10 Years of VLBA-BU-BLAZAR Monitoring: Relationship between $\gamma$-ray & Microwave Events in Blazar Jets

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***See posters by Jorstad et al. & by Weaver et al.***

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Flux & polarization vs. time are difficult to interpret without images of the jet of the blazar.
VLBA-BU-BLAZAR & Multi-waveband Monitoring Program

1. Monthly VLBA monitoring at 43 GHz (37 γ-ray blazars)

2. Multi-waveband light curves
   a) γ-ray (0.1-200 GeV): Fermi LAT
   b) Optical (BVRI) light curves (1.8 m Perkins Telescope)
   c) Optical polarization vs. time (Perkins Tel. + collaborators)
   d) Optical emission-line monitoring (4.3m DCT)
   e) UV & X-ray (0.3-10 keV) light curves: Swift
   f) Radio light curves: 230 & 350 GHz (SMA); 37 GHz (Metsähovi) from collaborators
The VLBA-BU-BLAZAR Sample

- Flux density at 43 GHz > 0.5 Jy (usually)
- Declination > $-30^\circ$
- Optical magnitude in R band < 18.5$^m$
- Detection by EGRET

→ 37 objects ($z = 0.017 - 2.17$): 21 FSRQs, 13 BL Lacs, 3 RGs

Goals of the Program:

- Monitor jet structure to relate changes to $\gamma$-ray (etc.) events (Jorstad & Marscher 2016)

→ Determine location(s) of high-energy emission sites
→ Determine Doppler & Lorentz factors, viewing & opening angles
→ Constrain emission mechanisms (e.g., source of seed photons)

- Study jets of blazars on (sub-)parsec scales (Jorstad et al. 2017)
Most prominent $\gamma$-ray blazars have Doppler factors of 10-40
$\Rightarrow \gamma$-rays are beamed by factor $\sim 10^4 - 10^6$

(Jorstad + 2017; see also Lister + 2011)
High-$\Gamma$ blazar jets are extremely narrow, $\sim 20^\circ/\Gamma$
(Emission concentrated over even narrower angle at any given time $\rightarrow$ shorter $t_{\text{var}}$)

$\theta_0 \approx 0.32/\Gamma$

43 GHz

Pushkarev et al. 2017
$\theta_0 = 0.35/\Gamma$

15 GHz (MOJAVE)
Stationary Features in Most Blazar Jets (Standing shocks?)
- Especially prominent in BL Lac objects

BL Lac: knots crossing stationary features coincide with VHE flares (e.g., Abeysekara + 2018; more examples: see poster by Jorstad et al.)
Magnetic Field: Some order, mostly disorder (turbulence)

BL Lac

Pol. Of core ~ 7% → ~100 turbulent cells
Time Sequences of VLBA Images:
What happens in jet during $\gamma$-ray outbursts & quiescence

$\gamma$ rays quiescent when radio jet is quiescent, & $\gamma$-ray outbursts occur when radio jet is very active

(Jorstad et al. 2010, 2013, 2016) See also poster by Weaver et al.
γ-ray outbursts only occur during strong activity in jet at millimeter wavelengths Example: BL Lac object 0235+164
Variability of 1222+216 (4C+21.35)

- Note optical flares with & without γ counterpart
New superluminal knot (83%) and/or brightening of “core” at 43 GHz coincides with every γ-ray flare.

But only 35% of superluminal knots are associated with γ-ray flares. Either acceleration of e⁻s to >10 GeV only occurs in 35% of knots or seed photon field is variable.
Timing of Gamma-Ray/Jet Events

\( \Rightarrow \gamma \)-ray flares mostly occur on parsec scales

- \( T_0 \): Time when centroid of knot crosses centroid of “core”

- Note that a blazar “core” is 2-20 pc from black hole

- At 43 GHz, “core” is usually consistent with a standing shock

- \( T_\gamma \): Time of peak of \( \gamma \)-ray flare

Peak of \((T_0 - T_\gamma)\) distribution corresponds to the centroid of knot crossing centroid of core 25-35 days before \( \gamma \)-ray flare peak

Even when \( T_\gamma > T_0 \) by < 60 days, most knots have not yet fully exited from “core”

Monte Carlo simulations \( \Rightarrow \) association of knots & flares significant at 1% confidence level
Possible Flare Sites in Blazars

Flare site 1: Inner jet, inside radii of BLR, dusty torus
Advantages: Dense seed photon field, small region → rapid variability
Disadvantages: Conflicts with flare vs. knot timing, $\Gamma$ probably not yet at maximum value

Flare site 2: pc scale - moving knot crosses "core" or other stationary feature
Advantages: Agrees with flare vs. knot timing, $\Gamma$ near maximum value
Disadvantages: Not as dense seed photon field, short $t_{\text{var}}$ → only small fraction of jet involved
Flare site 1: Broad emission lines from BLR or IR from dusty torus
+ Explains high-energy SED well
- BLR & torus photons not important on > few pc scales
- Unlikely to be strongly variable in a luminous blazar

Flare site 2: Synchrotron photons – SSC or from sheath or Mach disk
+ Highly variable
- SSC unlikely to give $L_\gamma/L_{\text{synchrotron}} > 10$ (good for most BL Lacs, though)

Polar clouds of gas + free electrons? (León-Tavares + 2013; Vittorini + 2014; Tavani + 2015; see poster by Jorstad et al.)
+ Variable in response to flares from jet → could explain diversity of flare behaviors

Nonthermal: Jet sheath (e.g., MacDonald + 2015) or standing shock (Marscher 2014)
+ Evidence for presence on parsec scales
+ Can be variable, explaining diversity of multi-waveband variability
- Fitting X-ray emission requires high minimum energy of electrons
Conclusions

VLBA images guide interpretation of light curves + polarization vs. time

$\gamma$-ray outbursts coincide with mm-wave activity in jet
$\rightarrow \quad \gamma$ rays are mainly produced on parsec scales

Only 35% of new knots/core flares associated with $\gamma$-ray flares $\rightarrow$ either seed photon field or $E_{\text{max}}$ of $e^{-}$s varies

Timing: $\gamma$-ray flares peak as moving knot crosses “core” or other stationary feature

Magnetic field in jet is mostly disordered $\rightarrow$ turbulence

Jets of most $\gamma$-ray bright blazars are very narrow with high Doppler factors $\rightarrow$ short time-scales of variability
Extra Slides Follow
Rules for Establishing Connection between Gamma-Ray/Radio Jet Events

I. Brightest γ-ray flares (3σ events):
   \[ S_\gamma > (\langle S_\gamma \rangle + 3\sigma) \]
   for \( \geq 2 \) consecutive measurements with 7-day binning
II. Two such events are different flares if separated by \( > 1 \) month
III. For each event a γ-ray light curve with a shorter binning interval (1-3 days) is produced to find ``true” γ-ray peak, \( S_\gamma^{\text{max}} \)
III. Duration of a flare: FWHM of \( S_\gamma^{\text{max}} \)
IV. Detection in the jet of a superluminal knot (at least at 6 epochs) with the ejection time, \( T_0 \pm 1\sigma(T_0) \), within the flare duration
V. 3σ flares of the VLBI core and mm-wave
Model of “Core”: Turbulent Plasma Crossing Conical Standing Shock (see also Cawthorne et al. 2013 ApJ)

Simulated polarized intensity image of turbulent plasma flowing through standing conical shock

- Pattern of polarization & total polarization similar to blazar core
What happens in jet during $\gamma$-ray outbursts & quiescence

3C 279

$S_{\text{opt}}$ (mJy)

$S_{\text{X}} \times 10^{11}$ (erg/s/cm$^2$)

$S_{\gamma} \times 10^0$ (ph/s/cm$^2$)

2009.07

0.5 mas

25 mJy

20000
Knots with & without γ-ray Flares (Jorstad + in prep)

Both types in Quasar 3C 279

Knots without γ-ray & optical flares must only energize electrons to \(\sim 1000 \text{ mc}^2\)
3C 454.3: All wavebands down to mm-wave peaked within 1 day during flare in VLBI core.

\[ F(\text{Jy}) \]

\[ F(\text{cts/s}) \]

\[ F(\text{mJy}) \]

\[ F(\text{phot cm}^{-2} \text{s}^{-1}) \]

\[ \gamma\text{-ray, etc.} \]

\[ X\text{-ray} \]

\[ R\text{-band} \]

\[ 230 \text{ GHz} \]

\[ \text{Nov. 20, 2010} \]

\[ \text{Wehrle et al. (2012 ApJ)} \]

VLBA images at 7 mm wavelength: flare in core + superluminal knot ejected.

\[ \text{Knot ejected in late 2009, } v_{\text{app}} = 10c \]

\[ \text{RJD=5502, 1 Nov 2010; core: 10.3 Jy} \]

\[ \text{RJD=5507, 6 Nov 2010; core: 14.1 Jy} \]

\[ \text{RJD=5513, 12 Nov 2010; core: 14.2 Jy} \]

\[ \text{RJD=5535, 4 Dec 2010; core: 17.7 Jy} \]