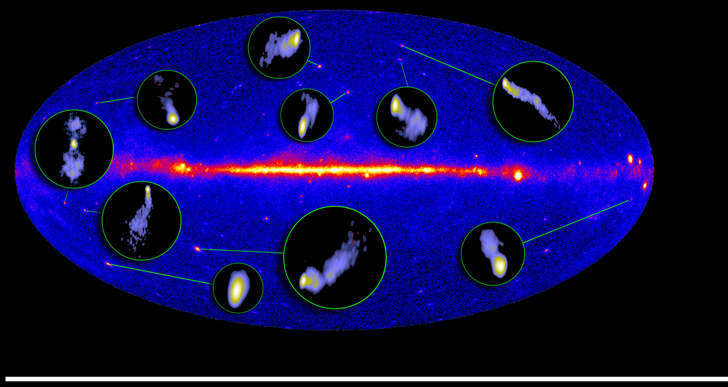
Jet opening angles and γ-ray brightness of AGN



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Apparent jet opening angles are on average wider in LAT-detected blazars than those in non-LAT-detected, suggesting smaller viewing angles.

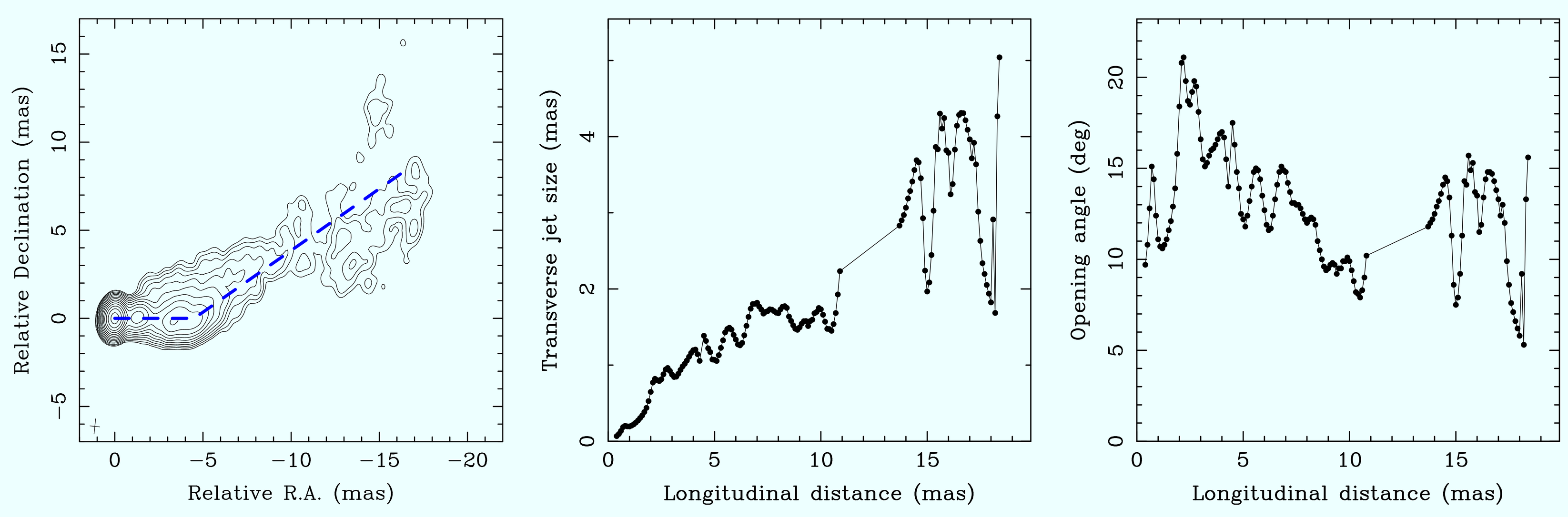

Fig. 1. *Left:* MOJAVE image of 1641+399 at 15 GHz observed on 2009 February 25. The jet axis is approximated by two straight lines in position angles of $-90°$ and $-50°$. *Middle:* Deconvolved FWHM transverse size of the jet along its axis. *Right:* Apparent opening angle of the jet along its axis.

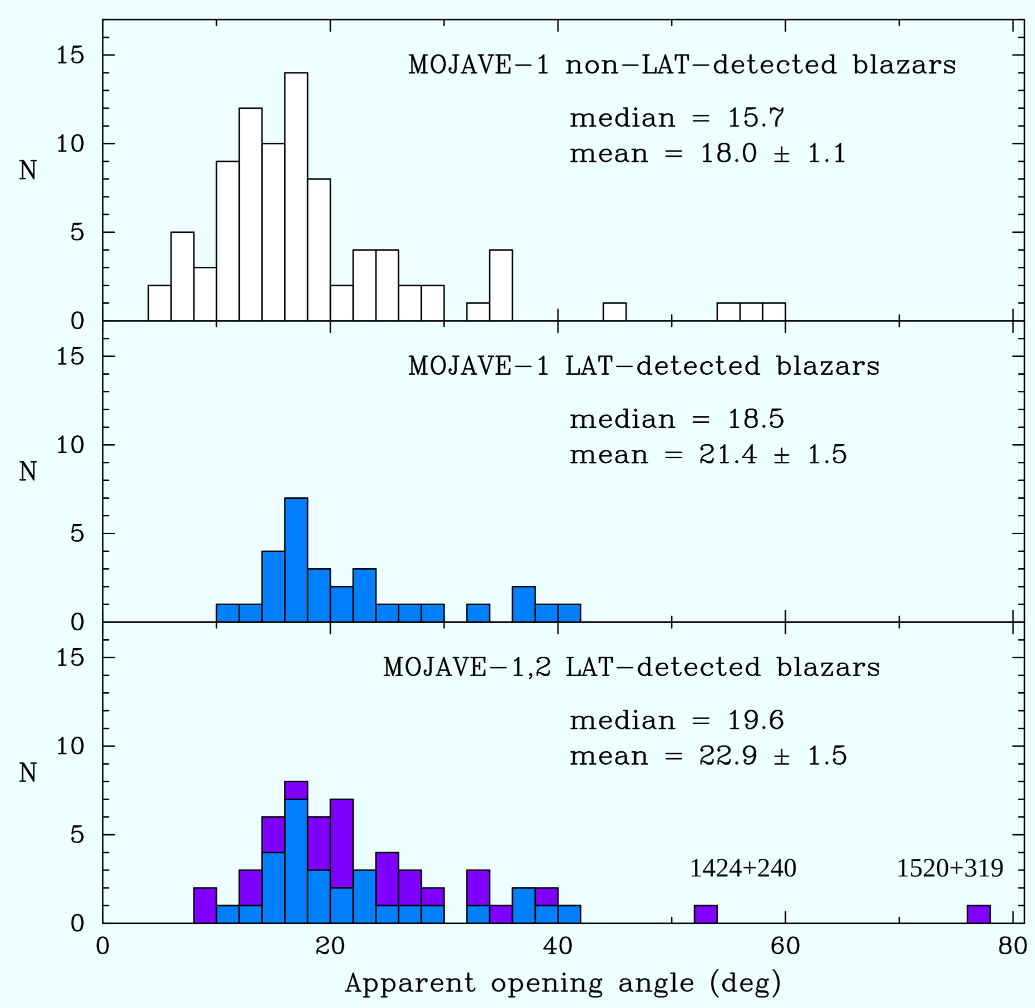

Fig. 2. Distributions of the **apparent opening angle** from jet-cut analysis for 86 non-LAT-detected (*top panel, unshaded*), 29 LAT-detected (*middle and bottom panel, blue*) MOJAVE-1 blazars, and 27 LAT-detected (*bottom panel, violet*) additional MOJAVE-2 blazars.

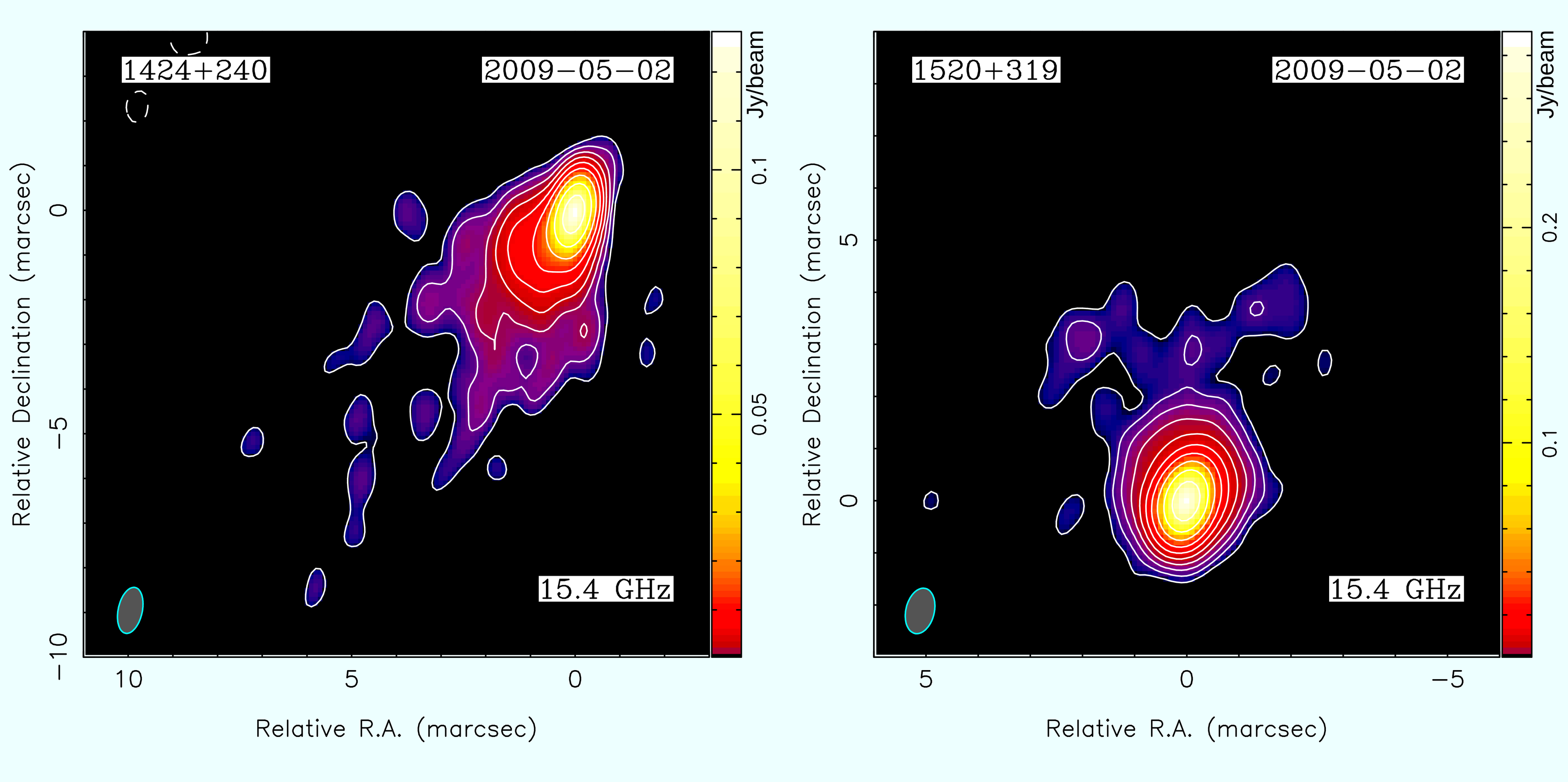

Fig. 3. MOJAVE images of LAT-detected quasars 1424+240 (left) and 1520+319 (right) that show the largest apparent opening angles 53° and 76°, respectively.

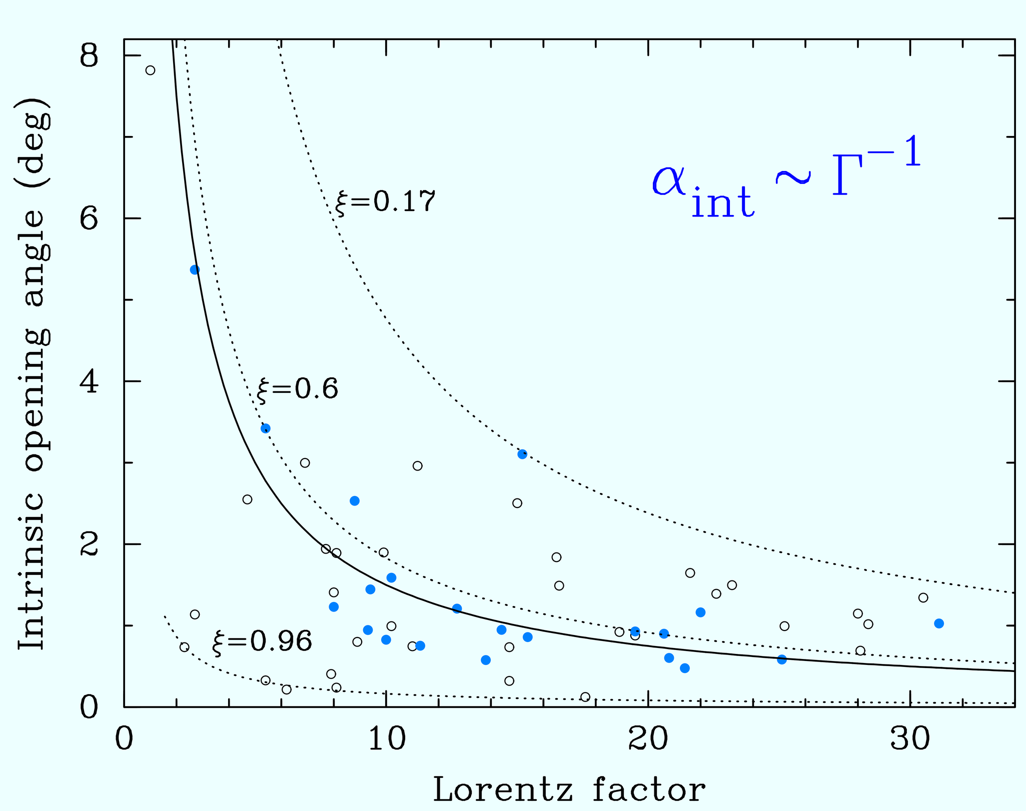

Fig. 4. Intrinsic opening angle vs. Lorentz factor for 56 jets. Two sources with $\Gamma, \alpha_{\rm int}$ values of (45, 0.96) and (65, 0.53) respectively are beyond the plot limits. The solid line shows the median curve fit with the assumed relation $\alpha = \rho/\Gamma$, where ρ is a constant. Filled blue circles correspond to LAT-detected sources, while open ones correspond to non-LAT-detected sources. The dotted curves represent relationships between the opening angle and Lorentz factor as predicted by the gas dynamical model for different values of the parameter ξ.

Abstract

- We have investigated the differences in apparent opening angles between the parsec-scale jets of the AGN detected by the *Fermi* Large Area Telescope during its first three months of operations and those of non-LAT-detected AGN.
- The apparent opening angles of γ-ray bright blazars are preferentially larger than those of γ-ray weak sources. At the same time, we have found the two groups to have similar intrinsic opening angle distributions, based on a smaller subset of sources. This suggests that the jets in γ-ray bright AGN are oriented at preferentially smaller angles to the line of sight resulting in a stronger relativistic beaming.
- The intrinsic jet opening angle and the bulk flow Lorentz factor are found to be inversely proportional, as predicted by standard models of compact relativistic jets. If a gas dynamical jet acceleration model is assumed, the ratio of the initial pressure of the plasma in the core region P_0 to the external pressure $P_{\rm ext}$ lies within the range 1.1 to 34.6, with a best fit estimate of $P_0/P_{\rm ext} \approx 2$.
- There is an indication for BL Lac objects to have on average wider intrinsic opening angles than those of quasars.

Apparent opening angles

We used the 15 GHz naturally weighted MOJAVE VLBA images from the most recent epoch available. The opening angle of the jet was calculated as the median value of $\alpha = 2\arctan[0.5(d^2 - b_\varphi^2)^{1/2}/r]$, where d is the full width at half maximum (FWHM) of a Gaussian fitted to the transverse jet brightness profile, r is the distance to the core along the jet axis, b_φ is the beam size along the position angle φ of the jet-cut, and the quantity $(d^2 - b_\varphi^2)^{1/2}$ is the deconvolved FWHM transverse size of the jet. In **Fig. 1** the 15 GHz total intensity map of 3C 345 (1641+399) is shown as an example together with the deconvolved size and opening angle of the jet as a function of angular distance to the core.

The distributions of the measured opening angle are shown in **Fig. 2**. A Kolmogorov-Smirnov (K-S) test indicates a probability of only $p = 0.019$ for these two samples being drawn from the same parent population. If we add 27 additional LAT-detected blazars from the extended MOJAVE-2 sample, the confidence level increases to 99.9% ($p < 0.001$). In **Fig. 3** we show 15 GHz MOJAVE VLBI images of two LAT-detected quasars with the largest apparent opening angles.

Intrinsic opening angles

We have derived the values of the viewing angle θ and the bulk Lorentz factor Γ for MOJAVE-1 blazars using jet speeds from the MOJAVE kinematic analysis (Lister et al. 2009b) and variability Doppler factor from the Metsähovi AGN monitoring program (Hovatta et al. 2009). The overlap of the MOJAVE and Metsähovi programs comprises 56 blazars with measured speeds and Doppler factors. Indeed, the viewing angles of 21 LAT-detected sources turned out to be slightly smaller, with a mean value of $3.^\circ6 \pm 0.^\circ4$ vs. $5.^\circ7 \pm 1.^\circ3$ for the non-LAT-detected sources. In addition, we have found an indication for BL Lacs to have on-average wider intrinsic opening angles ($2.^\circ4 \pm 0.^\circ6$) than those of quasars ($1.^\circ2 \pm 0.^\circ1$). The corresponding distributions are different at confidence levels of 94.6% according to the K-S test, the average values differ with a 96.1% confidence according to the Student's T-test.

The intrinsic opening angles $\alpha_{\rm int} = \alpha_{\rm app} \sin\theta$ were calculated for the 56 sources. The estimated values of this parameter range up to 8° (**Fig. 4**). A K-S test indicated no significant difference ($p = 0.797$) between the samples of LAT-detected and non-LAT-detected sources, suggesting that the established systematic difference in apparent opening angles is most probably the result of projection effects, i.e., the γ-ray bright jets are aligned closer to our line of sight.

We have also analyzed the observed dependence between the intrinsic opening angle and the Lorentz factor (**Fig. 4**), which are expected to be inversely proportional according to simple hydrodynamical models of relativistic jets (Blandford & Königl 1979). Both the gas dynamical model (Daly & Marscher 1988) and magnetic acceleration models (Komissarov et al. 2007) also predict this relation. The observed dependence was fitted assuming a relation $\alpha_{\rm int} = \rho/\Gamma$ with the coefficient ρ left as a free parameter. The best fit value of ρ was found to be 0.26 rad by fitting the median curve. (**Fig. 4**, *solid line*).

In the gas dynamical model of compact relativistic jets suggested by Daly & Marscher (1988) the opening angle of a jet is a function of the Lorentz factor and a ratio of the external pressure $P_{\rm ext}$ to the initial pressure P_0 of the plasma in the core region, $\xi = \sqrt{P_{\rm ext}/P_0}$. We applied this model for different values of ξ (**Fig. 4**, *dotted curves*) and were able to constrain the parameter ξ to lie within a range of [0.17, 0.96] with the best fit estimate $\xi = 0.67$, corresponding to a range of [1.1, 34.6] for $P_0/P_{\rm ext}$ with the best fit estimate $P_0/P_{\rm ext} \approx 2$. Our results confirm those obtained earlier by Jorstad et al. (2005) using a smaller sample of 15 blazar jets.

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