresolved VLBI core (C), a new component (N) is observed. Right panel: Flux density light-curves at 86 and 229 GHz (top) and 7-days binned γ-rays (bottom) during the period 2014-2015. The grey dashed line indicates the ejection time for the component N estimated from a kinematic analysis of the mm-VLBI data.

2. Data Sample

In order to study the kinematics of the inner jet region, we used VLBI data at 86 GHz obtained with the Global Millimeter VLBI Array (GMVA)[1] and 43 GHz VLBA data from the VLBA-BU-BLAZAR program [7]. We combined these data with the γ-ray light curve from the *Fermi* Large Area Telescope (*Fermi*-LAT)[2] observations and radio light curves at 86 and 229 GHz. The latter

[1] https://www3.mpifr-bonn.mpg.de/div/vlbi/globalmm/
[2] https://fermi.gsfc.nasa.gov/cgi-bin/ssc/LAT/LATDataQuery.cgi

result from the POLAMI flux density monitoring program[3] observed by the IRAM 30m Telescope [1, 2].

3. Imaging and Kinematics Analysis

The imaging and Gaussian model fitting of the VLBI data was done using the DIFMAP package (by using its CLEAN and MODELFIT procedures respectively [4]). The goodness of the fit was judged using the reduced chi-square (χ^2_r) [9] and by inspection of the residuals in visibility and image domains. The formal errors for the parameters of the Gaussian components were computed following [8]. Preliminary analysis of the images reveal the appearance of a new moving feature (labeled as N, see Fig 1), which after May 2014 propagates downstream of the jet with an apparent speed of $\beta \simeq (20 \pm 0.84)$ c. This motion continues until the component reaches a radial distance of $\sim$0.6 mas from the VLBI core. After this, its velocity decreases, becoming almost quasi-stationary. At the same time its flux density starts to fade. Previous VLBI studies reported the presence of recollimation shocks in this region [13, 6, 15]. The flux density evolution of the component N at 43 and 86 GHz is displayed in Fig. 2. We note that its flux density remains high and rises until the time when its velocity changes. The right panel of the same figure shows the variation of the radio spectral index. During the observing time period, the spectrum steepens from $\alpha_{43/86\mathrm{GHz}} = -0.4$ to -1.2. This trend is consistent with adiabatic expansion of the emission region [10]. To estimate the ejection time, T_0, of the component N, we linearly back-extrapolated the motion using the component kinematics prior to 2015.5 (i.e., excluding the later epochs when the component slowed down). Accordingly, we obtain $T_o \sim 2014.3 \pm 0.2$ yr.
The flux density light-curves (Fig. 1) reveal correlated variability between radio and γ-rays, with the γ-rays lagging about 2 months behind the mm-radio. Recent studies claim that the high energy emission is located outside of the VLBI core and the broad line region (BLR) [3]. It is therefore tempting to associate the γ-ray activity not directly with the VLBI core but with interaction of the new jet component N with a region in the jet which is located about 2 light-months ($\sim$0.1 mas) downstream of the core. Whether this is related to the presence of a recollimation shock or not remains to be explored.

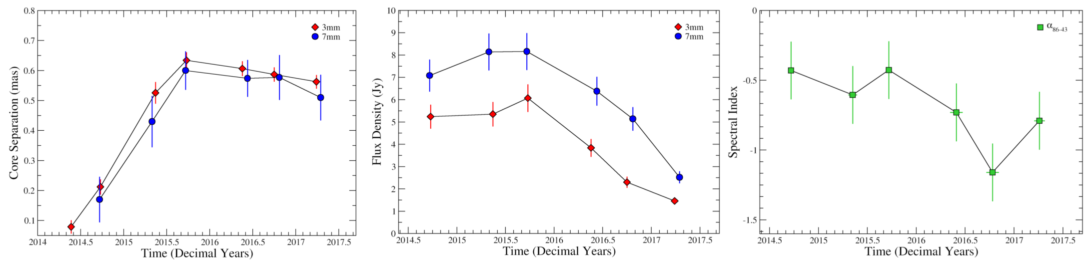

Figure 2: Core separation, flux density and spectral index evolution versus time for the component N over 8 years at 86 and 43 GHz respectively.

[3]http://polami.iaa.es

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4. Polarization Analysis

Figure 3 shows the linear polarization VLBI maps of 3C 454.3 at 43 & 86 GHz (epoch: Sep. 2014). The polarization imaging was performed after correcting the antenna D-terms using the AIPS task LPCAL [12]. For some stations the D-terms amplitudes reached the $\sim 10\,\%$ level. Such high D-terms may limit the dynamic range of the polarization images. At 86 GHz the absolute calibration of the electric vector position angle (EVPA) was obtained by comparing the VLBI EVPAs with close in time single-dish POLAMI measurements of 3C 454.3. From this, we find $\chi = -(35.4 \pm 5.3)^{\circ}$. We used this angle to calibrate the EVPA of the 86 GHz VLBI map. The most prominent polarized features are the VLBI core C and the component N, which are seen in both maps. At 86 GHz, the polarization degree of the VLBI core is $m_p = 25\,\%$ (for $S_{tot} = 5.0$ Jy), while the component N has $m_p = 19\,\%$ (for $S_{tot} = 6.25$ Jy). Similarly high values have been measured at 43 GHz ($m_p = 14\,\%$ for component C with $S_{tot} = 6.3$ Jy and $m_p = 32\,\%$ for component N with $S_{tot} = 9.3$ Jy). Such high fractional linear polarization indicates the presence of well ordered magnetic fields. We also note the very similar EVPA orientation for component C and N at 86 and 43 GHz, which can be used to set limits on the Faraday rotation measure.

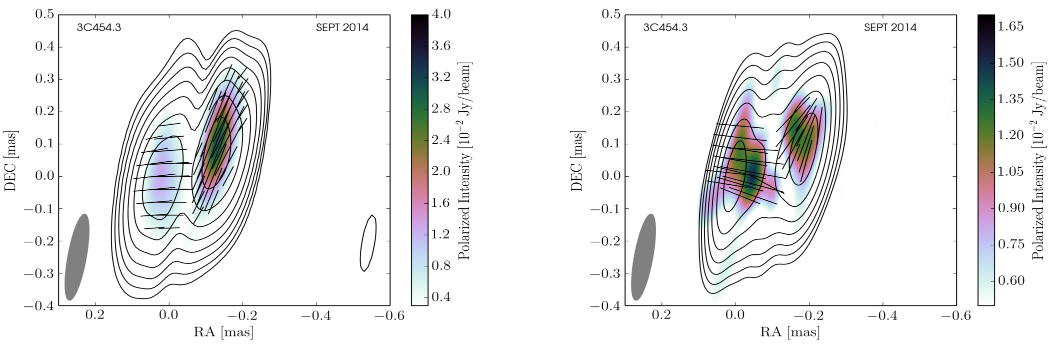

Figure 3: Comparison between polarimetric VLBI maps of 3C 454.3 at 43 GHz (left) and 86 GHz (right) as observed in September 2014. Both images are convolved with a beam size of 0.27×0.05 mas. The contour levels are 0.5, 1, 2, 4, 8, 16, 32, 64 % of the peak (5.22 and 4.51 Jy/beam respectively). The color scale represents the linearly polarized intensity and black sticks denote the electric vector polarization angle. The length of the sticks is proportional to the intensity of the polarized emission.

5. Conclusions

We have detected a new VLBI component N in the jet of 3C 454.3, which appeared early 2014. The jet component is moving with an apparent speed of $\beta \sim 20$ c until it reaches a core separation of $\sim$0.6 mas. Beyond this distance, it became stationary and its flux density begun to decay. Strong polarized emission has been detected from not only the core but also the new component N. Their high fractional polarization suggest well ordered magnetic fields in the inner jet region. The EVPAs of the two polarized sub-components C and N are roughly orthogonal at 43 and 86 GHz. The similar EVPAs at both frequencies suggest only a small Faraday rotation measure.

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