Parsec-Scale Studies of Blazar Jet Kinematics

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Talk Outline

• **AGN jet kinematics:**
  – MOJAVE, Walker M87, Boston U, Piner & Edwards
  – slow, non-radial, inward, & superluminal features
  – accelerations and trends down the jet

• **Demographics and Statistical Trends**
MOJAVE VLBA Program

- Milliarcsec-resolution 15 GHz images of over 400 AGN jets
  - 25 year baseline on many sources
  - full polarization since 2002

- 30 AGN observed per month, chosen from list of ~100 targets:
  decl. > - 30° and > 0.1 Jy

- Results published in series of papers, see list and data archive at
  www.astro.purdue.edu/MOJAVE

Blazar NRAO 140 at 15 GHz
Colors: fractional linear polarization
MOJAVE Kinematics Studies

- Gaussian models fit to visibilities at each epoch (at least 5 epochs per AGN).
  - rms positional accuracy: \(~ 0.06\) mas
  - track trajectories of bright jet features
  - probing jet kinematics at 10-1000 pc (de-projected) from central engine

- Latest analysis covers 1744 jet features in 382 AGNs, based on 7173 VLBA epochs from 1994 Sept to 2017 Jan 1.

- Typical angular speeds are \(~ 0.1\) mas/y, range from a few \(\mu\)as/y to 3 mas/y

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Speed Dispersion Within the Jet

- An AGN jet typically contains features with a range of bulk Lorentz factor and/or pattern speed
- A characteristic median speed exists for each jet

Normalized speed distribution within 26 jets, each having at least 10 moving features.

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Slow Pattern (‘Stationary’) Features

- Features that have:
  1. speed < 20 $\mu$as/y
  2. < 1/10th of max speed seen in the jet
  3. no significant acceleration

- 6% of all jet features

- Present in 25% of quasar and 24% of BL Lac jets

- Majority are located close to the base of the jet
Apparent Inward Motions

Statistics:
- Only 2.5% of all features are inward
- Seen in 9% of quasar and 10% of BL Lac jets

Likely explanations:
- Accelerated motion across the line of sight
- Inward pattern speed (e.g., reverse shock)
- Misidentification of true core feature
Acceleration Analysis

- Analyzed 880 features in 206 blazar jets which had at least ten VLBA epochs and known redshift.

- Measured accelerations in \( \parallel \) and \( \perp \) directions to fitted apparent motion vector on the sky.

Non-radial = proper motion vector does not point back to the core feature
AGN Jets Are Accelerating

- 60% of AGN jets studied have at least one feature with $>3\sigma$ acceleration.
- 37% of all individual jet features show evidence of acceleration.
- Parallel accelerations are of larger magnitude and more prevalent than $\perp$ accelerations.
-- primarily due to changes in Lorentz factor, not bending
- Similar results seen by Piner et al. 2012 (8 GHz) and Jorstad et al. 2017 (43 GHz)
Acceleration of Non-Radial Features

- Overall jet axis direction determined using stacked-epoch image.
- Most off-axis features have perpendicular accelerations that are steering them back towards the jet axis.
- We are seeing jet collimation at scales up to 50 pc.
Trends Downstream

• Features tend to speed up near the core, and slow down further out.

• Within ~10 pc (projected), for $\delta \sim 10$, in observer frame: 
  $\dot{\Gamma}/\Gamma \sim 10^{-3} - 10^{-2}$ per year

• Past 10 pc (projected), for $\delta \sim 10$, in observer frame: 
  $\dot{\Gamma}/\Gamma \sim -10^{-3}$ per year
Do the observed motions reflect the underlying jet flow?

- Any intrinsic shock speeds are added relativistically to the flow speed.
- Statistical trends in MOJAVE jet sample are impossible to reproduce with a random collection of inward & outward moving shocks.
Acceleration in M87 Jet

- Wavelet + cross-correlation image analysis of C. Walker 43 GHz VLBA M87 movie project and 15 GHz MOJAVE images

Mertens et al. 2016

Speeds of N and S jet sheaths:

- helical flow?

Walker et al. 2018
Side-to-Side Motion of M87 Jet

Sinusoidal transverse oscillation propagates outward at ~ 0.85c (slower than jet features)
Changes in Inner Jet Direction

- Half of best monitored MOJAVE jets show changes in their (projected) innermost jet position angle, at rate of ~1-3° y⁻¹

*3C 454.3*

*9.8 ± 1 °/y*

*NRAO 150*

*0748+126: Flux Weighted CC < 1 mas*

*0851+202 Mean CC PA = −118*

*OJ 287*
Energized Jet Channels

- At any given time, typically only a portion of the full (conical) outflow is energized/visible in a VLBA image
TeV-detected Quasar 1222+216 at $z = 0.43$

- Max speed = 27 c
- Viewing angle < 4°
- Deprojected opening angle < 1.6°
3C 273 at $z = 0.16$

- Max speed 15 c

25 pc
Statistical Trends
• **Peaked at low values**
  - only 10 jets with $\beta_{\text{app}} > 30$, distribution implies $\Gamma_{\text{max}} = 50$
    - parent population can’t all have the same Lorentz factor (Vermeulen & Cohen 1995)

• **Blazars are not typical AGN jets!**
  - most AGN jets in the parent population have much lower synchrotron power and a Lorentz factor $<< 10$. 

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Boston U. Blazar Monitoring Program

Monthly VLBA 43 GHz obs. of 36 AGN
- samples rapidly-fading features within ~1 mas of the jet base.

Results consistent with MOJAVE program:
- similar range of speeds
- 21% of features are stationary and most are within 3 pc of core
- 31% of features show accelerations
- parallel accelerations are larger and more common than perpendicular ones

Jorstad et al. 2017

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Jet Speed vs. 15 GHz Luminosity

Only the most intrinsically powerful AGN jets attain high bulk Lorentz factors

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Maximum Jet Speed vs. Core Compactness

\[ T_{B,\text{obs}} \sim \delta T_{B,\text{int}} \]

Homan et al., in prep.

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Jet Speed and γ-ray Emission

External IC model: more boosting in gamma-rays than radio

100 MeV lower cutoff and sensitivity of Fermi LAT biases it against detecting low-spectral peaked, lower Doppler factor blazars

All of the fastest jets in the 1.5 Jy sample have Fermi-LAT detections.

Lister et al. 2015, ApJL., 810, 1
Piner and Edwards TeV AGN Study

- Multiepoch 8 GHz VLBA study of 47 HSP BL Lacs in TeVCat catalog.
- Distribution implies $\Gamma \leq 4$
- Consistent with Doppler factor estimates from radio core brightness temperatures (MOJAVE, & Lico et al. 2016)
- Slow pattern speed features are rare, like MOJAVE blazars
- Very high Doppler factors (> 100) are typically required to fit SEDs and TeV variability timescales → fast TeV-emitting spine invisible in radio? break-out jet region? reconnection mini-jets?

38 of 47 HSP BLL
6 have $>3\sigma$ speeds
~4 epoch measurements per jet feature
Jet Speed vs. Synchrotron Peak Frequency

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Jet Speed vs. Cosmological Distance

Jet discovery region

3 mas/yr

TeV

TeV discovery region

Filled = TeV–detected

Luminosity Distance [Mpc]

Maximum apparent speed [c]
Summary

• The VLBA is an unparalleled instrument for studying the pc-scale kinematics of AGN jets:
  – the most powerful blazar jets have a wide range of bulk Lorentz factors up to \( \sim 50 \), while typical AGN jets have Lorentz factors of only \( \sim \) a few.
  – jet features tend to increase their Lorentz factors within \( \sim 100 \) pc of the jet base where jet is still collimating, and decelerate further out.
  – VLBI images trace out only the currently energized emission regions, which don’t fill the entire jet cross-section.
  – Fermi LAT is biased against detecting low-spectral peaked, lower Doppler factor blazars
  – TeV-detected blazars have radio-emitting jets with Lorentz factors \( \Gamma < 4 \), while TeV emission indicates much higher \( \Gamma \) values.

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