Structure & Emission of Compact Blazar Jets

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Research Web Page: www.bu.edu/blazars
See also posters by S. Jorstad & by S. Molina, talk by I. Agudo
Radio core must lie at least 0.5 pc from black hole to produce the observed X-ray dip/superluminal ejection delay of ~ 60 days (Marscher et al. 2002 Nature; Chatterjee et al. 2008 ApJ).

Strong optical/X-ray correlation: optical from disk.
FR II Radio Galaxy 3C 111 (z=0.0485) Does the Same

3C 111: Ejection & Superluminal Motion of Knots

VLBA images at 43 GHz (7 mm)

Moving Knots ("Blobs")

"Core"
3C 111: Distance of 43 GHz “Core” from Central Engine

Superluminal ejections follow X-ray dips by mean time of 55 days

→ Radio core must lie at 0.6±0.3 pc (0.2 mas, projected) from black hole
Quasar PKS 1510-089: first 140 days of 2009

- Same electron energies make synchrotron optical & GeV Compton photons
- High gamma-ray to synchrotron luminosity ratio: knot passes local source of seed photons that get scattered to gamma-ray energies
- Lower ratio: gamma-rays could come mainly from SSC
- Superluminal knot passes standing shock in "core"

Bright superluminal blob passed “core” in early May 2009
Apparent speed = 21c
Rotation of Optical Polarization in PKS 1510-089

Rotation starts when major optical activity begins, ends when major optical activity ends & superluminal blob passes through core.

- Non-random timing argues against rotation resulting from random walk caused by turbulence → implies single blob did all.
- Also, later polarization rotation similar to end of earlier rotation, as expected if caused by geometry of mag. field; event occurs as a weaker blob approaches core.

Model curve: blob following a spiral path through coiled magnetic field in an accelerating flow.

Γ increases from 8 to 24, δ from 15 to 38.
Blob moves 0.3 pc/day as it nears core.
Core lies > 17 pc from central engine.
Sites of $\gamma$-ray Flares in PKS 1510-089 (Marscher et al. 2010 ApJL)

Sketch of PKS 1510–089

- Streamline
- Moving emission feature
- Helical magnetic field
- Conical standing shock
- Mach disk
- Emission in sheath
- Acceleration & collimation zone
- mm-wave core
- Possible local sources of beamed seed photons: sheath & Mach disk

Distance from black hole

<table>
<thead>
<tr>
<th>$r=0$</th>
<th>0.002 pc</th>
<th>0.02 pc</th>
<th>0.2 pc</th>
<th>2 pc</th>
<th>20 pc</th>
</tr>
</thead>
</table>
Emission feature following spiral path down jet

Feature covers much of jet cross-section, but not all (magnetosonic shock in flow with high vorticity?)

Centroid is off-center

→ Net $\mathbf{B}$ rotates as feature moves down jet, $\mathbf{P}$ perpendicular to $\mathbf{B}$
Components as indicated by theory & observations of SED, variability & polarization
Evidence exists for velocity gradients transverse to axis (spine-sheath)
3C 454.3: Outbursts seen first at mm wavelengths, optical & gamma-ray closely related but do not vary exactly together on short time-scales.

![Graphs showing light curves for 3C 454.3 in different wavelengths](image)

- **R-Band**
  - 2009.0: Low activity
  - 2010.0: Outburst

- **0.3–10 keV**
  - 2009.0: Steady increase
  - 2010.0: Sharp peak

- **1 mm, 0.87 mm, 8 mm**
  - 2009.0: Slow change
  - 2010.0: Significant increase

- **γ-ray**
  - 2009.0: Baseline
  - 2010.0: Two distinct peaks

Note: The graph on the right shows the light curve from JD 5480 to 5560, scaled by JD - 2450000, with the knot passing the centroid of the core indicated.
3C 454.3: 2010 super-outburst from gamma-ray to mm-wave

- RJD=5502, 1 Nov 2010; core: 10.3 Jy
- RJD=5507, 6 Nov 2010; core: 14.1 Jy
- RJD=5513, 12 Nov 2010; core: 14.2 Jy
- RJD=5535, 4 Dec 2010; core: 17.7 Jy

Knot ejected in late 2009, \( v_{\text{app}} = 10c \)
3C 454.3: Knot from mega-outburst moving in new direction

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Jorstad et al. (2010 ApJ): core has triple structure, with a flare occurring as a knot passes each feature

Blob ejected in late 2010
Change in jet direction starting ~ 2005

Core is the more southern compact feature, C0

Flare B appears to occur as superluminal knot passes through C1, which is probably a quasi-stationary shock. The same may be true for Flare A based on the increase in polarization of C1.
Strong Outburst in 4C21.35 (1222+216) in 2010

Good optical-gamma correlation but not detailed agreement

Outburst started at mm wavelengths

Detection at 0.4 TeV (Aleksic et al. 2011) ➞ flare must occur on pc scales to avoid high pair-production opacity
Variations in Flux vs. Frequency

Gamma-ray + optical variations usually faster than X-ray, IR, & mm-wave variations

Shorter variations $\rightarrow$ smaller volume and/or more severe energy losses of radiating electrons

Smaller = closer to black hole?

Problems:
- Observed coincidence of $\gamma$-ray flares with events in radio jet
- high-E gamma-rays cannot escape before producing $e^+e^-$ pairs

Puzzle: How can high fraction of flux vary on intra-day scales parsecs from the black hole?

$\rightarrow$ High-$\Gamma$ jets are very narrow ($< 1^\circ$), $\Gamma \sim 50$ seen

$\rightarrow$ Proposal: Particle acceleration efficiency in jet is highly variable with position & time

- Related to direction of magnetic field?
SED can be described by broken power law
- break often by more or less than $1/2$ expected from radiative losses
- Break now seen in $\gamma$-ray spectra as well
Power-law Power Spectra of Blazar Variations

- Rapidly changing brightness across the electromagnetic spectrum
- Power spectrum of flux changes follows a power law
Working toward a Modified Model

Imagine that many “blobs” are just random fluctuations in turbulent jet flow (others might be strong moving shocks)
- Agrees with power-law power spectrum of fluctuations in flux

Electrons in blob are accelerated when blob passes through standing shock in core (or elsewhere)
- Maximum electron energy achieved varies from one turbulent cell to another → number of cells with energies as high as E depends on E

→ Frequency-dependent volume of emission $V(\nu) \propto \nu^{-p}$

 Flux density $F_\nu \propto \nu^{-(s-1)/2} V(\nu) \propto \nu^{-[p+(s-1)/2]}$ [where $N(E)=kE^{-s}$]
Radiative energy losses can steepen this further
Advantages of Model

1. Low frequency $\nu_1$
2. Frequency $\nu_2 = 10\nu_1$
3. Frequency $\nu_3 = 10^2\nu_1$
4. Frequency $\nu_4 = 10^3\nu_1$
5. Frequency $\nu_5 = 10^4\nu_1$

Smaller number of turbulent cells are involved in emission at higher frequencies
→ Variability time scale shorter (approx. $\propto \nu^{-p/2}$)
→ Linear polarization higher & more highly variable in degree & position angle at higher $\nu$ (as observed)

Works well for blazar AO 0235+164, $V(\nu) \propto \nu^{-0.32}$
Outburst of this type occurs when turbulent “blob” crosses standing oblique shock, perhaps with a Mach disk near the axis.

- Weak emission (low beaming)
- Standing Conical Shock
- 7 mm Core
- Superluminal Knot
- Acceleration of Flow
- γ-Ray Flare Site
- Emission-Line Clouds
- Broad
- Narrow
Turbulent Extreme Multi-zone (TEMZ) Model

60 turbulent cells across jet cross-section, each followed for 100 cell lengths after crossing shock → 6000 emission zones

- Each cell has random $B$ direction, $B$ & $N_0$ vary according to PSD

- 60 cells in each of 100 nested cones beyond shock

- Conical shock

- Mach disk (optional)

Note excellent general correlation but frequent deviation from one-to-one correspondence.

Also, optical fluctuations have higher amplitude (characteristic of external Compton scattering of a steady source of seed photons).

- Both characteristics caused by dependence of synchrotron flux on magnetic field amplitude & direction as well as number/energy distribution of electrons.

- Can create time delays if Mach disk is present since it provides time-variable synchrotron seed photons blueshifted in plasma frame.
Sample SED (seed photons from dust)

Breaks by more than 0.5 occur, but do not yet reproduce gamma-ray break by 1.3 seen in 3C 454.3

Lots more work to be done to add features to code

[e.g., polarization calculation & pair production opacity are not yet included, synchrotron self-absorption is calculated only crudely at this point, cell-to-cell SSC will require moving to a supercomputer]

and to explore different parameter regimes

So, no conclusions yet but the model looks promising