ON THE RELATION BETWEEN AGN GAMMA-RAY EMISSION AND PARSEC-SCALE RADIO JETS

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ABSTRACT

We have compared the radio emission from a sample of parsec-scale AGN jets as measured by the VLBA at 15 GHz, with their associated γ-ray properties that are reported in the Fermi LAT 3-month bright source list. We find in our radio-selected sample that the γ-ray photon flux correlates well with the quasi-simultaneously measured compact radio flux density. The LAT-detected jets in our radio-selected complete sample generally have higher compact radio flux densities, and their parsec-scale cores are brighter (i.e., have higher brightness temperature) than the jets in the LAT non-detected objects. This suggests that the jets of bright γ-ray AGN have preferentially higher Doppler-boosting factors. In addition, AGN jets tend to be found in a more active radio state within several months from LAT-detection of their strong γ-ray emission. This result becomes more pronounced for confirmed γ-ray flaring sources. We identify the parsec-scale radio core as a likely location for both the γ-ray and radio flares, which appear within typical timescales of up to a few months of each other.

Subject headings: galaxies: active — galaxies: jets — radio continuum: galaxies

1. INTRODUCTION

A number of authors have suggested a close connection between AGN γ-ray and radio emission, with the strong energetics of the jetted relativistic outflow being responsible for accelerating particles to the high energies needed for γ-ray production (e.g., Dermer & Schlickeiser 1993, Sikora et al. 1994, Beall & Bednarek 1999). Most of the high energy γ-ray sources detected by the EGRET telescope of the Compton Gamma Ray Observatory (Hartman et al. 1999) were identified with blazars (e.g., Mattox et al. 2001, Sowards-Emmerd et al. 2003, 2004) which indicates that relativistic jets with strong Doppler boosting are dominant sites of extragalactic γ-ray production. The EGRET results, however, were limited by the sensitivity of the telescope and the erratic sampling of observations. This did not allow a full systematic comparison of the γ-ray and radio properties for a complete sample of blazars.

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Jorstad et al. (2001) carried out 43 GHz Very Long Baseline Array (VLBA) monitoring of a sample of EGRET blazars and concluded that γ-ray events originate in parsec-scale radio knots that move down the jet at apparent superluminal speeds. Lähteenmäki & Valtaoja (2003) supported this finding on the basis of 37 GHz total flux density singledish monitoring observations of EGRET blazars. They concluded that the highest levels of γ-ray emission are observed during the initial or peak stages of radio/mm-wave flares. VLBA observations of a radio-selected sample of bright extragalactic sources at 15 GHz (Kellermann et al. 2004, Kovalev et al. 2008, Lister & Homan 2005) have shown that jets of EGRET-detected blazars are more compact, contain faster-moving knots, and are more luminous and more linearly polarized than non-EGRET blazars. Recent analysis of a large 6 cm VLBA survey (VIPS, Taylor et al. 2007) has shown that EGRET-detected blazars tend to have higher brightness temperatures and greater core dominance. However, a direct correlation between radio and γ-ray flux density and luminosity (e.g., Aller et al. 1996, Mücke et al. 1997, Lähteenmäki & Valtaoja 2003, Taylor et al. 2007) was not found.

The Fermi Gamma-Ray Space Telescope (previously known as GLAST) was successfully launched in June 2008. One of the two instruments on board the spacecraft, the Large Area Telescope (LAT, Atwood et al. 2009), is an imaging, wide-field telescope, covering the energy range from about 20 MeV to more than 300 GeV. Its characteristics allow for a quasi-continuous systematic study of the whole γ-ray sky with unprecedented sensitivity. The Fermi LAT team has recently released results of the first three months of observations (August – October 2008) in the form of a bright source list (Abdo et al. 2009b). In this Letter we compare the γ-ray and parsec-scale radio properties of the initial (>10) LAT AGN detections that are positionally associated with bright radio-loud blazars (Abdo et al. 2009b). We call this sample throughout the paper ‘ELBS’ — Extragalactic LAT Bright Source sample.

Throughout this letter, we use the term “core” as the appar-
ent origin of AGN jets that commonly appears as the brightest feature in VLBI images of blazars (e.g., Lobanov 1998, Marscher 2008). We use the CDM cosmology with \( H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_m = 0.27 \), and \( \Omega_{\Lambda} = 0.73 \) (Komatsu et al. 2008).

2. THE RADIO DATA AND SOURCE SAMPLES

The MOJAVE sample of 135 extragalactic radio sources was rigorously selected on the basis of the parsec-scale flux density at 15 GHz (\( S_{\text{VLBA}} > 1.5 \) Jy), and is part of an ongoing monitoring program with the VLBA at this frequency (for details, see Lister & Homan 2005, Lister et al. 2009a). The sample consists of the brightest extragalactic jets north of declination \(-20^\circ\), and is dominated by blazars (101 quasars and 22 BL Lac objects). Thirty one AGN from this sample are reported by the Fermi LAT team in the 3-month Fermi LAT Bright \( \gamma \)-ray Source List (Abdo et al. 2009b). The MOJAVE program also began, in late 2008, to monitor weaker LAT-detected AGN (flux density \( S > 0.2 \) Jy with \( \alpha > -30 \)), some of which were used for the analysis in § 3.1 where we supplement the MOJAVE complete sample with 46 other LAT-detected AGN with \( S > 0.2 \) Jy. We emphasize that the sources plotted in Figure 1 do not represent a complete sample selected on either parsec-scale radio or gamma-ray flux, but this Figure does show the best available comparison at this time. We also note that many LAT-detected BL Lacs (Abdo et al. 2009a) are radio weak and do not enter our radio-selected sample and analysis.

We have attempted to use radio data that are contemporaneous with the LAT measurements, to avoid, as much as possible, effects due to variability. We use VLBA observations made during May – December 2008 for most of the sources. For the remaining objects not observed then at the VLBA, we use recent data from RATAN-600 observations in September/October 2008 (e.g., Kovalev et al. 1999) or the UMRAO observations in August 2008 – January 2009 (e.g., Aller et al. 2009a). We infer the 15 GHz parsec-scale flux density with the assumption that the total single-dish flux well represents the parsec-scale emission. We used previous RATAN results together with the VLBA calibrator survey (Petrov et al. 2008, and references therein) to confirm this assumption, following the compactness analysis by Kovalev et al. 2005. Several sources with no VLBA flux density measurements but with strong kiloparsec-scale emission were not included in the analysis. If a source was observed more then once by RATAN or UMRAO, an average value is used. Note that Kovalev et al. 2005 have compared flux density scales of the three programs run at the VLBA, the UMRAO, and RATAN, and found that they agree within the errors, that typically are 5 per cent.

In addition to these quasi-simultaneous measurements of the radio flux densities, we have used in the analysis in § 3 (i) those results from our earlier 15 GHz flux density measurements within the 2cm VLBA/MOJAVE program presented by Lister et al. (2009a), and (ii) brightness temperature measurements of the jet cores made since 1999 (Kovalev et al. 2005, Homan et al. 2006) and recently updated by McCormick et al. (2009). We did not restrict the analysis in galactic latitude, \( b \); but galactic plane emission does decrease the LAT detection sensitivity for \( \gamma < 10 \) (Abdo et al. 2009b), and this could bias our conclusions. To test this we re-did our analysis for \( \gamma > 10 \), and achieved the same results at approximately the same confidence level in every single test. We also note that the two brightest radio lenses on the sky which were detected by Fermi LAT, B 0218+357 and PKS 1830–211, are not included in the MOJAVE sample (Lister et al. 2009a) and are not part of the analysis in this paper.

3. RESULTS

3.1. Quasi-simultaneous \( \gamma \)-ray vs. radio emission

Figure 1 plots the average photon flux measured by the LAT (Abdo et al. 2009b) in the energy range 100 MeV – 1 GeV versus quasi-simultaneous 15 GHz flux density. Filled circles represent total VLBI flux density while open ones — single-dish flux density. The single dish flux densities are representative of the parsec-scale emission in these objects as described in § 2.

![Figure 1](image_url)

Fig. 1. — Average Fermi LAT 100 MeV – 1 GeV photon flux (Abdo et al. 2009b) versus quasi-simultaneous 15 GHz flux density. Filled circles represent total VLBI flux density while open ones — single-dish flux density. The single dish flux densities are representative of the parsec-scale emission in these objects as described in § 2.

The non-parametric Kendall’s tau test confirms a positive correlation in Figure 1 at a confidence level > 99.9 per cent for the 100 MeV – 1 GeV energy band. The test provides the same result when restricted to only those sources measured by the VLBA (confidence 99.5 per cent) or when restricted to the radio brightest MOJAVE-ELBS sources (confidence 99.1 per cent) or when restricted to ELBS quasars only (confidence 98.9 per cent). See discussion on the possible bias by BL Lacs in Abdo et al. (2009a). The same analysis for the second LAT energy band, 1–100 GeV, also shows a positive correlation, but at a lower confidence level, 86 per cent.

These results indicate a direct relation between the \( \gamma \)-ray and parsec-scale synchrotron radiation. We note that Abdo et al. (2009a) found a much less significant correlation using non-simultaneous total radio (VLA) flux density in their \( \gamma \)-ray selected sample. In terms of previous EGRET results, it is possible that a positive correlation was not found by, e.g., Aller et al. (1996), Lähteenmäki & Valtaoja (2003);
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Taylor et al. (2007) in the EGRET vs. radio analyses because of the lack of homogeneous statistics, limited EGRET sensitivity and/or use of non-simultaneous measurements in the two bands. A more thorough analysis with direct implications for the emission models will be possible when the LAT -ray energy flux data become available.

3.2. 15 GHz parsec-scale flux density and its variability

The correlation reported in § 3.1 is further supported by the comparison of the average radio flux density of the objects detected by Fermi to that of the non-detected sources for the complete MOJAVE sample. We assume that LAT non-detected objects have statistically lower photon flux and therefore should have lower radio flux. We analyzed this with 114 VLBA data points and 21 single-dish measurements made in 2008 for the complete MOJAVE sample. The $S_{\nu}$ radio flux densities of parsec-scale jets detected by Fermi (ELBS sources) are higher (mean value 3.0 Jy vs. 1.6 Jy) and have a different distribution from the non-detected ones as indicated by the Kolmogorov-Smirnov (K-S) test at a confidence level 99.9 per cent (Figure 2).

The MOJAVE database contains a complete set of all calibrated VLBA observations of the MOJAVE sources since 1999 and includes data which we reduced from the public NRAO archive in addition to our own observations (Lister et al. 2009a). This provides us with an estimate of the mean flux density state of each source, $S_{\nu}$, over the previous eight years, between January 1999 and September 2007. We have made the same statistical test as above, flux of LAT-detected vs. LAT non-detected, using $S_{\nu}$, over the previous eight years, between January 1999 and September 2007. The general conclusion remains the same as indicated by the K-S confidence 99.9 per cent. The difference is also found at the 99.6 per cent K-S confidence for distributions of the 2008 radio luminosity, $L_{\nu}$, if compared for MOJAVE quasars only (Figure 3). BL Lacs in the MOJAVE sample have statistically lower redshifts (Lister et al. 2009a) and were excluded from the luminosity analysis.

Finally, an intriguing result emerges if we examine the radio activity level of the ELBS sources by comparing the flux density measurements in 2008, $S_{\nu}$, with the respective averages over previous eight years, $S_{\nu}$. We define the 2008 parsec-scale activity index as $V_{r} = (S_{\nu} - S_{\nu})/S_{\nu}$. The ELBS list includes a flag that indicates whether or not the source displays significant -ray variability during the first 3 months of LAT observations (Abdo et al. 2009b). In Figure 4, we plot the distributions of our radio activity index $V_{r}$ for three classes of sources, based on their LAT detection and LAT variability flag. The distributions indicate that radio-selected blazars were more likely to be detected in -rays by the LAT if they were in a particularly active radio state in May – December, 2008.

The average radio activity index $V_{r}$ for the non-ELBS MOJAVE sources is $-0.01 \pm 0.03$. For all ELBS-MOJAVE sources it is $0.23 \pm 0.07$, and it rises to $0.31 \pm 0.09$ if ELBS-
MOJAVE sources with the LAT variability flag only are selected. The K-S test confirms, at a 99.0 per cent confidence, that the ELBS and non-ELBS MOJAVE sources have different distributions of $V_{08}$. The confidence level rises to 99.7 per cent if $V_{08}$ distribution for confirmed -ray variable ELBS objects are compared to non-ELBS. Our conclusions stay the same even if a few outliers with very high radio activity index $V_{08} > 1$ are excluded from the analysis. In this case, the average $V_{08}$ values decrease to 0.16 – 0.05 (ELBS-MOJAVE) and 0.24 – 0.07 (ELBS-MOJAVE with the -ray variability flag). And we find the following confidence level of the K-S test for the $V_{08}$ distribution: 97.2 per cent for ELBS vs. non-ELBS, 99.5 per cent for ELBS confirmed variable vs. non-ELBS. The fact that the average value of $V_{08}$ for the entire MOJAVE sample (0 ± 0.03) is close to zero demonstrates a lack of overall bias. It is important to note that the same activity analysis was performed for VLBA data prior to 2008 and has shown no significant difference between ELBS and non-ELBS MOJAVE sources.

Thus we observe a radio activity index significantly greater than zero for the ELBS sources only for the time interval of VLBA observations which roughly coincides with the ELBS detections. This temporal coincidence suggests that the -rays are produced in a region close to or coincident with the radio core where radio flares originate (e.g., Kovalev et al. 2005). However, more densely sampled -ray Fermi LAT — radio VLBI and/or single dish monitoring is necessary to establish this robustly as the apparent time compression in relativistic jets can be quite large. The frequency dependent opacity effect which delays radio flares should also be accounted for.

Our conclusion is supported by the fact that we find extremely few blazars in their low radio activity state to be -ray bright. It is also interesting to note that the ELBS sources in Figure 3 with no variability flag (grey shading) span both moderate and high $V_{08}$ states. This suggests that AGN in this category might consist of both true -ray non-variable objects as well as moderately flaring ones.

3.3. Brightness temperature of jet cores

Further insight into the -ray/radio jet connection can be obtained by examining the radio core brightness temperature $T_b$. We have calculated median values of $T_b$ for the MOJAVE sample for the period 1999-2007 (McCormick et al. 2009). In less than 20 per cent of the cases only a lower limit could be found; this group of sources includes two ELBS objects. Gehan’s generalized Wilcoxon test from the ASURV survival analysis package (Lavalley et al. 1992) indicates, at a 99.9 per cent confidence, that the median $T_b$ values for LAT-detected sources are statistically higher than those for the rest of the sample (Figure 5). The same result is found if the maximum $T_b$ values are used in the analysis. Based on earlier brightness temperature findings of Homan et al. (2006), these results suggest higher Doppler factors for the LAT-detected sources, although their recent work (McCormick et al. 2009) indicates that variations in the intrinsic $T_b$ among jets may also play an important role in the brightest objects. Therefore, we expect that they might also have faster apparent jet speeds, which is indeed confirmed by results of the direct kinematics analysis presented by Lister et al. (2009b). Lister et al. have shown that LAT-detected quasars in the complete MOJAVE sample have preferentially faster jet motions than the non-detected ones.

4. SUMMARY

On the basis of the joint analysis of the Fermi -ray LAT and radio observations of parsec-scale jets in blazars we conclude the following. The -ray and parsec-scale radio emissions are strongly related in bright -ray objects detected by Fermi. At radio wavelengths, -ray bright sources are found to be preferentially brighter and more compact, which suggests that they might have higher Doppler factors than other blazars. The correlations found suggest that the prominent -ray flares in both -ray and radio bands are produced in the cores of parsec-scale jets, typically within an apparent time separation of up to a few months. These findings could be a consequence of relativistic beaming that boosts the jet emission in both bands.

The first three months of Fermi observations represent a significant improvement over the earlier EGRET results, due to the dramatic increase in sensitivity and temporal coverage. The combination of these Fermi LAT measurements and the extensive VLBA monitoring at 15 GHz by the MOJAVE program has proved to be a powerful tool to study the nature of the emission processes in extragalactic jets. We found a clear connection between the beamed relativistic radio jets and the -ray emission expected to originate in these regions, confirming and enhancing earlier results obtained by comparing radio data with the EGRET catalog.

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Facilities: VLBA, UMRAO, RATAN, Fermi (LAT).

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