Monitoring Of Jets in Active Galactic Nuclei with VLBA Experiments. XVIII.
Kinematics and Inner Jet Evolution of Bright Radio-loud Active Galaxies

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Supporting material: figure sets, machine-readable tables

Abstract

We have analyzed the parsec-scale jet kinematics of 447 bright radio-loud active galactic nuclei (AGN), based on 15 GHz Very Long Baseline Array (VLBA) data obtained between 1994 August 31 and 2019 August 4. We present new total intensity and linear polarization maps obtained between 2017 January 1 and 2019 August 4 for 143 of these AGN. We tracked 1923 bright features for five or more epochs in 419 jets. The majority (60%) of the well-sampled jet features show either accelerated or nonradial motion. In 47 jets there is at least one nonaccelerating feature with an unusually slow apparent speed. Most of the jets show variations of 10°–50° in their inner jet position angle (PA) over time, although the overall distribution has a continuous tail out to 200°. AGN with spectral energy distributions peaked at lower frequencies tend to have more variable PAs than the non-LAT AGN in our sample. We attribute these trends to smaller viewing angles for the lower spectral peaked and LAT-associated jets. We identified 13 AGN where multiple features emerge over decade-long periods at systematically increasing or decreasing PAs. Since the ejected features do not fill the entire jet cross section, this behavior is indicative of a precessing flow instability near the jet base. Although some jets show indications of oscillatory PA evolution, we claim no bona fide cases of periodicity since the fitted periods are comparable to the total VLBA time coverage.

Unified Astronomy Thesaurus concepts: Active galactic nuclei (16); BL Lacertae objects (158); Gamma-ray sources (633); Radio galaxies (1343); Radio jets (1347); Quasars (1319)

1. Introduction

Relativistic jets from active galactic nuclei (AGN) represent some of the most energetic long-term phenomena in the universe and played a key role in regulating galaxy formation via feedback processes (e.g., Fabian 2012). A powerful tool for investigating these outflows is the Very Long Baseline Array (VLBA), which provides full polarization, submilliarcsecond-scale imaging at radio wavelengths. The latter has revealed important details of the parsec-scale structural and magnetic field evolution of AGN jets (Wardle 2013; Blandford et al. 2019) and is a critical driver for state-of-the-art numerical jet simulations (Davis & Tchekhovskoy 2020; Komissarov & Porth 2021).

Since the VLBA’s commissioning in 1994, we have carried out a program to investigate the parsec-scale properties of several hundred of the brightest AGN jets in the northern sky above J2000 decl. −30°. This effort started out as the 2 cm VLBA survey (Kellermann et al. 1998) and continued as the Monitoring Of Jets in AGN with VLBA Experiments (MOJAVE) survey in 2002 with the addition of full polarization imaging of a complete flux-density-limited sample (Lister & Homan 2005). We have presented our findings in a number of papers in this series, including our most recent analysis of jet kinematics based on multiepoch data obtained between 1994 August 31 and 2016 December 26 (Lister et al. 2019).

In this paper, we perform a new kinematics analysis that adds VLBA data taken up to and including 2019 August 4 and increases the number of AGN jets in our study from 409 to 447. Some of these jets have no new data after the cutoff date of our previous kinematics paper (Lister et al. 2019), but we have made some revisions to their model fits. For this reason we tabulate here the fit values for all 447 jets, which supersede those presented in previous papers. We have excluded several AGN that were in the Lister et al. (2019) analysis since we subsequently determined that they have uncertain core locations and less reliable kinematic fits. These consist of NGC 1052, which has a heavily absorbed core at 15 GHz (Vermeulen et al. 2003), five compact symmetric objects (B2 0026+34, S4 0108+38, S4 0646+60, B3 0710+439, and TXS 2021+614), and five AGN with extremely compact radio structure that appear unresolved or barely resolved (PKS 0414-189, S5 0615+82, TXS 0640+090, TXS 1739+522, and B2 2023+33). We will present a kinematic analysis of the compact symmetric object jets in a future paper in this series.

The size and time coverage of our data set provides a unique opportunity to examine the stability of the innermost regions of
AGN jets over time. Although smoking-gun evidence of AGN jet precession has been seen on kiloparsec scales (e.g., Gower et al. 1982; Falceta-Gonçalves et al. 2010; Smith & Donohoe 2019), there have been few large systematic parsec-scale studies to date. In Lister et al. (2013) we identified several individual cases of AGN that may be undergoing periodic changes in their inner jet position angle (PA). We revisit our earlier study by analyzing a much larger data set consisting of 173 jets that have 12 or more VLBA observations acquired over a minimum 10 yr period. We provide evidence that over time, AGN eject narrow jet features at different PAs within a broader outflow, resulting in apparent changes in their inner jet direction on the sky. The range and variance of these changes is larger for jets oriented closer to the line of sight. In some AGN jets the PAs of successively ejected features follow a systematic trend over time, indicating a wobbling flow instability near the jet base from which the features emerge. Occasionally this instability may be disrupted and/or a new instability forms at another location, resulting in a sudden jump in the inner jet PA.

The layout of our paper is as follows. In Section 2, we describe our VLBA data and reduction methods, as well as the general properties of our AGN jet sample. We describe our kinematics analysis method in Section 3, and present our study of inner jet PA variations. We summarize our findings in Section 4. Throughout this paper we use the cosmological parameters \( \Omega_m = 0.27, \Omega_{\Lambda} = 0.73, \) and \( H_o = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \) (Komatsu et al. 2009) and define sky PAs in degrees east of north.

2. Observational Data

2.1. MOJAVE Data Archive

As of 2021, the MOJAVE data archive\(^{10}\) consists of nearly ten thousand 15 GHz (2 cm) VLBA observations of over 500 AGN dating back to 1994, obtained as part of the 2 cm VLBA survey (Kellermann et al. 1998), the National Radio Astronomy Observatory (NRAO) archive,\(^{11}\) and the MOJAVE program. The MOJAVE data archive provides public access to calibrated visibility and image FITS files for these observations. Over time, we have added AGN on the basis of their correlated flux density, high-energy gamma-ray emission, or membership in other AGN monitoring programs. The minimum criteria are a J2000 decl. \( \geq -30^\circ \) to ensure sufficient interferometric visibility plane coverage, and a 15 GHz VLBA flux density larger than \( \sim 50 \) mJy to ensure direct fringe detection and the ability to self-calibrate the data.

In Lister et al. (2019), we compiled a complete flux density limited AGN sample, the 1.5 Jy Quarter Century MOJAVE sample (1.5JyQC), consisting of all 232 AGN north of J2000 decl. \( \sim 30^\circ \) known to have exceeded 1.5 Jy in 15 GHz VLBA flux density at any time between 1994.0 and 2019.0. This is the largest and most complete radio-loud blazar sample to date, covering 75% of the entire sky. Being a multiepoch sample selected only on the basis of parsec-scale jet emission, it is well-suited for investigating the effects of relativistic beaming on observed blazar luminosity functions (Cara & Lister 2008), and the properties of the misaligned (parent) population (Lister et al. 2019).

In Lister & Homan (2005) and Lister et al. (2009a, 2013, 2018), we have published 15 GHz total intensity and linear polarization maps from the MOJAVE program up to 2016 December 26. Here we present new 15 GHz VLBA maps of 143 AGN obtained between 2017 January 3 and 2019 August 4. The 49 new AGN included here are members of either the Robopol optical polarization survey (Blinov et al. 2021), the Fermi2FHL catalog (Ackermann et al. 2016), the LAT-monitored list of flaring sources,\(^{12}\) or the MOJAVE–Fermi hard-spectrum gamma-ray sample (Lister et al. 2018). We list the general properties of all the MOJAVE AGN in Table 1. We have compiled synchrotron peak frequencies from the literature, or used the fit routines provided by the ASDC spectral energy distribution (SED) builder (Stratta et al. 2011). The optical classifications and redshifts are compiled from the NASA/IPAC Extragalactic Database, with the literature references listed in column 5 of Table 1. Of the 68 AGN with unknown redshift, 57 are classified as BL Lac objects due to their near-featureless optical spectrum in the reference listed in Table 1. Some of the remaining 11 AGN have been classified as BL Lac objects by other authors on the basis of their gamma-ray properties; however, we classify these as unknown since they lack published optical spectra. We provide notes on selected individual AGN in Appendix A.1.

2.2. Data Reduction

We processed the VLBA data using standard reduction methods in AIPS (Greisen 2003), and self-calibrated and imaged the visibilities in DIFMAP (Shepherd 1997). We determined the absolute electric vector polarization angle (EVPA) correction at each epoch via measurements of stable downstream polarized features, as described in our previous papers (Lister et al. 2018, 2019). The EVPAs were originally anchored using near-simultaneous single-dish polarization measurements at 15 GHz made at the University of Michigan Radio Observatory (Aller et al. 2003).

While comparing our total cleaned VLBA flux densities (\( S_{\text{VLBA}} \)) to near-simultaneous single-dish 15 GHz observations made by the Owens Valley 40 m radio monitoring program (\( S_{\text{OVRO}} \); Richards et al. 2011), we discovered a persistent error affecting the VLBA visibility amplitudes. All VLBA data obtained after 2019 April 15 have suffered from a systematic \( \sim 15%–25% \) decrease in correlated flux density on all baselines. At the time of writing, the cause of this drop is unknown and is being investigated. We applied flux density correction factors to all the visibilities in four affected VLBA epochs listed in Table 2. We determined these corrections by first estimating the amount of arcsecond-scale flux density resolved by the VLBA (\( S_{\text{res}} \)) for individual MOJAVE AGN based on multiple previous near-simultaneous OVRO–VLBA measurements dating back to 2008. These were typically \( \lesssim 5\% \) of the Owens Valley Radio Observatory (OVRO) flux density, reflecting the highly core-dominated nature of the MOJAVE sample AGN. At each VLBA epoch, we determined a correction factor for each AGN \( c = (S_{\text{OVRO}} - S_{\text{res}})/S_{\text{VLBA}} \) and computed the median of these values.

\(^{10}\) http://www.physics.purdue.edu/MOJAVE

\(^{11}\) http://archive.nrao.edu

\(^{12}\) https://heasarc.gsfc.nasa.gov/W3Browse/fermi/fermilasp.html
Notes. Columns are as follows: (1) B1950 name; (2) other name; (3) optical spectroscopic classification, where B = BL Lac, Q = quasar, G = radio galaxy, N = narrow-line Seyfert 1, and U = unknown; (4) redshift; (5) reference for redshift and/or optical classification; (6) high-confidence GeV gamma-ray association from Fermi LAT catalogs, where 4FGL = Abdollahi et al. (2020) and Ballet et al. (2020), 3FGL = Acero et al. (2015), 2FGL = Nolan et al. (2012), 1FGL = Abdo et al. (2010); (7) known TeV gamma-ray emitter (http://tevcat.uchicago.edu); (8) member of the VLBA 15 GHz flux-density-limited 1.5 Jy Quarter Century Sample (Lister et al. 2019); (9) log frequency of synchrotron peak in SED in Hz; (10) reference for synchrotron peak frequency, where 1. ASDC SED builder (Stratta et al. 2011), 2. Meyer et al. (2011), 3. Nieppola et al. (2008), 4. Ackermann et al. (2011), 5. Nieppola et al. (2006), 6. Abdo et al. (2009a), 7. Abdo et al. (2009b), 8. Hervet et al. (2015), 9. Ajello et al. (2020), 10. Ackermann et al. (2015), 11. Xiong et al. (2015), 12. Chang et al. (2017), 13. Ajello et al. (2017), 14. Chang et al. (2019). 

Table 1

| B1950  | Alias     | Opt. | z    | Optical Reference | LAT Association | TeV    | 1.5 Jy | t_ref | Ref. |
|--------|-----------|------|------|-------------------|-----------------|--------|--------|-------|------|
| 0003+380 | S4 0003+38 | O    | 0.229| Schramm et al. (1994) | 4FGL J0005.9+3824 | ...   | ...   | 13.1  | 10   |
| 0003-066 | NRAO 005  | B    | 0.347| Jones et al. (2005)  | 4FGL J0006.3-0620 | Y     | 12.9  | 9     |      |
| 0006+061 | TXS 0006+061 | B    | ...  | Rau et al. (2012)    | 4FGL J0009.1+0628 | ...   | 13.4  | 10    |      |
| 0007+106 | III Zw 2   | G    | 0.089| Sargent (1970)       | 4FGL J0014.4+1910 | ...   | 13.7  | 9     |      |
| 0011+189 | RGB J0013+191 | B    | 0.477| Shaw et al. (2013)   | 4FGL J0013.6+0541 | ...   | 12.8  | 9     |      |
| 0010+405 | 4C +40.01  | B    | 0.256| Thompson et al. (1992)| 4FGL J0013.6+0541 | ...   | 12.8  | 9     |      |
| 0012+610 | 4C +60.01  | U    | ...  | ...              | 4FGL J0014.8+6118 | ...   | 13.1  | 10    |      |
| 0014+813 | SS 0014+813 | Q    | 3.382| Varshalovich et al. (1987) | ...   | ...   | 12.5  | 1      |
| 0015-054 | PMN J0017–0512 | Q    | 0.226| Shaw et al. (2012)  | 4FGL J0017.5+0514 | ...   | 13.6  | 10    |      |
| 0016+731 | SS 0016+73  | Q    | 1.781| Lawrence et al. (1986)| 4FGL J0019.6+7327 | Y     | 12.3  | 9     |      |
| 0019+058 | PKS 0019+058 | B    | ...  | Truebenbach & Darling (2017)| 4FGL J0022.5+0608 | ...   | 13.1  | 10    |      |

Table 2

| Epoch | Obs. Code | Correction Factor |
|-------|-----------|-------------------|
| 2019 Jun 13 | BL229AX | 1.18 |
| 2019 Jun 29 | BL229AY | 1.15 |
| 2019 Jul 19 | BL229AZ | 1.27 |
| 2019 Aug 4 | BL273A | 1.26 |

Table 1: MOJAVE AGN Properties

Table 2: VLBA Flux Density Correction Factors

2.3. VLBA 15 GHz Maps

In Figure Set 1, we present 648 maps of 142 AGN spanning epochs from 2017 January 1 to 2019 August 4. To supplement our kinematics analysis we processed two data sets (3C 264 and IVS B1147+245; epoch 2018 March 30, VLBA observation code BM482) from the VLBA archive, and one from Lister et al. (2020) (TXS 0128+554 epoch 2018 June 29, VLBA observation code BL251). The remaining data come from the MOJAVE program (VLBA observation codes BL229 and BL273).

Since any absolute sky positional information is lost during the self-calibration process, we shifted the origin of each map to the total intensity Gaussian-model-fit position of the core feature, as described in Section 3.1. The core is typically the brightest feature in the map, located at the optically thick surface close to the base of the jet.

In each “dual-plot” map in Figure Set 1, we indicate the FWHM dimensions and orientation of the naturally weighted elliptical Gaussian restoring beam by a cross in the lower left corner. The beam size varies with the decl. of the AGN and number of available antennas, but has typical dimensions of 1.1 × 0.5 mas. We gridded the Stokes maps with a scale of 0.1 mas per pixel. We list the parameters of the restoring beam, base contour levels, total cleaned flux densities, and blank sky map noise levels for each map in Table 3. The false color
corresponds to fractional polarization and is superimposed on a total intensity contour map of the radio emission. No fractional polarization is plotted in regions that lie below the lowest total intensity contour level. The latter typically corresponds to roughly 3 times the \( \sigma \) rms noise level of the map, although this can be higher in the cases of AGN with poorer interferometric coverage due to extreme southern or near-equatorial decl., or very bright jet cores due to dynamic range limitations.

We plot a second map of the source, in blue linear polarization contours increasing by successive factors of 2, at an arbitrary sky position offset from the total intensity map, along with a single lowest total intensity contour in gray. The overlaid sticks indicate the observed electric vector directions and are of arbitrary fixed length. We have not corrected their orientations for any Faraday rotation either internal or external to the AGN jet. Our rotation measure study of the MOJAVE sample (Hovatta et al. 2012) showed that the emission from most of these jets experiences only a few degrees of Faraday rotation at 15 GHz, typically in the region near the base of the jet. The lowest polarization contour is typically 3 times \( \sigma_{Q,U} \), but in \( \sim 14\% \) of the epochs is more than 5 times \( \sigma_{Q,U} \) due to a high peak total intensity in the map, or residual polarization feed leakage errors. We have not applied any Rician de-biasing corrections (i.e., \( P_{\text{corr}} = P_{\text{obs}} \sqrt{1 - (\sigma_f/P_{\text{obs}}^2)} \); Wardle & Kronberg 1974 ) to the maps, since these are \( \lesssim 5\% \) for regions above our lowest polarization contour level.

### 3. Data Analysis

For our kinematics analysis, we have used 15.4 GHz VLBA observations of 447 AGN obtained between 1994 August 31 and 2019 August 4 as part of the MOJAVE and 2 cm VLBA survey programs, with supplementary data from the NRAO archive. There are 49 AGN that have not appeared previously in any MOJAVE kinematics analysis. Although the density and span of time coverage varies considerably among the sample, all of the AGN in the kinematics analysis have at least 5 high quality VLBA epochs over a 1.5–25 yr time span.

#### 3.1. Gaussian Modeling

We modeled the sky brightness distribution for each VLBA observation in the \((u, v)\) visibility plane using the `modelfit` task in DIFMAP. We list the properties of the fitted features in Table 4. In some instances, it was impossible to robustly cross-identify the same features in a jet from one epoch to the next. We indicate the features with robust cross identifications across at least five epochs in column 10 of Table 4. In making robustness determinations, we considered the consistency of evolution in the sky position, flux density, and brightness temperature of the features over time. For the nonrobust features, we caution that the assignment of the same identification number across epochs does not necessarily indicate a reliable cross identification. We initially assigned the identification numbers in ascending order roughly based on their distance from the core, but in many cases the original order had to be modified during the cross-identification process.

Based on previous analysis (Lister et al. 2009b), we estimate the typical uncertainties in the feature centroid positions to be \( \sim 20\% \) of the FWHM naturally weighted image restoring beam dimensions. For isolated bright and compact features, the positional errors are smaller by approximately a factor of 2. We estimate the formal errors on the feature sizes to be roughly twice the positional error, according to Fomalont (1999). The flux density accuracies are approximately 5\% (see Appendix A.1 of Homan et al. 2002), but can be significantly larger for features located very close to one another. Also, at some epochs which lacked data from one or more antennas, the fit errors of some features are much larger. We do not use the latter in our kinematics or jet PA analysis, and indicate them with flags in Table 4.

#### Table 3

| Source (1) | Epoch (2) | \( B_{\text{maj}} \) (3) | \( B_{\text{min}} \) (4) | \( B_{\text{PA}} \) (5) | \( I_{\text{tot}} \) (6) | \( \sigma_I \) (7) | \( I_{\text{peak}} \) (8) | \( P_{\text{peak}} \) (9) | \( \sigma_{Q,U} \) (10) | \( P_{\text{corr}} \) (11) | EVPA (12) | Fig. (13) |
|------------|-----------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-------|--------|
| 0012+610   | 2017 Jan 3| 0.80            | 0.64            | −6              | 257             | 0.12            | 0.33            | <0.4            | 0.13            | 0.44            | ...   | 1.1    |
|            | 2017 Mar 11| 0.73            | 0.66            | 0               | 252             | 0.09            | 0.26            | 2.3             | 0.13            | 0.30            | 0.32  | 1.2    |
|            | 2017 Jun 17| 0.66            | 0.66            | −17             | 232             | 0.10            | 0.23            | 1.6             | 0.11            | 0.30            | 0.17  | 1.3    |
|            | 2017 Aug 25| 0.71            | 0.58            | −6              | 235             | 0.11            | 0.21            | 2.7             | 0.12            | 0.35            | 0.34  | 1.7    |
|            | 2018 May 31| 0.68            | 0.60            | −2              | 247             | 0.10            | 0.25            | 2.4             | 0.10            | 0.40            | 0.12  | 1.5    |
|            | 2019 Jun 29| 0.86            | 0.66            | −28             | 274             | 0.14            | 0.35            | 1.5             | 0.15            | 0.46            | 0.19  | 1.6    |
| 0014+813   | 2017 Jan 28| 0.71            | 0.66            | 70              | 828             | 0.10            | 0.33            | 10              | 0.10            | 0.35            | 0.17  | 1.8    |
|            | 2017 Jun 17| 0.67            | 0.59            | 82              | 853             | 0.10            | 0.30            | 10              | 0.10            | 0.35            | 0.17  | 1.8    |
|            | 2017 Nov 18| 0.82            | 0.72            | −52             | 922             | 0.11            | 0.90            | 7.1             | 0.13            | 0.51            | 0.17  | 1.9    |
|            | 2018 Feb 2| 0.72            | 0.68            | 23              | 904             | 0.11            | 0.34            | 11              | 0.14            | 0.52            | 0.18  | 1.0    |
|            | 2018 Jul 8| 0.63            | 0.55            | −12             | 849             | 0.12            | 0.35            | 20              | 0.12            | 0.46            | 0.15  | 1.1    |
|            | 2018 Nov 11| 0.67            | 0.59            | 42              | 963             | 0.13            | 0.38            | 27              | 0.13            | 0.60            | 0.17  | 1.2    |
|            | 2019 Jun 19| 0.63            | 0.61            | 19              | 957             | 0.12            | 0.47            | 26              | 0.18            | 0.65            | 0.17  | 1.3    |
|            | 2019 Jun 29| 0.74            | 0.71            | 14              | 1077            | 0.14            | 1.04            | 27              | 0.15            | 0.75            | 0.14  | 1.1    |

**Notes.** Columns are as follows: (1) B1950 name; (2) date of VLBA observation; (3) FWHM major axis of restoring beam (milliarcseconds); (4) FWHM minor axis of restoring beam (milliarcseconds); (5) PA of major axis of restoring beam (degrees); (6) total cleaned I flux density (mJy); (7) rms noise level of Stokes I image (mJy per beam); (8) lowest I contour level (mJy per beam); (9) total cleaned P flux density (mJy), or upper limit, based on 3 times the P rms noise level; (10) average of blank sky rms noise level in Stokes Q and U images (mJy per beam); (11) lowest linear polarization contour level (mJy per beam); (12) integrated electric vector PA (degrees); (13) figure number.

* NRAO archive epoch.

(This table is available in its entirety in machine-readable form.)


3.2. Jet Kinematics

We analyzed the kinematics of all individual robust jet features using three methods: (i) a simple one-dimensional radial motion fit, (ii) a nonaccelerating vector fit in two dimensions (R.A. and decl.), and (iii) a constant acceleration two-dimensional fit (for features with 10 or more epochs). We use the radial fit for diagnostic purposes only, and do not tabulate those fit results here. In all cases, we assume the bright core feature (id 0 in Table 4) to be stationary and measure the positions of jet features at all epochs with respect to it. We described the details of the fitting method in Lister et al. (2019). We note that flaring activity, a not-yet-resolved newly ejected feature, or the variable core-shift effect (Plavin et al. 2019) can sometimes result in core positional variations. In cases where a large shift of the core was observed, we flagged that epoch from the kinematics analysis.

We made radial and vector motion fits using all of the available data from 1994 August 31 to 2019 August 4 on 1923 robust jet features in 447 jets. A total of 28 of these jets had no robust features for kinematic analysis due to weak/absent downstream jet flux density, an insufficiently stable core feature, and/or insufficient angular resolution.

In Table 5 we list the results of our vector motion fits. Due to the nature of our kinematic model, which naturally includes the possibility of accelerated motion, we did not estimate ejection epochs (Column 12) for any features where we could not confidently extrapolate their motion to the core. Jet features for which we list an ejection epoch had the following properties: (i) significant motion ($\mu \geq 3 \sigma_\mu$), (ii) no significant acceleration, (iii) a velocity vector direction $\phi$ within 15° of the outward radial direction to high confidence, i.e., $|\langle \dot{\phi} \rangle - \phi | + 2 \sigma \leq 15^\circ$, where $\dot{\phi}$ is the mean PA, (iv) an extrapolated position at the ejection epoch no more than 0.2 mas from the core, and (v) a fitted ejection epoch that differed by no more than 0.5 yr from that given by the radial motion fit.

Approximately half ($N = 926$) of the robust features met the $\geq 10$ epoch criterion for an acceleration fit, and we tabulate these results in Table 6. The majority (60%) of these well-sampled features display either significant acceleration or nonradial motion.

We have marked 64 features in Table 6, in 47 different AGN, that have appreciably slower speeds than other features in the same jet. These slow pattern speed features (i) do not have a $\geq 3 \sigma$ acceleration, (ii) have an angular speed smaller than 20 $\mu$as yr$^{-1}$, and (iii) have a speed at least 10 times slower than the fastest feature in the same jet.

We also include flags in Table 5 and 6 for inward-moving features. In Lister et al. (2019) we discuss the possibility that some of these may be the result of centroid shifts in diffuse emission regions, or curved trajectories crossing the line of sight. Of the 1923 robust features in our latest analysis, only 48 show apparent inward motion. Although this fraction (2.5%) is small, 39 of the AGN jets in our sample (8.7%) show this phenomenon. We provide updated information on selected AGN with inward-moving features in Appendix A.1.

In an earlier paper (Lister et al. 2009a), we discussed the five AGN in the original flux-density-limited MOJAVE sample that have counter-jet features: 0238-084 (NGC 1052), 0316+413 (3C 84), 1228+126 (M87), PKS 1413+135, and 1957+405 (Cyg A). With the exception of PKS 1413+135, these are all nearby ($z < 0.06$) radio galaxies with jets much closer to the plane of the sky than the other AGN in our sample. PKS 1413+135 is a peculiar AGN with blazar properties that may be a gravitationally lensed system (see Readhead et al. 2021 and references therein).

In our current analysis, we find only two new examples of candidate counter-jets in the 1.5JyQC sample: 1928+738 and 1253-055 (3C 279), but in both cases we believe that these are not actual counter-jets, and that the true core is visible only at some epochs (see Appendix notes). Among the non-1.5JyQC AGN presented in this paper, there are only a handful with counter-jet features. These consist of two compact symmetric objects TXS 0128+554 and 1509+054 (PMN J1511+0518), two giant radio galaxies 1637+826 (NGC 6251) and 2043+749 (4C +74.26), the nearby ($z = 0.029$) radio galaxy 0305+039 (3C 78), and the quasar 1148-001 (4C –00.47). In the latter AGN, we have assumed the core to be the most compact feature of the jet, but higher-frequency VLBA observations are needed to more precisely determine its location. In Table 4, we also list a counter-jet feature for the high redshift $z = 2.624$ quasar PKS B0742+103, but the core location is uncertain in this source as noted in the Appendix.

In Table 7, we tabulate a median speed for each jet having at least five features with $\geq 3 \sigma$ speeds; we excluded any counter-jet features.

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**Table 4**

| Source (1) | I.D. (2) | Epoch (3) | $I$ (mJy) (4) | $r$ (mas) (5) | P.A. ($^\circ$) (6) | Maj. (mas) (7) | Ratio (8) | Maj. P.A. ($^\circ$) (9) | Robust? (10) |
|-----------|---------|-----------|-------------|-------------|---------------|--------------|-----------|----------------|-----------|
| 0003+380  | 0       | 2006 Mar 9| 489         | 0.04        | 290.7         | 0.23         | 0.33      | 292          | Y         |
| 0003+380  | 1       | 2006 Mar 9| 7.2         | 3.98        | 121.8         | 0.72         | 1         | ...          | Y         |
| 0003+380  | 2       | 2006 Mar 9| 42.1        | 1.25        | 110.5         | 0.51         | 1         | ...          | Y         |
| 0003+380  | 6       | 2006 Mar 9| 104         | 0.28        | 114.6         | 0.27         | 1         | ...          | Y         |
| 0003+380  | 7       | 2006 Mar 9| 2.9         | 2.31        | 119.3         | ...         | ...       | N           | ...       |
| 0003+380  | 0       | 2006 Dec 1| 320         | 0.10        | 308.1         | 0.25         | 0.29      | 295          | Y         |
| 0003+380  | 1       | 2006 Dec 1| 4.8         | 3.65        | 120.8         | 1.63         | 1         | ...          | Y         |
| 0003+380  | 2       | 2006 Dec 1| 20.9        | 1.56        | 111.0         | 0.25         | 1         | ...          | Y         |
| 0003+380  | 5       | 2006 Dec 1| 22.9        | 0.75        | 116.2         | 0.32         | 1         | ...          | Y         |
| 0003+380  | 6       | 2006 Dec 1| 145         | 0.45        | 116.3         | 0.05         | 1         | ...          | Y         |

**Notes.** Columns are as follows: (1) B1950 name; (2) feature identification number (zero indicates core feature); (3) observation epoch; (4) flux density at 15 GHz in mJy; (5) position offset from the core feature (or map center for the core feature entries) in milliarcseconds; (6) PA with respect to the core feature (or map center for the core feature entries) in degrees; (7) FWHM major axis of fitted Gaussian in milliarcseconds; (8) axial ratio of fitted Gaussian; (9) major axis PA of fitted Gaussian in degrees; (10) robust feature flag.

* Individual feature epoch not used in kinematic fits.

(This table is available in its entirety in machine-readable form.)
### Table 5
Vector Motion Fit Properties of Jet Features

| Source I.D. N | (mJy) | (mas) | (pc) | (deg) | (deg) | (deg) | (μas yr⁻¹) | (c) | (μas) | (μas) |
|---------------|-------|-------|------|-------|-------|-------|------------|-----|-------|-------|
| 0003+380 1 8 5 | 4.23  | 15.36 | 120.7| 96 ± 17| 24 ± 17| 158 ± 43| 2.30 ± 0.63| ... | 2008.81| 3691 ± 74| −2169 ± 80|
| 0003+380 2 6 19 | 1.78  | 6.45  | 112.6| 7.5 ± 3.1| 37 ± 25| 4.61 ± 0.36| ... | 2007.71| 1662 ± 29| −694 ± 11 |
| 0003+380 4 5 16 | 1.25  | 4.53  | 114.9| 90 ± 14 |
| 0003+380 5 8 40 | 0.75  | 2.71  | 117.5| 21 ± 89 |
| 0003+380 6 10 98 | 0.39  | 1.43  | 115.4| 335 ± 46 |
| 0003-066 2 5 222 | 1.05  | 5.12  | 322.9| 226.3 ± 4.9 |
| 0003-066 3 9 119 | 2.82  | 13.73 | 296.9| 284.8 ± 4.7 |
| 0003-066 4 a 26 | 6.61  | 32.23 | 285.6| 284 ± 11 |
| 0003-066 5 a 14 | 0.70  | 3.40  | 10.7| 350.9 ± 5.3 |
| 0003-066 6 a 10 | 1.01  | 4.92  | 290.2| 210 ± 15 |

Notes. Columns are as follows: (1) B1950 name; (2) feature number; (3) number of fitted epochs; (4) mean flux density at 15 GHz in mJy; (5) mean distance from core feature in mas; (6) mean projected distance from core feature in parsec; (7) mean PA with respect to the core feature in degrees; (8) PA of velocity vector in degrees; (9) offset between mean PA and velocity vector PA in degrees; (10) proper motion in μas yr⁻¹; (11) apparent speed in units of the speed of light; (12) estimated epoch of origin; (13) date of reference (middle) epoch used for fit; (14) fitted R.A. position with respect to the core at the middle epoch in μas; (15) fitted decl. position with respect to the core at the middle epoch in μas.

A question mark indicates a feature whose motion is not consistent with outward, radial motion but for which the possibility of inward motion and its degree of nonradialness are uncertain.

A加速模型fit indicates significant accelerated motion.

Feature has significant nonradial motion according to the vector motion fit.

Feature has significant inward motion according to the vector motion fit.

Feature has slow pattern speed.

(This table is available in its entirety in machine-readable form.)
Table 6
Acceleration Fit Properties of Jet Features

| Source | L.D. | $\phi$ (deg) | $|\langle \phi \rangle - \phi|$ (deg) | $\beta_{\text{app}}$ (mas yr$^{-1}$) | $\beta_1$ (mas yr$^{-2}$) | $\psi$ (deg) | $\rho_1$ (mas yr$^{-2}$) | $\rho_1$ (mas yr$^{-2}$) | $\alpha_m$ (mas) | $\delta_m$ (mas) |
|--------|------|--------------|-------------------------------------|-----------------|-----------------|---------------|-----------------|-----------------|-----------------|-----------------|
| 0003+380 | 6    | 333 ± 44     | 142 ± 44                            | 13.4 ± 8.6      | 0.20 ± 0.12     | 9.8 ± 8.4     | 309 ± 53       | −4.0 ± 9.4      | 9.0 ± 9.0       | 371 ± 33        | −175 ± 28       |
| 0003–066 | 5a  | 277.3 ± 3.8  | 8.3 ± 3.8                           | 50.9 ± 5.3      | 1.09 ± 0.11     | 28.5 ± 2.3    | 73.7 ± 3.1     | 11.4 ± 2.1      | −26.1 ± 2.5     | −6582 ± 32      | 1693 ± 20       |
| 0003–066 | 5a  | 353.9 ± 3.0  | 16.8 ± 3.1h                         | 87.2 ± 4.4      | 1.868 ± 0.093   | 26.6 ± 4.9    | 274 ± 10       | −26.3 ± 4.9     | 4.5 ± 4.8       | 199 ± 15        | 630 ± 14        |
| 0003–066 | 6a  | 211.3 ± 9.6  | 78.9 ± 9.6b                         | 54 ± 11         | 1.16 ± 0.24     | 65 ± 16       | 336 ± 11       | 54 ± 13         | −37 ± 18        | −901 ± 16       | 268 ± 35        |
| 0003–066 | 8a  | 290.7 ± 1.6  | 3.5 ± 1.6                           | 330.4 ± 9.7     | 7.08 ± 0.21     | 67 ± 12       | 127 ± 10       | −19 ± 12        | −64 ± 12        | −2444 ± 30      | 1121 ± 28       |
| 0003–066 | 9   | 295.2 ± 4.1  | 7.5 ± 4.3                           | 278 ± 20        | 5.96 ± 0.42     | 99 ± 35       | 110 ± 22       | 9 ± 37          | −99 ± 35        | −1769 ± 52      | 582 ± 53        |
| 0010+405 | 1    | 340.7 ± 4.4  | 11.9 ± 4.4                          | 432 ± 42        | 6.99 ± 0.68     | 44 ± 83       | 147 ± 76       | 11 ± 53         | −43 ± 70        | −4259 ± 76      | 6991 ± 107      |
| 0010+405 | 2    | 9 ± 123      | 41 ± 123                           | 2 ± 14          | 0.04 ± 0.23     | 4 ± 22        | 152 ± 123      | 2 ± 21          | −3 ± 23         | −898 ± 30       | 1470 ± 48       |
| 0010+405 | 3    | 138 ± 83     | 170 ± 83                           | 2.5 ± 5.4       | 0.041 ± 0.088   | 6.9 ± 6.1     | 99 ± 57        | −4.3 ± 8.8      | 5.4 ± 9.0       | −493.6 ± 9.5    | 783 ± 15        |
| 0010+405 | 4    | 113 ± 98     | 145 ± 98                           | 1.4 ± 4.5       | 0.022 ± 0.072   | 5.2 ± 8.9     | 318 ± 69       | −2.2 ± 7.1      | −4.7 ± 8.1      | −240.6 ± 9.0    | 382 ± 14        |

Notes. Columns are as follows: (1) B1950 name; (2) feature number; (3) proper motion PA in degrees; (4) offset between mean PA and proper motion PA in degrees; (5) proper motion in mas yr$^{-1}$; (6) apparent speed in units of the speed of light; (7) acceleration in mas yr$^{-2}$; (8) acceleration vector PA in degrees; (9) acceleration perpendicular to velocity direction in mas yr$^{-2}$; (10) acceleration parallel to velocity direction in mas yr$^{-2}$; (11) fitted R.A. position with respect to the core at the middle epoch in mas; (12) fitted decl. position with respect to the core at the middle epoch in mas.

A question mark indicates a feature whose motion is not consistent with outward, radial motion but for which the possibility of inward motion and its degree of nonradialness are uncertain.

a Feature shows significant accelerated motion.
b Feature shows significant nonradial motion according to the acceleration fit.
c Feature shows significant inward motion according to the acceleration fit.

(This table is available in its entirety in machine-readable form.)
features and those flagged as having inward motion. For features with \( \geq 3\sigma \) accelerations, we used the speed from the acceleration fit, otherwise we used the vector motion fit speed. The error for the median speed in Table 7 is either that of the middle value in the distribution, or the mean of the two middle values for jets with an even number of speed measurements. We also tabulated a

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Table 7

| B1950     | \( \mu_{\text{max}} \)  | \( \mu_{\text{med}} \)  | \( \beta_{\text{max}} \) | \( \beta_{\text{med}} \) | \( N_{\text{ep}} \) | \( N_{\text{r}} \) | Ref. | PA | \( \Delta PA \) | \( \log \text{Var}(PA) \) | \( \Delta \tau \) |
|-----------|--------------------------|--------------------------|---------------------------|---------------------------|-------------------|-------------------|-----|---|----------------|--------------------|------------------|
| 0003+380  | 317 \( \pm \) 25         | \( \ldots \)             | 4.61 \( \pm \) 0.36       | \( \ldots \)              | 10                | 5                 | 3               | 115 | 17          |\(-2.5\)             | 7.4               |
| 0003-066  | 330.4 \( \pm \) 9.7      | 116 \( \pm \) 23          | 7.08 \( \pm \) 0.21       | 2.48 \( \pm \) 0.49       | 27                | 9                 | 3               | 15  | 12          |\(-2.8\)             | 17.3              |
| 0006+061  | 221 \( \pm \) 43         | \( \ldots \)             | \( \ldots \)              | \( \ldots \)              | 5                 | 2                 | 6               | 63  | 4           |\(-3.5\)             | 1.4               |
| 0007+106  | 269 \( \pm \) 50         | \( \ldots \)             | 1.58 \( \pm \) 0.29       | \( \ldots \)              | 25                | 2                 | 3               | 292 | 32          |\(-2.2\)             | 12.9              |
| 0011+189  | 159 \( \pm \) 16         | \( \ldots \)             | 4.54 \( \pm \) 0.46       | \( \ldots \)              | 8                 | 2                 | 3               | 219 | 3           |\(-3.9\)             | 2.1               |
| 0010+405  | 428 \( \pm \) 40         | \( \ldots \)             | 6.92 \( \pm \) 0.64       | \( \ldots \)              | 12                | 4                 | 3               | 328 | 4           |\(-4.0\)             | 5.2               |
| 0012+610  | 7.2 \( \pm \) 6.3a       | \( \ldots \)             | \( \ldots \)              | \( \ldots \)              | 6                 | 2                 | 6               | 37  | 4           |\(-3.5\)             | 2.5               |
| 0014+813  | 87.8 \( \pm \) 8.5       | \( \ldots \)             | 9.47 \( \pm \) 0.91       | \( \ldots \)              | 14                | 3                 | 6               | 184 | 22          |\(-2.1\)             | 22.7              |
| 0015-054  | 50 \( \pm \) 20a         | \( \ldots \)             | 0.72 \( \pm \) 0.28a      | \( \ldots \)              | 8                 | 1                 | 3               | 242 | 16          |\(-2.2\)             | 3.5               |
| 0016+731  | 98.5 \( \pm \) 4.1       | \( \ldots \)             | 7.64 \( \pm \) 0.32       | \( \ldots \)              | 16                | 2                 | 6               | 126 | 43          |\(-1.8\)             | 24.8              |
| 0019+058  | 257 \( \pm \) 35         | \( \ldots \)             | \( \ldots \)              | \( \ldots \)              | 7                 | 2                 | 3               | 285 | 14          |\(-2.5\)             | 2.6               |

Notes. Columns are as follows: (1) B1950 name; (2) maximum jet speed in \( \mu \text{as} \ \text{y}^{-1} \); (3) median jet speed in \( \mu \text{as} \ \text{y}^{-1} \); (4) maximum jet speed in units of the speed of light; (5) median jet speed in units of the speed of light; (6) number of VLBA epochs; (7) number of robust fitted jet features; (8) reference for jet kinematics, where 1: Lister et al. (2013), 2: Lister et al. (2016), 3: Lister et al. (2019), 4: Piner et al. (2010), 5: Jorstad et al. (2017), 6: this paper, (9) mean innermost jet PA in degrees, (10) range of innermost jet PA in degrees, (11) log of circular variance of innermost jet PA, (12) time coverage used to determine jet PA statistics in years. 

a Speed is \( < 3\sigma \).

(This table is available in its entirety in machine-readable form.)

Figure 2. Histogram plots of median jet speed (top panels) and fastest jet speed (bottom panels) for AGN with known redshifts. The histograms in the right-hand panels show AGN in the flux-density-limited MOJAVE 1.5 Jy QC sample.
maximum speed for each jet using the same criteria. If a jet had no \( \geq 3\sigma \) speed features, we used the fastest \( \geq 2\sigma \) speed, or otherwise, the speed with the lowest error value.

In the left-hand panels of Figure 2, we plot the distribution of median and maximum apparent jet speeds of all the AGN in our sample with known redshifts. We show the distributions for the 1.5 Jy QC sample AGN in the right hand panels. The maximum speed distribution for the full sample (lower left panel) is peaked below 2c, but 45% of the jets in the first bin have 2 or fewer robust features. The maximum speed distribution for jets with at least five robust features (lower panel, shaded) is not sharply peaked, suggesting that multiple features must typically be tracked in a jet to get a more robust measure of the overall flow speed. The 1.5 Jy QC sample AGN have typically been tracked in the MOJAVE program for longer time periods, so their maximum speed distribution is not as sharply peaked.

In Figure Set 3, we plot the angular separation of features from the core in each jet versus time. The robust features have filled colored symbols and solid lines representing the fit. The feature identification number is overlined if the acceleration model was fit and yielded a \( \geq 3\sigma \) acceleration. An underlined identification number indicates a feature with nonradial motion, i.e., its velocity vector does not point back to the core location within the errors. We plot the individual trajectories and fits on the sky for all the robust features in Figure Set 4.

### 3.3. Inner Jet Position Angle Analysis

In Lister et al. (2013), we presented the first large survey of inner PA variations in AGN jets based on data from 1994 to 2011, where we found evidence for large changes in jet PA within \( \sim 1 \text{ mas} \) (\( \sim 8 \text{ pc} \) projected at \( z = 1 \)) of the core over decadal timescales, in some cases as fast as \( 10^9 \text{ yr}^{-1} \). Here we carry out a new analysis, using additional data obtained between 2011 May 21 and 2019 August 4. Our main goals are to: (i) determine the PA of the jet as close as possible to the core feature, using the maximum angular resolution of the VLBA data at 15 GHz, and (ii) examine the behavior of the inner jet PA over time in individual jets and among different AGN classes.

In our previous study, we determined the inner jet PA using a flux-density weighted PA average of components from the CLEAN imaging algorithm within an annular region from 0.15 mas to 1 mas from the core. This method fails, however, for AGN with faint jet structure and/or insufficient CLEAN components near the core. Because the method relies on images restored with a Gaussian (natural-weighted) beam, it also does not yield optimal values for many jets in the MOJAVE sample that have sharp apparent bent jet ridge lines near the core. The latter are better traced using the Gaussian model components that are modeled in the visibility plane, which takes advantage of the high positional measurement accuracy of the VLBA for bright features.

We have therefore chosen to use the position of the innermost Gaussian model component with respect to the core to measure the jet PA at each epoch. This generally yields robust results, as exhibited by the good continuity of jet PAs over time in individual AGN. In a few rare cases, there are two Gaussian model components located roughly equidistant from
of the feature at the measured epochs. The right-hand panel shows the radial separation of the feature from the core feature over time.

Well due to features with second-order accelerations that are not have large PA error values. Most of these are overestimates, the majority of the values lie between 1° and 10°, with the most common error being ~4°. A small number of source epochs have large PA error values. Most of these are overestimates, due to features with second-order accelerations that are not well fit by a constant acceleration model (e.g., PKS 1510-089 id 15, 1641+399 id 12), and therefore have large fit residuals.

3.3.1. Trends with Time

We calculated for each jet the circular mean (\(\overline{PA}\)), the full range over which the PA varies (\(\Delta PA\)), and the circular variance. Although the latter quantity formally spans a possible range between 0 \(<\text{Var}(PA)\) \(<1, we use the base 10 logarithm of Var(PA) as there are a large number of values very close to zero. We list these quantities in Table 7.

To mitigate the possible effects of sampling bias, we restricted our statistical analysis to those jets with 12 or more VLBA epochs over a minimum 10 yr period. A total of 173 jets met this criterion, 143 of which are in the MOJAVE 1.5JyQC sample. Most of the jets have inner PAs that vary on decadal timescales over a range of 10° to 50°. However, some jets display very large changes in PA, with the overall distribution having a continuous tail out to \(\Delta PA = 200°\).

A jet can change its apparent PA over time in several different ways. One way is to eject a feature that moves steadily outward on a curved or nonradial trajectory, resulting in a smooth evolution of the inner jet PA. We show some examples of this in Figure 6. A newly ejected feature may also experience a very rapid fading, reverting the innermost PA to the next significantly different PA from previous ones. An example is 0851+202 (OJ 287), which underwent a monotonic ~3° per year change in jet PA from 1995 to 2010 due to the nonradial motion of feature id 10. In 2010 May the inner PA jumped ~100° when a new bright feature (id 19) emerged from the core region with a substantially different trajectory. Other examples have occurred in the jets of PKS 0420-014, 1253-055 (3C 279), and 1633+382 (4C +38.41) (Figure 8).
3.3.2. Jet Nozzle Wobbling

There has been extensive discussion in the literature about possible causes of nozzle wobbling in AGN jets (see, e.g., review by Qian et al. 2014), which include MHD flow instabilities (Matveyenko & Seleznev 2015), Lense–Thirring precession of the accretion disk (Liu & Melia 2002; Caproni et al. 2004), or the influence of a binary black hole companion (Dey et al. 2021). Precession is well-characterized in stellar jet systems such as SS 433 (Roberts et al. 2008), but the much longer timescales and vastly larger distances associated with AGN jets and their accretion disks make their study more challenging.

A complicating factor in using VLBA data to investigate jet precession is that we are not seeing the full extent of the jet. Our long-term monitoring has shown that at any given epoch, only certain portions of the flow are sufficiently energized to appear in VLBA images, which typically have dynamic ranges of a few thousand to one (Lister et al. 2013). A good example is quasar 1308+326 (OP 313), which in the mid 1990 s showed no apparent downstream jet emission on parsec scales (Ojha et al. 2004). Throughout the following 25 yr, this AGN launched a series of bright features that moved downstream on trajectories with a variety of individual PAs, giving an illusory bent jet appearance in individual epoch images. When the images over a 25 yr period are stacked, however, a smooth conical jet structure emerges (Pushkarev et al. 2017).

Because the ejected features do not fill the entire jet cross section in observed emission, a wobbling flow instability generated near the jet base is the most likely mechanism for the observed PA variations in many jets. As this region of enhanced magnetic field strength and/or plasma density...
Section 3.3.3. Trends with AGN Classes

We have examined the PA range and variance statistics with respect to general AGN properties using Anderson–Darling tests (Stephens 1974). Our subsample is made up of 117 quasars, 43 BL Lac objects, 10 radio galaxies, and 3 narrow-line Seyfert Is. All but 18 of these AGN have been listed as Fermi LAT gamma-ray associations (Table 1).
With respect to optical classification, we find that BL Lac objects have smaller PA ranges \( (p_{\text{null}} = 0.0037) \) and PA variances \( (p_{\text{null}} = 0.001) \) than quasars (Figure 10). Our tests indicate that these two subsamples have indistinguishable VLBA epoch coverage, but substantially different redshift distributions, with the BL Lac objects having generally lower \( z \) values. It is unlikely that the PA differences are due to redshift, however, since we find (i) no trend of \( \Delta PA \) with \( z \) within the quasar subsample (which spans \( 0.16 < z < 3.4 \)) and (ii) no significant difference in the \( \Delta PA \) distributions of quasars and radio galaxies, where the latter are all at low redshift \( (0.004 < z < 0.14) \).

We do not find any statistically significant differences in the PA ranges or PA variances of the 23 TeV-detected AGN compared to the other AGN in our sample. However, we find that the 18 non-LAT-associated AGN have smaller PA ranges \( (p_{\text{null}} = 0.0098) \) and PA variances \( (p_{\text{null}} = 0.0076) \) than the LAT-associated AGN (Figure 11). There are no significant differences in the epoch coverage or redshift distributions of the LAT versus non-LAT AGN.

There are several possible factors that could increase the range and variance of a jet’s PA over time, including a wider apparent opening angle of its overall plasma outflow, and a less stable jet base. Also, as more emerging features are tracked in a jet over time, the spread of initial trajectory PAs \( (\Delta PA) \) may be expected to increase until it approaches the full jet opening angle. The BL Lac objects, quasars, and LAT and non-LAT AGN show no significant differences in their number of robust jet features, which suggests that the feature ejection rate (which is not affected by Doppler time compression effects) does not have a strong influence on the PA variance. We have also ruled out the possible effects of observational time coverage and redshift based on our statistical tests. The remaining factors to consider are the intrinsic nozzle stability, intrinsic opening angles, and viewing angles of the jets.

In a previous analysis of the MOJAVE sample (Lister et al. 2015), we found that non-LAT-associated AGN tend to have lower Doppler boosting factors and SEDs that are peaked at lower frequencies. All of the 43 BL Lac objects in our subsample are LAT-associated, which is consistent with their generally harder gamma-ray spectra and SED peaks that span a large range, up to \( 10^{17} \) Hz. The non-LAT radio galaxies and quasars, on the other hand, have SED peaks that range up to only \( 10^{13.4} \) Hz.

In Figures 12 and 13, we plot Var(\( PA \)) and \( \Delta PA \) versus the SED peak frequency for the 174 AGN in our subsample. The non-LAT-associated AGN are plotted with filled symbols. There is a tendency for lower synchrotron peaked AGN to have more variable inner jet PAs \( (p_{\text{null}} = 0.006 \) for \( \Delta PA \) and \( p_{\text{null}} = 0.0003 \) for Var(\( PA \)), according to Spearman’s \( \rho \) tests). We have determined Doppler factors \( (\delta) \) for the jets in our sample as part of a MOJAVE study of core brightness temperatures (Homan et al. 2021). The latter follows on our previous work (Homan et al. 2006) and exploits the fact that

![Figure 8. Plots of inner jet PA vs. time for several individual AGN that show sudden jumps in PA due to the emergence of a new feature with a substantially different trajectory than previous features. This occurred in 2002 and 2007 for 0420-014, in 2010 for 0851+202 (OJ 287), in 2005 and 2013 for 1253-055 (3C 279), and in 2005 for 1633+382.](image-url)
in their median low-brightness temperature \( (T_b) \) state, the MOJAVE AGN cores have a narrow range of intrinsic \( T_b \) values \( (T_{\text{int}}) \). Homan et al. derived Doppler factors from the observed \( T_b \) values according to \( T_{\text{obs}} = \delta T_{\text{int}} \), and jet viewing angles \( (\theta) \) from the maximum measured jet speeds presented in this paper.

The jets in our sample with \( \delta \lesssim 10 \) show a smaller range of jet PA (Figure 14) and PA variance (Figure 15). This is

\[ \text{Figure 9.} \text{ Plots of inner jet PA vs. time for individual AGN (blue circles) overplotted with best-fit sinusoid curves (red dotted lines). These represent the best cases in the sample for possible periodicity. Each panel is plotted with the same vertical scaling for comparison purposes.} \]
primarily a consequence of their larger jet viewing angles. As a
conical jet is oriented closer to the plane of the sky ($\theta \rightarrow 90^\circ$),
itself apparent half opening angle $\phi_{\text{app}}$ will approach its intrinsic
half opening angle $\phi$, where

$$\tan \phi_{\text{app}} = \frac{\tan \phi}{\sin \theta \left(1 - \frac{\tan^2 \phi}{\tan^2 \theta}\right)^{1/2}}.$$  \hspace{1cm} (1)

Conversely, as a conical jet is oriented closer to the line
of sight, it will be viewed inside its opening angle when $\theta \lesssim \phi$.

In Figure 16, we plot the inner jet PA range versus jet viewing
angle. A Spearman nonparametric test indicates a strong trend ($p_{\text{null}} = 10^{-16}$) of smaller PA ranges for jets viewed farther from
the line of sight. We have overplotted dashed curves showing the
full apparent jet opening angle as a function of viewing angle $\theta$
for several values of intrinsic half opening angle. We have
truncated the top of each plotted curve at $\theta = \phi$, beyond which
the expected apparent PA range increases to $360^\circ$. As evident
from Figure 16, the majority of the jets have intrinsic half
opening angles between $\sim 0^\circ.5$ and $\sim 2^\circ$.

It can be seen in Figure 16 that there are no obvious
differences in the intrinsic jet opening angles of the
BL Lac objects versus quasars. The BL Lac objects in the
MOJAVE sample are a mixture of low- and high-spectral
peaked blazars, with the latter generally having lower
Lorentz factors, lower Doppler factors, and larger
viewing angles than the quasars (Homan et al. 2021). We
conclude that the overall larger viewing angles of BL Lac
jets are responsible for their smaller jet PA ranges and
variances.

The LAT- and non-LAT-associated AGN have a similar
intrinsic median opening angle, although we note there is
only one non-LAT jet (PKS 0607-15) narrower than 0°.4. The non-LAT jets have larger viewing angles ($p_{null} = 0.002$) and lower Doppler factors ($p_{null} = 0.003$). Their respective Lorentz factor distributions have a marginal probability ($p_{null} = 0.04$) of being drawn from the same population. As it was in the case of the BL Lac objects versus quasars, the non-LAT jets have smaller PA ranges and variances than LAT-associated AGN because they are oriented at larger angles to the line of sight.

4. Summary and Conclusions

We have analyzed the parsec-scale jet kinematics of 447 bright radio-loud AGN based on 15 GHz VLBA data obtained between 1994 August 31 and 2019 August 4. This represents the largest and most complete AGN jet kinematics study to date. These northern sky AGN (J2000 decl. $>-30^\circ$) have been part of the 2 cm VLBA survey or MOJAVE programs and have correlated flux density $>50$ mJy at 15 GHz. There are 49 AGN that have not appeared in previous MOJAVE kinematics papers. These were added on the basis of their gamma-ray emission properties or membership in the Robopol optical polarization monitoring program. We present new total intensity and linear polarization maps obtained between 2017 January 1 to 2019 August 4 for 143 AGN in our sample.

By modeling the jet emission with a series of Gaussians in the interferometric visibility plane, we identified and tracked 1923 individual features over at least five epochs. We fitted their sky trajectories with simple radial and vector motion models and additionally carried out constant acceleration fits for 926 features that had ten or more epochs.

We summarize our findings as follows:

1. We tracked at least one robust bright jet feature across five or more epochs in 419 of the 447 AGN jets in our analysis. The majority (60%) of the well-sampled jet features showed evidence of either accelerated or nonradial motion at the $\geq 3\sigma$ level.

2. Only 2.5% of the robust jet features had velocity vectors apparently directed inward toward the core. However, 8.7% of the AGN jets in the sample had at least one inward-moving feature. These features may be the result of centroid shifts in diffuse emission regions, or curved trajectories crossing the line of sight.

3. We identified 64 nonaccelerating features with unusually slow pattern speeds ($\mu < 20$ $\mu$as yr$^{-1}$) and at least 10
times slower than the fastest feature in the jet) in 47 jets that may be standing shocks in the flow.

4. We have analyzed variations of the innermost jet PAs in our AGN sample over time. We restricted our analysis to 173 jets that had 12 or more VLBA epochs over a minimum 10 yr period. By using the PA of the closest fitted Gaussian feature to the core at each epoch, we derived a mean jet PA, as well as the range of jet PA and its circular variance. Most of the jets have inner PAs that vary on decadal timescales over a range of 10°–50°. However, some jets display very large changes in PA, with the overall distribution having a tail out to ΔPA = 200°. Some jets show a monotonic evolution of PA after ejecting a feature that moves outward on a curved or nonradial trajectory. In some cases, a jet experiences a sudden large jump in PA when a new bright feature emerges with a substantially different trajectory than previously ejected features.

5. We find that AGN with SEDs peaked at lower frequencies tend to have more variable jet PAs. This is reflected in a tendency for the BL Lac objects in our sample to have less variable PAs, since their SED peak distribution extends to much higher frequencies than the quasars and radio galaxies. Furthermore, the Fermi LAT gamma-ray associated AGN in our sample tend to have more variable PAs than the non-LAT AGN. We have ruled out the possible effects of redshift, time sampling, and feature ejection rate as the cause of these differences. By using Lorentz factor and Doppler factor measurements from a MOJAVE analysis of AGN core brightness temperatures (Homan et al. 2021), we conclude that the non-LAT and higher synchrotron peaked (BL Lac) jets show smaller variance and range in their inner jet PAs because they are viewed at slightly larger angles to the line of sight.

6. We have identified 13 AGN where over a decade long period, multiple features emerge from the core with ejection PAs that follow a systematic trend. Since the ejected features do not fill the entire jet cross section, this behavior is indicative of a wobbling flow instability near the jet base. New features may emerge from this region of enhanced magnetic field/plasma density as it precesses on ~decadal timescales. Occasionally this instability may be disrupted and/or a new instability forms at another location, resulting in a sudden jump in the inner jet PA. We have looked for evidence of periodic PA behavior in 67 jets that show back and forth PA evolution using Lomb–Scargle periodograms. The best-fit periods range from 6 to 16.7 yr; however, we cannot claim any bona fide cases of periodicity since these periods are comparable to the 10–25 yr VLBA time coverages of the AGN.

The MOJAVE project was supported by NASA-Fermi grants 80NSSC19K1579, NNX15AU76G, and NNX12A087G. YYK is supported in the framework of the State project “Science” by the Ministry of Science and Higher Education of the Russian Federation under contract 075-15-2020-778. TS was supported by the Academy of Finland projects 274,477 and 315,721. The Very Long Baseline Array and the National Radio Astronomy Observatory are facilities of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. This work made use of the Swinburne University of Technology software correlator (Deller et al. 2011), developed as part of the Australian Major National Research Facilities Programme and operated under licence. This research has used observations with RATAN-600 of the Special Astrophysical Observatory, Russian Academy of Sciences (SAO RAS). The observations with the SAO RAS telescopes are supported by the Ministry of Science and Higher Education of the Russian Federation. This research has made use of data from the OVRO 40 m monitoring program Richards et al. (2011), which is supported in part by NASA grants NNX08AW31G, NNX11A043G, and NNX14AQ89G and NSF grants AST-0808050 and AST-1109911. This research has made use of data from the University of Michigan Radio Astronomy Observatory, which has been supported by the University of Michigan and by a series of grants from the National Science Foundation, most recently AST-0607523. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

Facility: VLBA, OVRO:40 m, RATAN, UMRAO, NED, ADS.
Software: astropy (Astropy Collaboration et al. 2013, 2018), DIFMAP (Shepherd 1997), AIPS (Greisen 2003).

Appendix

A.1. Notes on Individual AGN

Here we provide comments on individual AGN supplementing those given in Lister et al. (2013, 2016) and Lister et al. (2019).

0106+678 (4C +67.04): An additional VLBA epoch in 2019 has shown that a jet feature (id 4) in this BL Lac no longer has statistically significant inward motion.

0420+417 (4C +41.11): With the addition of new epochs after 2017.0, the centroid of the large diffuse feature (id 6) at the end of the jet shows inward motion. The evolution of the innermost feature (id 11) is not consistent with radial, outward motion.
0518+211 (RGB J0521+212): Additional epochs obtained since 2017.0 indicate that the innermost jet feature in this BL Lac object (id 10) no longer has statistically significant inward motion in the vector fit, but continues to be inward in the acceleration fit.

S 0636+680: This quasar at $z = 3.177$ has a radio spectrum peaked at 5 GHz and compact radio structure $\sim$1 mas in extent. We assume the core lies in the northernmost feature, which has the highest brightness temperature and flux density.

PKS B0742+103: This quasar has a radio spectrum peaked at 3 GHz and an uncertain core location in our 15 GHz images. We therefore classified none of the jet features as robust. We assigned the core to the brightest jet feature at each epoch, which lies in between two features (id 4 and id 5). A recent 43 GHz VLBA image by Cheng et al. (2020) shows a core-dominated morphology with jet emission to the N and NW.

0743-006 (0I -072): This quasar at $z = 0.996$ has a radio spectrum peaked at 7 GHz and compact radio structure only 2 mas in extent. A VLBA 43 GHz by Cheng et al. (2020) shows the brightest feature at the southern end of the jet, which we use as the core location for our kinematics analysis.

0810+646 (87 GB 081008.0+644032): This BL Lac at $z = 0.239$ had no bright robust jet features.

MRC 0910-208: None of the new features in this quasar at $z = 0.198$ were sufficiently bright or compact to be labeled as robust.

1101+384 (Mrk 421): Two features (id 9 and id 11) show significant inward motion in the vector motion fit but not in the acceleration fit. Another feature (id 8) has inward motion in both fits.

PKS 1118-056: New epochs obtained after 2017.0 show a new feature (id 8) to have inward motion.

1142+198 (3C 264): Additional kinematics analyses of the VLBA data on this AGN jet have been published by Archer et al. (2020) and Boccardi et al. (2019).

2153+081: In 2012 an apparent counter-jet emerged in this quasar at $z = 2.06$. After these features were ejected they faded in 2018 if the quasi-stationary feature is used as a reference point.

PKS 1725-301: The VLBA epochs in 2013 showed a jet feature $0.198$ were sufficient.

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An abstract.

S5 2353+816: No robust jet features could be identified in this BL Lac object due to the large gap in the VLBA time coverage.

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Astronomy II, ed. G. B. Taylor, C. L. Carilli, & R. A. Perley
San Francisco, CA: ASP

The Astrophysical Journal.
Erratum: “Monitoring of Jets in Active Galactic Nuclei with VLBA Experiments. XVIII. Kinematics and Inner Jet Evolution of Bright Radio-loud Active Galaxies” (2021, ApJ, 923, 30)

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Received 2023 April 18; published 2023 May 24

Supporting material: machine-readable table

Due to an internal MOJAVE database error, the mean flux density column in the machine-readable version of Table 5 is incorrectly tabulated for 32 model components. None of the data analysis in the paper is affected. The corrected version of Table 5 is included in this erratum in machine-readable format.

We are grateful to Philip Weber for discovering this issue.
### Table 5
Vector Motion Fit Properties of Jet Features

| Source I.D. | Source I.D. | $N$ | $S$ | $R$ | $\langle f \rangle$ | $d_{proj}$ | $\langle \varphi \rangle$ | $\langle \varphi - \varphi \rangle$ | $\langle S \rangle$ | $\langle R \rangle$ | $\langle \mu \rangle$ | $\beta_{app}$ | $t_{ej}$ | $t_{mid}$ | $\alpha_{tr}$ | $\alpha_{ln}$ |
|-------------|-------------|-----|-----|-----|-----------------|------------|-----------------|-----------------|----------------|-------------|---------------|-------------|---------|---------|----------|----------|
| 0003+380    | 0003+380    | 2   | 1   | 8   | 5               | 15.36      | 120.7          | 96 ± 17         | 24 ± 17         | 158 ± 43     | 2.30 ± 0.63   | ...        | 2008.81   | 3691 ± 74 | −2169 ± 80 |
| 0003+380    | 0003+380    | 6   | 2   | 19  | 17.8           | 6.45       | 112.6          | 120.1 ± 3.1     | 7.5 ± 3.1       | 317 ± 25     | 4.61 ± 0.36   | ...        | 2007.71   | 1662 ± 29 | −694 ± 11  |
| 0003+380    | 0003+380    | 16  | 4   | 5   | 1.25           | 4.53       | 114.9          | 205 ± 14        | 90 ± 14         | 39 ± 10      | 0.57 ± 0.15   | ...        | 2009.54   | 1130 ± 11 | −527 ± 14  |
| 0003+380    | 0003+380    | 40  | 5   | 8   | 0.75           | 2.71       | 117.5          | 21 ± 89         | 96 ± 89         | 2.7 ± 7.6    | 0.04 ± 0.11   | ...        | 2010.26   | 663 ± 20  | −342 ± 10  |
| 0003+380    | 0003+380    | 98  | 6   | 10  | 0.39           | 1.43       | 115.4          | 335 ± 46        | 141 ± 46        | 12.7 ± 8.4a  | 0.19 ± 0.12   | ...        | 2009.90   | 350 ± 22  | −158 ± 19  |
| 0003-066    | 0003-066    | 222 | 2   | 5   | 1.05           | 5.12       | 322.9          | 226.3 ± 4.9     | 96.6 ± 5.0b     | 191 ± 15     | 4.09 ± 0.33   | ...        | 1997.80   | −585.9 ± 8.9 | 883 ± 37  |
| 0003-066    | 0003-066    | 119 | 3   | 9   | 2.82           | 13.73      | 296.9          | 284.8 ± 4.7     | 12.1 ± 4.8      | 250 ± 39     | 5.36 ± 0.83   | ...        | 1999.33   | −2375 ± 98 | 1237 ± 41  |
| 0003-066    | 0003-066    | 120 | 4   | 26  | 6.61           | 32.23      | 285.6          | 284 ± 11        | 2 ± 11         | 41 ± 14      | 0.87 ± 0.29   | ...        | 2004.83   | −6326 ± 60 | 1768 ± 22  |
| 0003-066    | 0003-066    | 1031| 5   | 14  | 0.70           | 3.40       | 107            | 350.9 ± 5.3     | 19.9 ± 5.5b     | 88.1 ± 4.3   | 1.888 ± 0.091| ...        | 2004.37   | 138 ± 18  | 634.1 ± 9.0|
| 0003-066    | 0003-066    | 97  | 6   | 10  | 1.01           | 4.92       | 290.2          | 210 ± 15        | 81 ± 15b       | 55 ± 17      | 1.18 ± 0.37   | ...        | 2003.78   | −941 ± 15 | 359 ± 33  |

**Notes.** Columns are as follows: (1) B1950 name, (2) feature number, (3) number of fitted epochs, (4) mean flux density at 15 GHz in mJy, (5) mean distance from core feature in milliarcseconds, (6) mean projected distance from core feature in parsecs, (7) mean position angle with respect to the core feature in degrees, (8) position angle of velocity vector in degrees, (9) offset between mean position angle and velocity vector position angle in degrees, (10) proper motion in $\mu$as yr$^{-1}$, (11) apparent speed in units of the speed of light, (12) estimated epoch of origin, (13) date of reference (middle) epoch used for fit, (14) fitted R.A. position with respect to the core at the middle epoch in $\mu$as, (15) fitted decl. position with respect to the core at the middle epoch in $\mu$as.

A question mark indicates a feature whose motion is not consistent with outward, radial motion but for which the possibility of inward motion and its degree of nonradialness is uncertain.

*a Acceleration model fit indicates significant accelerated motion.

*b Feature has significant nonradial motion according to the vector motion fit.

*c Feature has significant inward motion according to the vector motion fit.

*d Feature has slow pattern speed.

(This table is available in its entirety in machine-readable form.)
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