IDENTIFICATION OF THE EARLY FERMI/LAT GAMMA-RAY BRIGHT OBJECTS WITH EXTRAGALACTIC VLBI SOURCES

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ABSTRACT

A list of 205 γ-ray strong objects was reported recently as a result of a three-month integration with the Large Area Telescope on board the Fermi Gamma-Ray Space Telescope. We attempted identification of these objects, cross-correlating the γ-ray positions with very long baseline interferometry (VLBI) positions of a large all-sky sample of extragalactic radio sources selected on the basis of their parsec-scale flux density. The original associations reported by the Fermi team are confirmed, and six new identifications are suggested. A Monte Carlo analysis shows that the fraction of chance associations in our analysis is less than 5%, and confirms that the vast majority of γ-ray bright extragalactic sources are radio-loud blazars with strong parsec-scale jets. A correlation between the parsec-scale radio and γ-ray flux is supported by our analysis of a complete VLBI flux-density-limited sample of extragalactic jets. The effectiveness of using a VLBI catalog to find associations between γ-ray detections and compact extragalactic radio sources, especially near the Galactic plane, is demonstrated. It is suggested that VLBI catalogs should be used for future identification of Fermi/LAT objects.

Key words: catalogs – galaxies: active – gamma rays: observations – radio continuum: galaxies

Online-only material: machine-readable table

1. INTRODUCTION

The Fermi Gamma-Ray Space Telescope (previously known as the Gamma-Ray Large Area Space Telescope (GLAST)) was successfully launched in 2008 June. Even with the modern Large Area Telescope (LAT) on board (Atwood et al. 2009), the positional uncertainty of γ-ray measurements in the energy range from about 20 MeV to more than 300 GeV remains relatively poor, typically 3′−20′. This provides a challenge for γ-ray source identification. A large fraction of the high-energy γ-ray sources detected by the EGRET telescope on board the Compton Gamma-Ray Observatory (Hartman et al. 1999) was identified with blazars (e.g., Mattox et al. 2001; Sowards-Emmerd et al. 2003, 2004). This fact critically helps in identifying objects detected by the Fermi/LAT. In order to help the identification process, several samples of blazars and blazar candidates were constructed recently (Healey et al. 2007, 2008; Massaro et al. 2009). These compilations of many thousands of extragalactic objects, together with other catalogs covering radio to γ-ray bands, were successfully used for identifying the LAT-detected sources by Abdo et al. (2009).

Results of parsec-scale Very Long Baseline Interferometry (VLBI) measurements were not applied by Abdo et al. (2009) in the process of identifying bright LAT sources. However, this can provide important extra information and improve the estimation of the probability of correct identification since VLBI filters out objects which do not host strong compact jets at parsec scales. The latter is a strong characteristic of a radio-loud blazar. VLBI can especially help in the region around the Galactic plane where the available multi-band coverage of the sky is much poorer due to Galactic absorption. An obvious weakness of the VLBI approach is the fact that radio weak objects (e.g., high-energy-selected BL Lac objects) are missed in the currently available large VLBI all-sky surveys.

During the last several decades, a number of large VLBI surveys were conducted covering the frequency range between 2 and 100 GHz (e.g., Beasley et al. 2002; Fomalont et al. 2000; Pollack et al. 2003; Kovalev et al. 2005; Ojha et al. 2004; Lovell et al. 2004; Helmboldt et al. 2007; Lanyi et al. 2005; Lee et al. 2008) including dedicated surveys in the Galactic plane (e.g., Petrov et al. 1998; Fey et al. 2004) and to find extragalactic sources which are compact at parsec scales and are suitable for phase referencing (Petrov et al. 2008, and references therein). We note that while the majority of those are of a blazar type, Helmboldt et al. (2007) have found 10% of compact extragalactic radio sources to be optically associated with galaxies from the Sloan Digital Sky Survey. In this Letter, we use the 2/8 GHz VLBI surveys to associate the early Fermi/LAT bright source (LBS) list with radio counterparts at parsec scales, make a statistical check on the reliability of these identifications, and analyze the radio properties of the VLBI counterparts of the γ-ray bright active galactic nuclei (AGNs).

2. VLBI CATALOG IN USE

The VLBI positions for more than 4000 extragalactic sources covering the whole sky were used in this analysis. They are based on 2 and 8 GHz VLBI observations, most of which were performed in the period 1994–2007 (Ma et al. 1998; Fey et al. 2004; Beasley et al. 2002; Fomalont et al. 2003; Petrov et al. 2005, 2006, 2008, 2009a, 2009b; Kovalev et al. 2007). The accuracy of VLBI astrometric position determinations is typically better than 1 mas. For details of the observations, data processing, and analysis, see the cited papers. Kovalev et al. (2007) have made an additional dedicated effort to construct a complete parsec-scale flux-density-limited sample with the following characteristics: the flat radio spectrum with

http://astrogeo.org/vlbi/solutions/2009b_astro/
the spectral index $\alpha > -0.5$ ($S \sim \nu^{\alpha}$), parsec-scale 8 GHz flux density (integrated flux density over the VLBI map) $\delta_{\text{VLBI}} > 0.2$ Jy, declination (decl.) $\delta > -30^\circ$, Galactic latitude $|b| > 1.5$. Known Galactic objects were excluded. The full all-sky astrometric 2/8 GHz VLBI source (AVS) catalog of 4338 objects is used for cross-identification with the three-month Fermi LBS list from Abdo et al. (2009b) while the complete flux-density-limited VLBI source (FVS) sample of 1848 objects is used for statistical tests and analysis.

3. FERMI/LAT–VLBI CROSS-IDENTIFICATION

A number of authors have suggested a close connection between the bright $\gamma$-ray and parsec-scale radio emission from analyzing EGRET (e.g., Lähteenmäki & Valtaoja 2003) and early Fermi (e.g., Kovalev et al. 2009; Lister et al. 2009a) data. They concluded that the related $\gamma$-ray and parsec-scale radio emission should originate in spatially close regions. This means that VLBI positions might serve very well as an estimate of a location of the source of $\gamma$-ray emission detected by Fermi/LAT for extragalactic objects. Taking this assumption as our starting point, we have applied a simple approach to cross-identify bright Fermi/LAT sources from Abdo et al. (2009b). A Fermi source will be called successfully identified with a VLBI one if the difference between the Fermi/LAT position and the VLBI position of the AVS sample is less than the 95% confidence radius, $r_{95}$, estimated by Abdo et al. (2009b).

3.1. Results of the Cross-identification

The results of this cross-identification can be found in Table 1. We have successfully identified 111 out of 205 Fermi/LAT sources. We note that the full list of the 205 bright $\gamma$-ray sources presented by Abdo et al. (2009b) includes both Galactic and extragalactic objects. No single Fermi detection was identified with more than one VLBI source. Figures 1 and 2 present the results of these identifications. The square root of the Fermi Test Statistics ($\sqrt{TS}$) provides an estimate of the signal-to-noise ratio (S/N) for every Fermi/LAT detection. As expected, the difference, $\Delta P$, between the Fermi position and that of its VLBI identification becomes smaller with increasing $\sqrt{TS}$ (Figure 1). There are no identifications found with high Fermi/LAT S/N and high relative Fermi–VLBI positional difference, $\Delta P/r_{95}$. This could be explained by an overestimated systematic uncertainty which was added in quadrature (Abdo et al. 2009b) while calculating $r_{95}$. The systematic uncertainty dominates the $r_{95}$ value for high S/N Fermi sources becoming less dominant with decreasing Fermi TS. Abdo et al. reported this systematic uncertainty to be conservative; they expect it to improve. The distribution of $\Delta P$ (Figure 2) agrees well with the results of Abdo et al. (2009b, Figure 9), who discuss this distribution in detail.

Cross-identification of the Fermi LBS versus AVS lists resulted in 111 identifications out of 4338 VLBI sources (2.6%...
of the VLBI sample), while LBS versus FVS lists comparison gave 79 identifications out of 1848 VLBI sources (4.3%). We note that the fraction of identifications within the complete parsec-scale FVS list is about two times higher than that for the deeper AVS list of sources. This could be the case if the bright γ-ray sources from the LBS list "prefer" stronger parsec-scale radio counterparts, i.e., if there is a correlation between the γ-ray flux and parsec-scale radio flux density. We note that the flux density cutoff of the FVS sample is significantly higher than that for the AVS sample (200 mJy versus about 50 mJy). The correlation suggested is indeed confirmed by an analysis in Section 4.

Comparison with the association results presented by Abdo et al. (2009b) has shown the following. One hundred and five Fermi/LAT detections have identifications common to the Abdo et al. analysis and the current study. All the extragalactic associations, suggested by Abdo et al. but not found by us, have radio flux densities less than 0.2 Jy or declinations less than −30°, i.e., belong to the flux density and/or declination range where our VLBI catalog is not complete. All the objects which are identified by us but have no counterparts suggested by Abdo et al. are located close to the Galactic plane—a region of special difficulty for identification by the standard method of Abdo et al., as discussed above.

3.2. New Identifications

The following six new identifications, not reported by Abdo et al. (2009b), were found by our analysis: 0FGL J0643.2+0858 (galactic latitude $b = 2^\circ$29), 0FGL J1123.0−6416 ($b = -3^\circ$02), 0FGL J1328.8−5604 ($b = 6^\circ$41), 0FGL J1604.0−4904 ($b = 2^\circ$54), 0FGL J1830.3+0617 ($b = 7^\circ$54), 0FGL J2001.0+4352 ($b = 7^\circ$12). All these are within 10° from the Galactic plane. Details on these objects can be found in Table 1. We note that identifications with the same objects for two of these six Fermi detections were independently proposed recently by Bassani et al. (2009) for 0FGL J2001.0+4352 and Mirabal & Halpern (2009) for 0FGL J1830.3+0617 on the basis of a multi-band analysis. Mirabal & Halpern (2009) have also discussed possible flat-spectrum radio source associations for 0FGL J0643.2+0858 and 0FGL J1328.8−5604 which agree with our identifications. Mirabal (2009) presented an X-ray point-source catalog from Swift X-Ray Telescope (XRT) observations of unidentified Fermi sources including discussion of a potential counterpart for 0FGL J1604.0−4904.

3.3. Chance Association Analysis

We have performed a Monte Carlo simulation to measure the chance coincidence probability. We kept the Fermi LBS catalog unchanged while the VLBI catalog was scrambled; every source in the VLBI catalog was shifted in a random position angle for a random angular distance on the sky between 0° and 5°. After that, cross-identification of the catalogs was done as described above. This exercise was performed 1000 times. The analysis was done independently for the LBS versus AVS and LBS versus FVS lists. The mean number of chance associations was found to be 4.5 (4.1% of 111 true identifications; see Section 3.1) and 2.9 (3.7% of 79 identifications), respectively. This shows with a very high level of significance that (1) almost all of the associations found are firm identifications, (2) the original assumption of the method that the γ-ray sky is dominated by blazars with strong parsec-scale jets is confirmed.

The above-described method of VLBI catalog scrambling was applied to represent the non-uniformity of the AVS list, where sky regions of a special interest (e.g., the Galactic plane) are populated more densely. The 5° radius was chosen as an optimal size to represent the non-uniformity being in the same time significantly greater than the $r_{95}$ values. We note that, for a uniform sky coverage in an original catalog, this method reproduces uniformity in the Monte Carlo test. If we consider as a match Fermi and VLBI sources with positional difference less than $r_{95}/2$, we lose about 30% of identifications (see Figures 1 and 2) while the chance coincidence probability drops only down to about 2%.

4. VLBI PROPERTIES OF THE γ-RAY IDENTIFICATIONS FOUND

We have performed a correlation analysis between the average Fermi/LAT 100 MeV–1 GeV photon flux (Abdo et al. 2009b) versus 8 GHz parsec-scale flux density measured by VLBI between 1994 and 2008 (Figure 3). The non-parametric Kendall τ test confirms a positive correlation in Figure 3 at a confidence level greater than 99.9% for the 100 MeV–1 GeV energy band (the two upper limits were ignored by the test which did not affect the conclusion). This agrees with results of a similar analysis performed by Kovalev et al. (2009) for simultaneous LAT γ-ray–15 GHz VLBA MOJAVE (Lister et al. 2009b) measurements. Possible systematics in this dependence resulting from the different properties of two populations of extragalactic γ-ray sources (low-energy peaked versus high-energy peaked) were mentioned by Abdo et al. (2009a). We do
for the complete flux-density-limited sample (FVS) with $S > 0.2$ Jy and declination $\delta > -30\degree$. Left panel: positive Fermi–VLBI associations. Right panel: Fermi–VLBI non-associations.

Figure 4. Distribution of parsec-scale flux density measured by VLBA at 8 GHz for the complete flux-density-limited sample (FVS) with $S_{\text{LVLB}} > 0.2$ Jy and declination $\delta > -30\degree$. Left panel: positive Fermi–VLBI associations. Right panel: Fermi–VLBI non-associations.

not go into detailed analysis of this in the present Letter since Kovalev et al. (2009) have addressed this issue in their study.

An even stronger test is done by analyzing the full FVS sample of 1848 sources which complete down to 0.2 Jy, separating them into LAT detected and LAT non-detected (Figure 4). We assume that LAT non-detected objects have statistically lower $\gamma$-ray photon flux and therefore should have lower radio flux. The Kolmogorov–Smirnov test shows with a confidence greater than 99.99% that the distributions of the parsec-scale flux density for the LAT detected and non-detected VLBI sources are drawn from different parent distributions. The median flux densities of these two distributions differ by a factor of 2.5, 0.84 Jy versus 0.34 Jy. This strongly supports the correlation between $\gamma$-ray and parsec-scale radio emission, confirming again the recent finding by Kovalev et al. (2009).

5. SUMMARY

It has been shown that VLBI provides a very efficient tool to identify bright $\gamma$-ray detections which have poor positional accuracy. Application of this method is especially important for Fermi/LAT identifications near the Galactic plane where VLBI observations are affected by absorption and extended Galactic emission to a much lesser degree than other radio observations. It is suggested that this method should be incorporated into the process of identification of the Fermi/LAT catalogs and for estimation of systematics in $\gamma$-ray positions. The results of $\gamma$-ray source identification by Abdo et al. (2009b) have been confirmed. Six new identifications are reported for a follow-up analysis, all within 10$\degree$ from the Galactic plane. It is estimated that more than 95% of the VLBI associations found are firm identifications.

Direct cross-correlation of the Fermi/LAT and VLBI catalogs has confirmed with a very high level of significance the early finding of EGRET (Hartman et al. 1999) and Fermi (Abdo et al. 2009a) that most of the bright $\gamma$-ray sources on the sky are compact blazars. It was found that Fermi/LAT preferentially “selects” the brightest objects from a flux-density-limited sample of radio-loud parsec-scale jets which supports the hypothesis of a direct correlation and physical connection between emission in the $\gamma$-ray and radio bands.

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Facilities: VLBA, LBA, Fermi (LAT)

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