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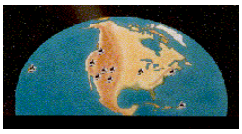

Analysis of the Millimeter Wave Variability of TeV Quasars

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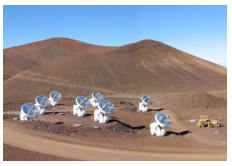
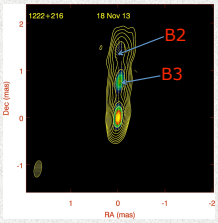


Data: We use photon and spacecraft data obtained by the Fermi Large Area Telescope (LAT) to construct γ-ray light curves at 0.1-200 GeV of a sample of 36 γ-ray blazars, which we monitor monthly with the VLBA at 43 GHz (www.bu.edu/blazars), allowing us to image the parsec-scale jet of the blazars with very high resolution, ~0.1 mas. Within this program we have collected 60, 74, and 68 total and polarized intensity images of the quasars 1222+216 (z=0.435), 3C279 (z=0.536), and 1510-089 (z=0.361), respectively, from 2007 June to 2013 November. We perform optical photometric and polarimetric observations at the Perkins telescope of Lowell Obs. (Flagstaff, AZ) and supplement these data with data from collaborators around the world. We combine data obtained with the SMA (Gurwell et al. 2007) and the IRAM 30m telescope (Agudo et al. 2010) to construct a light curve at 1.3 mm. We use linear and circular polarization measurements performed at 1.3 and 3 mm with the IRAM 30m telescope.

1222+216



←Fig.1a. Total (contours) and polarized (color scale) intensity image at 43 GHz; yellow sticks within the image indicate direction of polarization.
Table 1 gives parameters of jet knots: proper motion, apparent speed, position angle with respect to the core, and epoch of the ejection.

Table 1. Kinematics of Knots

Knot	μ(mas yr^{-1})	β_{app}(c)	ϕ (°)	T_o
B1	0.44±0.02	11.5 ±0.3	8.8 ±0.3	2010.39 ±0.13
B2	0.50±0.01	13.2 ±0.2	-6.4 ±0.2	2011.03 ±0.11
B3	0.93±0.05	22.6 ±1.2	-4.5 ±0.4	2012.95 ±0.12

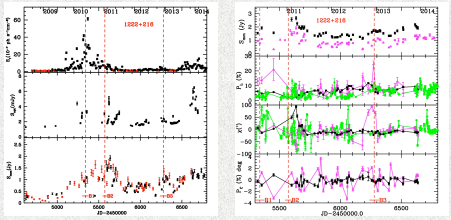


Fig. 1b (left). *From top:* 1) γ-ray light curve at 0.1-200 GeV with a 7-day binning interval; 2) optical light curve in R band; and 3) mm-wave light curves at 1.3mm (filled triangles – SMA, open triangles – IRAM) and at 7 mm from the VLBI core (red circles). Red dashed lines indicate the epochs of ejection of superluminal knots B1-B3.
Fig. 1c (right). *From top:* 1) mm wave light curves (3mm – black, 1.3mm – magenta); 2) degree of linear polarization P_L (green – R band); 3) position angle of linear polarization, χ; 4) degree of circular polarization, P_C.

Remarks: 1). Activity at mm wavelengths manifested by the ejection of a superluminal knot coincides with outbursts in optical and γ-ray bands. 2). Ejection of B1 occurred within 1σ uncertainty of T_o with respect to the TeV flare of 1222+216 detected by MAGIC (Aleksić et al. 2011) on June 17, 2010. 3). Parameters of linear polarization at 3 mm (P_L and χ) show a close connection with those at optical wavelengths. 4). A difference between χ at 1.3 and 3 mm arises at epochs of knot ejections. 5). The circular polarization shows significant variability with a change of sign.

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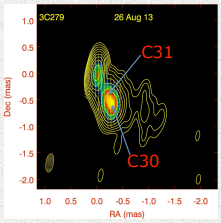


←Fig.2a. Total (contours) and polarized (color scale) intensity image at 43 GHz.
Table 2 gives parameters of 6 out og 8 knots detected in the jet from 2007 June to 2013 November. Designation of knots follows Unwin et al. 1989, Wehrle et al. 2001, Jorstad et al. 2004, & Chatterjee et al. 2008.

Table 2. Kinematics of Knots

Knot	μ(mas yr^{-1})	β_{app}(c)	ϕ (°)	T_o
C27	0.36±0.02	11.4 ±0.7	-134 ± 2	2008.79 ±0.10
C28	0.31±0.01	9.8 ±0.3	-132 ± 1	2009.15 ±0.07
C29	0.41±0.06	13.2 ±2.0	-121 ± 3	2009.87 ±0.04
C30	0.26±0.01	8.4 ±0.2	-146 ± 3	2010.13 ±0.09
C31	0.18±0.01	5.6 ±0.3	-142 ± 2	2010.38 ±0.11
C32	0.39±0.02	12.6 ±0.6	-133 ± 1	2010.75 ±0.13

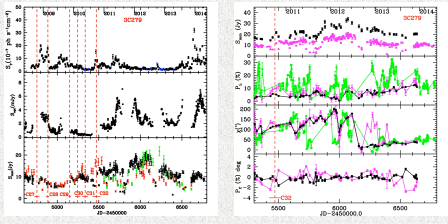
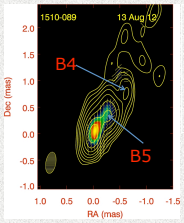


Fig. 2b (left). Gamma-ray, optical, and mm-wave light curves similar to Fig. 1b including the light curve of C30 (green circles). Fig. 2b (right) 1.3 and 3mm light curves, optical and mm-wave polarization parameter curves similar to Fig. 1c.

Remarks: 1). Although the appearance of C27, C28, and C32 coincides with γ-ray and possibly optical outbursts, the most prominent knot C30 was ejected during moderate γ-ray flux. 2). P_L at optical wavelengths is significantly higher than that at mm waves. 3). χ_{opt} shows similarity with χ_{3mm}. 4). The circular polarization shows significant variability with a change of sign during ejection of knot C32.

Conclusion: γ-ray outbursts show a tight connection with events in the parsec scale jet, although details vary from source to source. Observations of $P_C > 1\%$ suggest an anisotropy of pitch angles of the radiating relativistic electrons, especially during ejection events. This needs to be confirmed by more sensitive observations when measurements of circular polarization with ALMA and SMA become available.

1510-089



←Fig.3a. Total (contours) and polarized (color scale) intensity image at 43 GHz.
Table 3 gives parameters of 6 knots detected in the jet from 2007 June to 2013 November.

Table 3. Kinematics of Knots

Knot	μ(mas yr^{-1})	β_{app}(c)	ϕ (°)	T_o
B1	1.04±0.03	23.4 ±0.7	-18.9 ±1.4	2008.46 ±0.08
B2	0.99±0.02	21.9 ±0.5	-40.6 ±2.8	2009.35 ±0.03
B3	1.32±0.12	29.6 ±2.6	-39.3 ±6.9	2009.92 ±0.05
B4	0.66±0.03	14.8 ±0.8	-39.4 ±1.9	2011.79 ±0.05
B5	0.70±0.04	15.8 ±0.9	-30.6 ±2.3	2012.07 ±0.04
B6	0.93±0.05	20.8 ±1.2	-28.7 ±3.0	2013.09 ±0.08

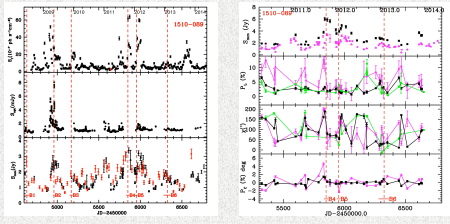


Fig. 3b (left). Gamma-ray, optical, and mm-wave light curves similar to Fig. 1b. Fig. 3b (right) 1.3 and 3mm light curve, optical and mm-wave pol. parameter curves similar to Fig. 1c.

Remarks: 1). Five out of 6 knots appeared in the jet during high γ-ray states. 2). Ejection of B5 occurred simultaneously with the TeV flare of 1510-089 detected by MAGIC (Aleksić et al. 2014) in 2012 February. 3).The γ-ray outburst in Autumn 2013 coincides with a bright state of the VLBI core on November 18, 2013. 4). The correlation between the γ-ray and mm light curves is statistically significant. 5). There is rather good correspondence between parameters of the optical and 3mm linear polarization, especially during enhanced mm-wave emission. 6). P_C increases in magnitude and changes sign at epochs of knot ejections.

References: Agudo, I. et al. 2010, ApJS, 189, 1; Aleksić, J. et al. 2011, ApJL, 730, L8; 2014, arXiv:1401.7154; Chatterjee, R. et al. 2008, ApJ, 689,79; Gurwell, M. A. et al. 2007, ASP Conf. Series, 375, 234; Jorstad, S. G. et al. 2004, AJ, 127, 3115; Unwin, S. C. et al. 1989, ApJ, 340, 117; Wehrle, A. E. et al. 2001, ApJS, 133, 297.