Imaging and variability studies of CTA 102 during the 2016 January γ-ray flare

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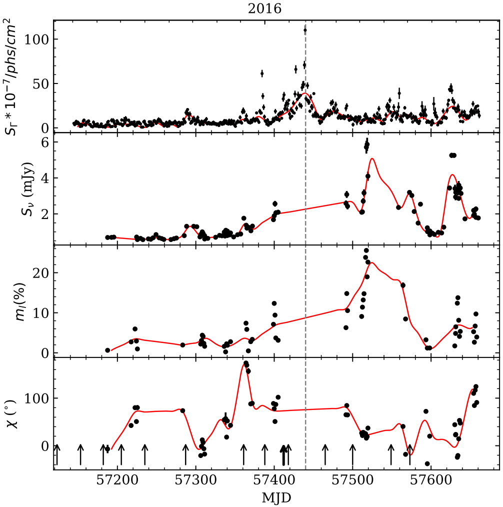
Intro. of CTA 102

CTA 102 ($z = 1.037$) is a flat-spectrum radio-loud quasar (FSRQ) with high polarizaton degree. It is a prominent γ-ray source and detected by Fermi-LAT.
15 GHz VLBA images indicate a twisted morphology with jet bending on a scale of $\sim$20 mas (Kellermann et al. 1998)
The jet knots displaying complex kinematics involving a mixture of apparent superluminal motion and stationary components in multi-epoch 43 GHz observations (Jorstad et al. 2001, 2005).



VLBA observations of CTA 102

Table : Image parameters of VLBA observation

Epoch yyyy-mm-dd (1)	Code (2)	ν (GHz) (3)	S_{tot} (Jy) (4)	rms (mJy) (5)	b_{maj} (mas) (6)	b_{min} (mas) (7)	P.A. (deg) (8)
2016-01-01	BM413M	43	2.7	2.1	0.55	0.18	−12.1
2016-01-25	BA113C	15	2.7	0.4	1.65	0.69	−19.7
2016-01-31	BM413N	43	2.2	1.4	0.34	0.16	−7.2
2016-03-18	BM413O	43	2.4	1.0	0.44	0.18	−5.9
2016-04-22	BM413P	43	2.3	1.0	0.37	0.16	−6.9
2016-06-10	BM413Q	43	3.0	0.7	0.42	0.17	−4.7
2016-07-04	BM413R	43	2.9	0.7	0.45	0.19	−10.8

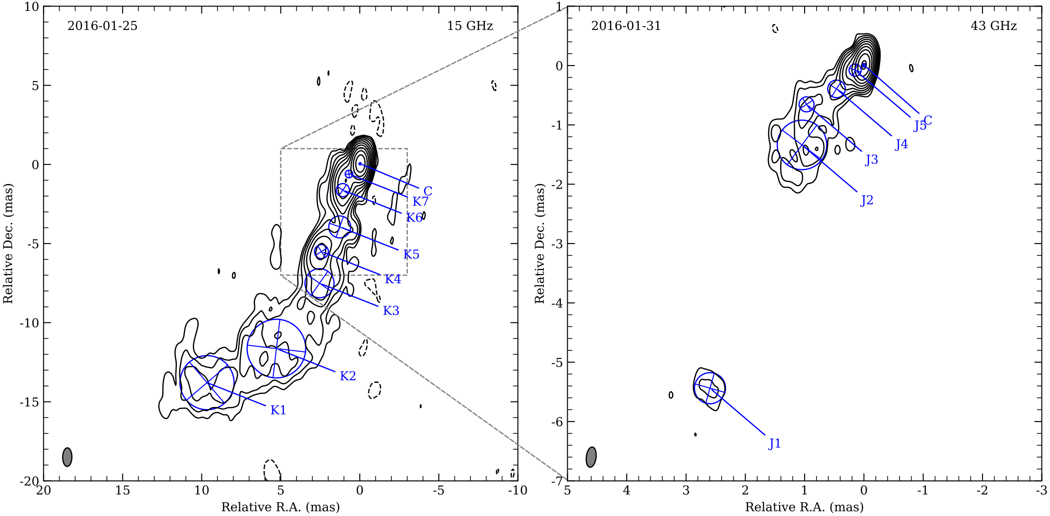
Notes: Columns are as follows: (1) date of observation; (2) VLBA experiment code; (3) observing frequency in GHz; (4) total flux density in millijansky; (5) rms noise level of image; (6) FWHM major axis of restoring beam; (7) FWHM minor axis of restoring beam; (8) position angle of major axis restoring beam in degrees.

Our 15 GHz VLBA observations were carried out on 2016 January 25 (code: BA113; PI: T. An) during the 2016 January γ-ray flare event.

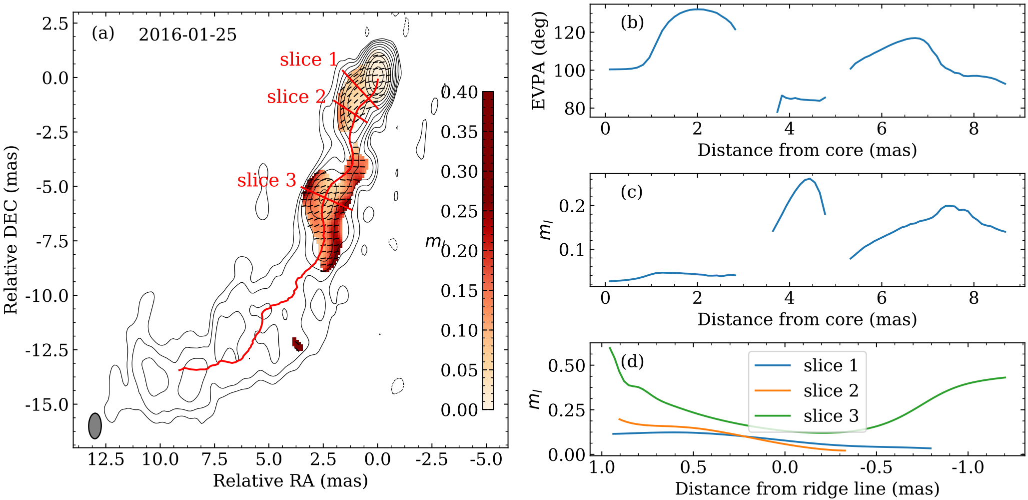
The 43 GHz VLBA data were collected from The VLBA-BU-BLAZAR Program (PI: Alan Marscher,

http://www.bu.edu/blazars/VLBAproject.html).

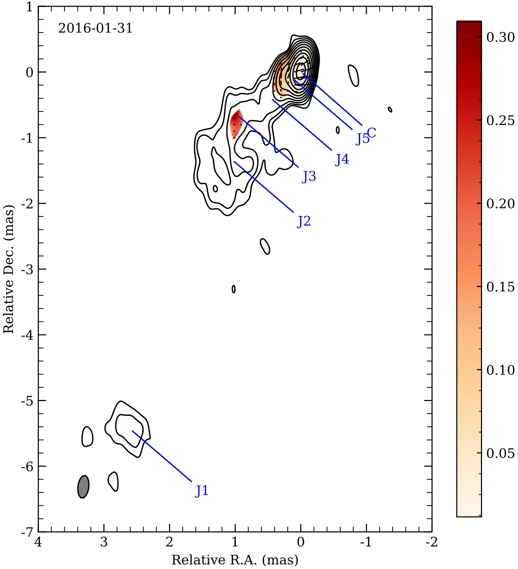
Images at 15 GHz and 43 GHz

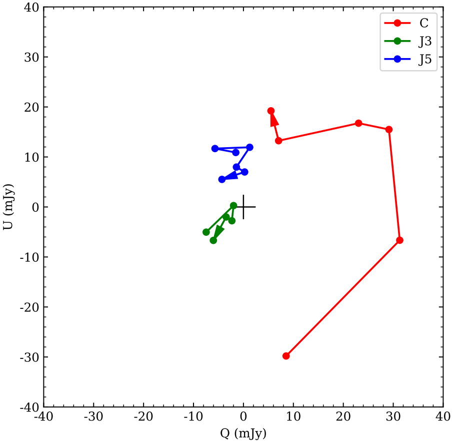


Polarization images at 15 GHz



Polarization images at 43 GHz

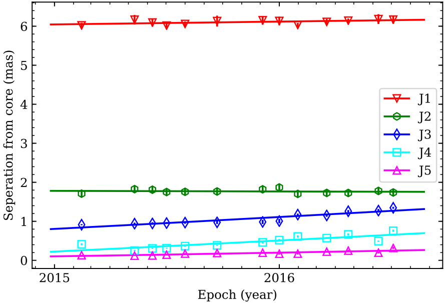




Jet properties

Table : Component kinematics and jet properties from 43 GHz data.

Kinematic quantity	Symbol	Estimate
Component proper motion (mas yr^{-1})	J1	0.07
	J2	0.04
	J3	0.33
	J4	0.30
	J5	0.11
Apparent bulk speed (units of c)	$\beta_{\perp}$	17.5
Intrinsic bulk speed (units of c)	β	$\geq$ 0.998
Bulk Lorentz factor	Γ	$\geq$ 17.5
Position angle	λ	128.3°
Inclination angle	i	$\leq$ 6.6°
Projected half opening angle	ψ	15.6°
Intrinsic half opening angle	θ_0	$\leq$ 1.8°



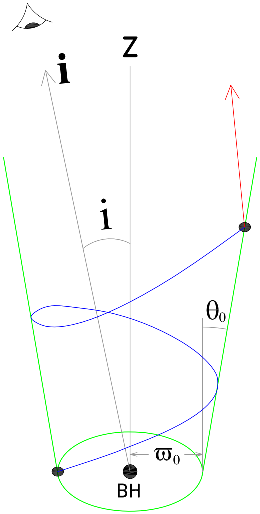
Helical jet model

$$\begin{aligned}
\varpi &= f\left(1+\left(\frac{at+b}{f}\right)^2\right)^{\frac{1}{2}}; \ \dot{\varpi} = \frac{a}{\varpi}(at+b), \\
z &= \frac{\varpi-\varpi_0}{\tan\theta_0}; \ \dot{z} = \frac{\dot{\varpi}}{\tan\theta_0}, \\
\phi &= \frac{1}{\sin\theta_0}\left(\tan^{-1}\frac{at+b}{f} - \tan^{-1}\frac{b}{f}\right); \ \dot{\phi} = \frac{af}{\varpi^2\sin\theta_0},
\end{aligned} \tag{1}$$

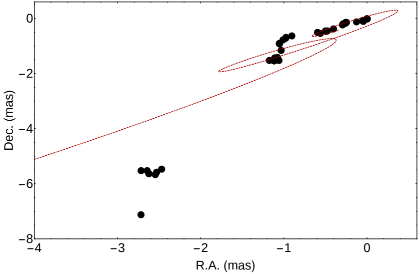
where $a = \beta_0 \sin\theta_0$, $b = (\varpi_0^2 - j^2/\beta_0^2)^{1/2}$, $f = j/\beta_0$ and the dimensionless coordinate time parameter $t = (\tilde{t}/t_0) - 1$. The angle between the observer's line of sight and the direction of the instantaneous velocity vector of the jet component ξ is given by

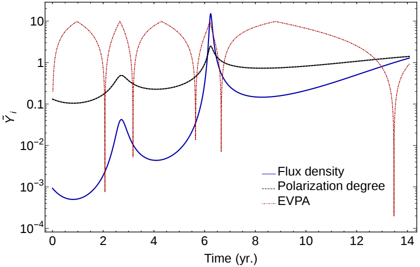
$$\cos\xi = \frac{\dot{\varpi}\cos\phi\sin i - \varpi\dot{\phi}\sin\phi\sin i + \dot{z}\cos i}{(\dot{\varpi}^2 + \varpi^2\dot{\phi}^2 + \dot{z}^2)^{1/2}}, \tag{2}$$

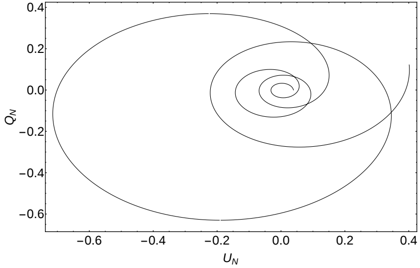
(Mohan et al. 2015)



Simulation results







Magnetic field strength

Assuming a conical jet geometry and equipartition between the magnetic energy density and the particle kinetic energy density in the pc-scale jet, the core offset per unit observation frequency $\Omega_{r\nu}$ (pc GHz), core distance $r_{\rm core}$ (pc) and the magnetic field strengths at 1 pc (B_1 in G) and at the core ($B_{\rm core}$ in G) are

$$\Omega_{r\nu} = 4.85 \times 10^{-9} \frac{D_L \Delta\theta}{(1+\tilde{z})^2 \left(\nu^{-1} - \nu_0^{-1}\right)}, \tag{3}$$

$$r_{\rm core} = \frac{\Omega_{r\nu}}{\nu \sin i}, \tag{4}$$

$$B_1 \cong 0.025 \left(\frac{\Omega_{r\nu}^3 (1+\tilde{z})^2}{\Gamma^2 \theta_0 \sin^2 i} \right)^{1/4}, \tag{5}$$

$$B_{\rm core} = B_1 r_{\rm core}^{-1}. \tag{6}$$

where D_L is the luminosity distance, $\tilde{z}$ is the redshift, ν_0 is a reference observation frequency, and $\Delta\theta$ is the difference between the apparent core position measured at frequencies ν and ν_0.

we obtain $\Omega_{r\nu} = 40.5$ pc GHz, $r_{\rm core} = 22.9$ pc, $B_1 = 0.96$ G and $B_{\rm core} = 0.04$ G, which is roughly consistent with the estimated $B_{\rm core} = 0.07 - 0.11$ G in Fromm et al (2013) for this source.

Summary

The presented 15 GHz VLBA observations were carried out on 2016 January 25, during a prominent γ-ray flare with quasi-simultaneous monitoring also at 43 GHz in an ongoing survey of γ-ray blazars by the Boston University group. The main results from this study include:

1. An oscillatory and bending pc-scale ($\leq$ 17 mas) jet structure is inferred from the 15 and 43 GHz multi-epoch VLBA images spanning $\sim$ 17 months.
2. Proper motions for the innermost ($\leq$ 1 mas) jet components (J3, J4, J5) were determined in the range of 0.04 – 0.33 mas yr^{-1}. The jet proper motions were employed to estimate the maximum bulk Lorentz factor $\Gamma \geq 17.5$, mean jet position angle $\lambda = 128.3^\circ$, inclination angle $i \leq 6.6^\circ$ and intrinsic half opening angle $\theta_0 \leq 1.8^\circ$.
3. The 15 and 43 GHz polarization images indicate a weakly polarized core and moderately polarized jet components. The polarization is observed to increase along the jet walls, likely manifesting the helical magnetic field.
4. A helical jet model was applied to simulate long-term optical-band variability. The contrast in estimates for flux density, polarization degree and EVPA from the simulation suggest that long term variability is sufficiently captured in the helical scenario. A developing observed anti-clockwise rotation of the polarization vector in the Stokes Q-U plane is consistent with expectation from the simulations.
5. An oscillatory pc-scale jet morphology, polarization behaviour and the expectation of γ-ray emission from the pc-scales are employed to argue for a long timescale (years) dominance by the helical jet scenario with kinematics being supported by a magnetic surface.
6. Apparent core shift of $\Omega_{r\nu} = 40.5$ pc GHz the magnetic field strength at the core $B_{\mathrm{core,43GHz}} = 0.04$ G are estimated.

Thanks