The Properties of Parsec-Scale Blazar Jets

Submitted to ApJ

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Using the Blandford-Konigl jet model and five observables, one can determine a number of properties of blazar jets.

**Observables:**
1. Redshift
2. Core flux density
3. Extended flux density
4. Core shift
5. Apparent opening angle

**Nuisance parameters:**
1. Electron distribution parameters ($\gamma_1, \gamma_2, p$)
2. Equipartition parameters ($\xi_e, \xi_p$)

**Results (jet parameters):**
1. Lorentz factor ($\Gamma$)
2. Angle to line of sight ($\theta$)

**Other parameters:**
1. Doppler factor ($\delta$)
2. Jet opening angle ($\alpha$)
3. Magnetic field $B(1 \text{ pc})$
Redshift

Gives distance to source, determines luminosities from fluxes

Shaw et al. (2012)
Core Flux Density

Core radio spectra seen in VLBI images are flat. BK model explains this as the superposition of several self-absorbed components. $F_\nu(\Gamma, \theta, \alpha, P_j)$. Also depends on electron distribution $N_e(\gamma) = N_{e0} \gamma^{-p}$.

MOJAVE website
http://www.physics.purdue.edu/astro/MOJAVE/

Marscher (1995)
VLBI core position is dependent on frequency. Core’s position “shifts” when viewed at different frequencies. $\Delta \phi(\Gamma, \theta, \alpha, P_j)$. Also depends on electron distribution $N_e(\gamma) = N_{e0} \gamma^{-p}$.
Extended Radio Flux and Jet Power

The Power needed to inflate cavities in hot ICM is well-correlated with extended radio luminosity. So measuring extended radio flux gives jet power.

Birzan et al. (2008)

Cavagnolo et al. (2010)
Jet opening angle projected on the sky can be measured by analyzing transverse jet profiles from VLBI images. $\alpha = \alpha_{\text{app}} \sin \theta$

Pushkarev et al. (2009)
Finding Jet Parameters

Using observables, we can get two equations:
\[ F_v(\Gamma, \theta, \alpha, P_j) \rightarrow F_v(\Gamma, \theta, \alpha_{\text{app}}, L_{\text{ext}}) \]
\[ \Delta \phi(\Gamma, \theta, \alpha, P_j) \rightarrow \Delta \phi(\Gamma, \theta, \alpha_{\text{app}}, L_{\text{ext}}) \]

Two equations, two unknowns, can be solved for \( \Gamma \) and \( \theta \).

Once these are known, one can find:
\[
\begin{align*}
\delta_D &= [\Gamma(1-\beta \cos \theta)]^{-1} \\
\alpha &= \alpha_{\text{app}} \sin \theta \\
\beta_{\text{app}} &= (2\delta_D \Gamma - \delta_D^2 - 1)^{1/2} \\
B(1 \text{ pc}) &\sim P_j^{1/2} \\
[ B \sim r^{-1} \text{ in BK model}] 
\end{align*}
\]
Finding Jet Parameters

Nuisance parameters drawn from flat priors:

1. electron distribution parameters
   1. \( \log(\gamma_1) \): between 0 and 4.
   2. \( \log(\gamma_2) \): between 3 and 7.
   3. \( p \): between 1 and 5.
2. equipartition parameters
   1. \( \log(\xi_e) = \log(u_e/u_B) \): between -1 and 1.
   2. \( \log(\xi_p) = \log(u_p/u_B) \): between -4 and 1.

\[
\begin{align*}
\Phi & = 5(e^2 - 2.6) \\
\tau & = 10^{\Gamma}
\end{align*}
\]
Observables taken from literature:
1. core flux density → MOJAVE website (e.g. Lister et al. 2009)
2. extended flux density → Meyer et al. (2011)
3. core shift → Pushkarev et al. (2012)
4. apparent opening angle → Pushkarev et al. (2009).

64 sources: 11 BL Lacs, 52 FSRQs, 1 NLSy1

<table>
<thead>
<tr>
<th>Source</th>
<th>Alias</th>
<th>Typea</th>
<th>z</th>
<th>log_{10} [\frac{L_{\text{ext}}}{\text{erg s}^{-1}}]</th>
<th>\mathit{F}_\nu(\text{core}) [\text{Jy}]</th>
<th>2\alpha_{\text{app}} [\circ]</th>
<th>\Delta \phi [\text{mas}]</th>
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Results

<table>
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<tr>
<th>Source</th>
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<th>$\Gamma$</th>
<th>$\theta$ [°]</th>
<th>$\alpha$ [°]</th>
<th>$B$(1 pc) [G]</th>
<th>$\delta_D$</th>
<th>$\beta_{app}$</th>
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<td>0133+476</td>
<td>DA 55</td>
<td>$7.5^{+36.6}_{-5.8}$</td>
<td>$3.6^{+12.6}_{-2.9}$</td>
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Results for all 64 sources.

Errors are quite large. Dominated by errors on core shift and unknown electron spectral index.
### TABLE 2

**Blazar Jet Parameter Results**

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<tr>
<th>Source</th>
<th>Alias</th>
<th>$\Gamma$</th>
<th>$\theta$ [°]</th>
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<tr>
<td>1101+384</td>
<td>Mrk 421</td>
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<td>1652+398</td>
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<td>$0.8^{+1.0}_{-0.8}$</td>
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</table>

For Mrk 421, Mrk 501 and other TeV blazars, $\Gamma$, $\delta_D$ and $\beta_{app}$ are low, consistent with observations of jet components.
Relation between jet power and extended radio luminosity is controversial (e.g., Godfrey & Shabala 2016). Different expressions for jet power don’t have strong effect on results.

Proxies for jet angle

Core dominance: ratio of core to extended radio flux.

Not significantly correlated with observing angle (< 4σ).

Core Shift

Significantly correlated with observing angle. (>5σ)
Some expectation that $\theta$ and $v_{pk}$ are correlated for BL Lacs (Meyer et al. 2011). Did not find significant evidence for this (but large errors and few sources).
My magnetic field values are consistent with values found by Pushkarev et al. (2012) using a different method.
Of all the parameters I determine, magnetic field is best-correlated with γ-ray luminosity ($> 5\sigma$).

But is this a selection effect? 

$$P_j \sim \alpha \Gamma B^2$$
My results are consistent with a constant $\alpha \Gamma$, i.e., $\alpha \sim 1/\Gamma$. Similar results found by others (e.g., Jorstad et al. 2005, 2017; Clausen-Brown et al. 2013; Pushkarev et al. 2009, 2017).
Following Zamaninasab et al. (2014) Parsec-scale magnetic flux can be computed from:

\[ \Phi_{\text{jet}} = 1.2 \times 10^{34} \Gamma \alpha \left( \frac{M_{\text{BH}}}{10^9 M_\odot} \right) \left( \frac{B(1 \text{ pc})}{1 \text{ G}} \right) \text{ G cm}^2 \]

Expectation from jets launched from MADs:

\[ \log_{10} \left( \frac{\Phi_{\text{jet}}}{M_{\text{BH}}} \right) = 0.5 \log_{10} L_{\text{acc}} + 34.4 \]

This is not consistent with my results. May be due expression above assuming \( a \sim 1 \) and \( \eta = 0.4 \) for all sources.
• I describe a method to determine parameters of parsec-scale blazar jets from observable quantities.

• I compute properties for 64 sources.

• Errors are large. Errors dominated by error in core shift measurement and uncertainty in electron spectral index (p). Variability is another issue.

• Properties are consistent with previous results. Results are consistent with slow $\beta_{\text{app}}$ for many TeV BL Lacs.

• Find little evidence for MAD-launched jets, or scenario of Meyer et al. (2011) ($\theta$ and $v_{\text{pk}}$ correlation for BL Lacs).

• A promising method for studying jets, especially if ways can be found to reduce errors!