Polarization and Variation of Near-Infrared Light from Fermi/LAT \( \gamma \)-Ray Sources

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ABSTRACT

We present the results of our follow-up observation program of \( \gamma \)-ray sources detected by the Large Area Telescope (LAT) on board the Fermi Gamma-ray Space Telescope. Twenty-six blazars and thirty-nine sources unidentified at other wavelengths were targeted at the Infrared Survey Facility 1.4 m telescope equipped with the SIRIUS/SIRPOL imager and polarimeter. \( H \)-band magnitudes of the blazars at the epoch of 2010 December–2011 February are presented, which reveal clear flux variation since the Two Micron All Sky Survey observations and can be useful data for variation analyses of these objects in longer periods. We also find that nearly half of the \( \gamma \)-ray blazars are highly (>10%) polarized in near-infrared wavelengths. Combining the polarization and variation properties, most (~90%) of the blazars are clearly distinguished from all other types of objects at high Galactic latitudes.

On the other hand, we find only one highly polarized and/or variable object in the fields of unidentified sources. This object is a counterpart of the optical variable source PQV1 J131553.00–073302.0 and the radio source NVSS J131552–073301 and is a promising candidate of new \( \gamma \)-ray blazars. From the measured polarization and variation statistics, we conclude that most of the Fermi/LAT unidentified sources are not likely similar types of objects to the known \( \gamma \)-ray blazars.

Key words: BL Lacertae objects: general – galaxies: active – galaxies: jets – gamma rays: galaxies – polarization – quasars: general

1. INTRODUCTION

A new era of blazar studies has arrived with the advent of the Fermi Gamma-ray Space Telescope. Fermi has been carrying out an all-sky survey with its main instrument, the Large Area Telescope (LAT), since the science mission phase started in 2008. The first Fermi-LAT catalog (1FGL; Abdo et al. 2010a) lists 1451 \( \gamma \)-ray detections in which 821 sources are associated (or identified) with objects found at other wavelengths. The majority of the associated objects are active galactic nuclei (AGNs) dominated by blazars, while other extragalactic sources as well as Galactic objects such as pulsars and supernova remnants make smaller contributions. The remaining 630 sources are left unidentified in 1FGL.

Blazars are considered to be AGNs whose jets are aligned with the observer’s line of sight. Emission from the relativistically boosted jets dominates the observed flux, resulting in two broad peaks in the spectral energy distribution (SED): one at radio to X-rays arising from synchrotron emission of accelerated, high-energy particles, and another at X-rays to \( \gamma \)-rays arising from the inverse Compton scattering of the lower energy photons. Because of these emission mechanisms, blazars are characterized by strong radio, X-ray, and \( \gamma \)-ray radiations as well as high polarization and variation across the entire SED. Since blazars dominate the \( \gamma \)-ray sky at high Galactic latitudes, the Fermi all-sky survey is expected to shed new light on this relatively rare and poorly understood population.

An investigation of blazar radiation mechanisms (hence the intrinsic SED) is important not only for revealing the nature of blazars themselves, but also for measuring the extragalactic background light (EBL). Since high-energy photons from blazars interact with optical to near-infrared (IR) EBL in the intergalactic space, observations of distant blazars can be used to infer the EBL spectrum if the intrinsic blazar SED is precisely known. With this indirect method, Aharonian et al. (2006) obtained significantly lower upper limits of near-IR EBL than those derived from the direct measurements by, e.g., Matsumoto et al. (2005). Recently, Matsuoka et al. (2011) succeeded in directly measuring the optical EBL by re-analyzing the Pioneer 10/11 data, which is on the smooth extension of the near-IR upper limits obtained by Aharonian et al. (2006).

In this paper, we present the results of our near-IR follow-up observation program of \( \gamma \)-ray blazars and unidentified sources in 1FGL. Despite the wealth of information there, the near-IR wavelength of the whole AGN population is still poorly understood (e.g., Matsuoka et al. 2007, 2008, 2012). We aim to quantify the most distinct features of blazars in near-IR wavelengths, i.e., polarization and variation, in part as a benchmark for future observations. At the same time, we explore the nature of 1FGL unidentified sources by comparing their near-IR properties to the known \( \gamma \)-ray blazars. The dominance of blazars in the \( \gamma \)-ray sky implies that some of the unidentified sources at high Galactic latitudes are similar objects missed in past surveys at other wavelengths. Revealing the origin of these unidentified \( \gamma \)-ray emissions is of greatest importance, and therefore many follow-up studies are being dedicated to this subject (e.g., Ackermann et al. 2012). We aim to provide complementary information to these follow-up programs from a near-IR viewpoint.

While the second Fermi-LAT catalog (2FGL; Nolan et al. 2012) has already been released, this paper is based on 1FGL for consistency with the sample selection of the presented observations. We discuss the new 2FGL identifications of the sample later. Magnitudes are presented on the Vega-based system throughout this paper.

2. OBSERVATIONS AND REDUCTION

The sample consists of blazars and unidentified sources extracted from 1FGL. We selected targets at high Galactic
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Table 1
Observation Journal of Blazars

| IFGL ID      | Associated Blazar | Obs. Date | \(H_{\text{MABSS}}\) (mag) | \(H_{\text{IRSF}}\) (mag) | \(H_{\text{lim,IRSF}}\) (mag) | Polarization (%) |
|--------------|-------------------|-----------|-----------------------------|----------------------------|------------------------|-----------------|
| J0021.7−2556 | CRATES J0021−2550 | Dec 7     | 14.05 ± 0.03               | 15.06 ± 0.02               | 15.54                  | 13.8 ± 2.2      |
| J0033.5−1921 | RBS 76            | Dec 13    | 14.08 ± 0.03               | 14.18 ± 0.01               | 14.86                  | 6.8 ± 1.8       |
| J0038.4−2504 | PKS 0035−252      | Dec 13    | 13.12 ± 0.03               | 15.92 ± 0.07               | 14.84                  | 6.4 ± 1.9       |
| J0506.0−0928 | PKS 0048−09       | Dec 8     | 13.60 ± 0.03               | 13.17 ± 0.01               | 15.65                  | 15.5 ± 0.5      |
| J1020.5−2700 | PKS 0118−272      | Dec 8     | 13.40 ± 0.03               | 13.38 ± 0.01               | 15.57                  | 6.5 ± 0.6       |
| J1032.6−1655 | PKS 0130−17       | Dec 8     | 14.26 ± 0.05               | 14.90 ± 0.01               | 14.44                  | 6.4 ± 1.9       |
| J0209.3−5229 | BZB J0209−529     | Dec 9     | 13.80 ± 0.04               | 14.38 ± 0.01               | 15.95                  | 3.6 ± 1.0       |
| J0210.6−5101 | PKS 0208−512      | Dec 7     | 12.86 ± 0.02               | 14.64 ± 0.01               | 15.66                  | 11.6 ± 1.4      |
| J0238.6−3117 | BZB J0238−3116    | Dec 9     | 14.43 ± 0.06               | 14.36 ± 0.01               | 16.01                  | 3.5 ± 0.9       |
| J0303.5−2406 | PKS 0301−243      | Dec 7     | 13.69 ± 0.04               | 13.17 ± 0.01               | 15.51                  | 3.6 ± 0.5       |
| J0325.9−1649 | RBS 421           | Dec 8     | 14.46 ± 0.04               | 14.78 ± 0.01               | 15.41                  | 3.2 ± 1.8       |
| J0334.4−3727 | CRATES J0334−3725 | Dec 7     | 14.00 ± 0.03               | 13.36 ± 0.01               | 15.35                  | 4.3 ± 0.7       |
| J0423.2−0118 | PKS 0420−01       | Dec 7     | 14.53 ± 0.05               | 15.48 ± 0.02               | 15.57                  | 8.8 ± 3.0       |
| J0449.5−4350 | PKS 0447−439      | Dec 7     | 13.20 ± 0.03               | 11.87 ± 0.01               | 15.23                  | 4.5 ± 0.3       |
| J0455.6−4618 | PKS 0454−46       | Dec 11    | 14.82 ± 0.05               | 15.62 ± 0.03               | 15.43                  | 11.7 ± 3.9      |
| J0522.8−3632 | PKS 0521−36       | Dec 12    | 12.21 ± 0.04               | 12.02 ± 0.01               | 14.95                  | 10.9 ± 0.4      |
| J0538.8−4404 | PKS 0537−441      | Dec 12    | 12.38 ± 0.03               | 11.72 ± 0.01               | 15.24                  | 12.8 ± 0.3      |
| J0953.0−0838 | CRATES J0953−0840 | Dec 9     | 14.18 ± 0.04               | 14.39 ± 0.01               | 15.35                  | <3.8            |
| J1022.8−0115 | BZB J1022−0113    | Dec 12    | 14.92 ± 0.07               | 15.41 ± 0.02               | 15.89                  | <3.7            |
| J1059.3−1132 | PKS B1056−113     | Dec 23    | 14.80 ± 0.05               | 13.85 ± 0.01               | 15.57                  | 11.6 ± 0.8      |
| J1126.8−1854 | PKS 1124−186      | Dec 23    | 13.30 ± 0.03               | 13.57 ± 0.01               | 15.28                  | 12.6 ± 0.8      |
| J1204.3−0714 | CRATES J1204−0710 | Feb 14    | 14.12 ± 0.09               | 13.85 ± 0.01               | 16.12                  | 3.0 ± 0.7       |
| J2158.8−3013 | PKS 2155−304      | Dec 13    | 10.76 ± 0.03               | 10.46 ± 0.01               | 14.04                  | 3.7 ± 0.3       |
| J2222.5−5218 | BZB J2221−5225    | Dec 13    | 14.92 ± 0.09               | 14.40 ± 0.01               | 15.09                  | 9.2 ± 1.8       |
| J2235.7−4817 | PKS 2232−488      | Dec 8     | 12.95 ± 0.03               | 15.47 ± 0.03               | 15.43                  | <5.8            |
| J2359.0−3035 | IH 2351−315       | Dec 13    | 14.72 ± 0.07               | 14.33 ± 0.01               | 15.23                  | 1.8 ± 1.5       |

Notes.

- The observations were carried out from 2010 December to 2011 February.
- Limiting magnitudes below which photometry error in a single wave-plate image is less than 0.05 mag.

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Data were reduced in a standard manner with a dedicated package of the Image Reduction and Analysis Facility (IRAF) called SIRPOL, including dark subtraction, flat fielding, and substitution of bad pixels. Photometric calibration was achieved by referring to several 2MASS sources within each observed field. While simultaneous \(J\)-, \(H\)-, and \(K\)\(_s\)-band images were obtained, we use \(H\)-band images in this study because they are of the highest quality (signal-to-noise ratios). We show an example of a reduced \(H\)-band image in the left panel of Figure 1.

We used SExtractor (Bertin & Arnouts 1996), version 2.5, for aperture photometry of detected sources. Aperture sizes were determined to be twice the mean FWHMs of stellar profiles in each image. We required photometry errors to be less than 0.05 mag for polarization measurements, which defines our limiting magnitudes \(H_{\text{lim,IRSF}}\). The average values are \(H_{\text{lim,IRSF}} = 15.4\) and 16.0 mag for the fields of blazars and unidentified sources, respectively. The polarization degree \(P_{\text{raw}}\) was then calculated from measured fluxes \(F_{000}, F_{225}, F_{450}\).
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Table 2

| 1FGL ID    | Obs. Date | $H_{\text{lim}}^\text{IRSF}$ | $P_{\text{raw}}$ |
|-----------|----------|-----------------|-----------------|
| J001.9−4158 | Dec 26   | 15.58           | 0.157           |
| J028.9−7028  | Dec 27   | 15.12           | 0.087           |
| J032.7−5519  | Dec 25   | 15.67           | 0.123           |
| J010.0−6423  | Dec 27   | 15.68           | 0.134           |
| J013.6−2220  | Dec 13   | 15.29           | 0.098           |
| J014.3−5845  | Dec 23, Feb 7 | 15.95          | 0.109           |
| J022.0−1118  | Feb 13   | 16.16           | 0.096           |
| J024.4−6003  | Dec 9, Feb 6 | 16.21          | 0.105           |
| J031.3−0922  | Dec 24   | 15.67           | 0.096           |
| J016.3−6438  | Dec 23, Feb 11 | 15.96         | 0.096           |
| J035.5−4501  | Dec 26   | 16.16           | 0.094           |
| J034.5−2355  | Dec 24   | 15.86           | 0.098           |
| J040.4−0850  | Dec 22   | 15.44           | 0.095           |
| J040.9−0357  | Dec 25, Feb 11 | 15.84          | 0.096           |
| J043.9−0538  | Dec 24   | 15.71           | 0.095           |
| J043.9−1857  | Dec 24, Feb 6 | 15.84          | 0.096           |
| J051.5−4404  | Dec 22   | 15.68           | 0.095           |
| J052.3−2529  | Feb 7    | 16.67           | 0.095           |
| J061.4−3328  | Feb 7    | 16.61           | 0.095           |
| J0829.9+0901 | Feb 13   | 16.34           | 0.095           |
| J1101.3+1009 | Feb 7    | 16.73           | 0.095           |
| J1119.9−2205 | Feb 6    | 16.45           | 0.095           |
| J1124.4−3654 | Feb 14   | 16.12           | 0.095           |
| J1141.8−1403 | Feb 11   | 16.65           | 0.095           |
| J1223.4−3034 | Feb 13   | 16.72           | 0.095           |
| J1231.1−1410 | Feb 6    | 16.59           | 0.095           |
| J1311.7−3429 | Feb 14   | 16.15           | 0.095           |
| J1312.6+0048 | Feb 11   | 16.39           | 0.095           |
| J1315.6−0729 | Feb 11   | 16.75           | 0.095           |
| J1351.8−1523 | Feb 6    | 16.71           | 0.095           |
| J1511.8−0513 | Feb 6    | 16.67           | 0.095           |
| J2118.3−3237 | Dec 25   | 15.20           | 0.095           |
| J2152.4−7532 | Dec 25   | 15.53           | 0.095           |
| J2227.4−7804 | Dec 28   | 15.33           | 0.095           |
| J2228.5−1633 | Dec 29   | 14.93           | 0.095           |
| J2241.9−5236 | Dec 25   | 15.39           | 0.095           |
| J2251.2−4928 | Dec 29   | 14.97           | 0.095           |
| J2330.3−4745 | Dec 28   | 15.58           | 0.095           |
| J2355.9−6613 | Dec 28   | 16.07           | 0.095           |

Notes.

a The observations were carried out from 2010 December to 2011 February.

b Limiting magnitudes below which photometry error in a single wave-plate image is less than 0.05 mag.

Figure 1. IRSF/SIRPOL $H$-band image of intensity (a) and Stokes $U/I$ (b) of a field around the blazar 1FGL J0538.8−4404. The blazar is marked with the boxes.

and $F_{675}$ as follows:

$$Q = F_{000} - F_{450},$$
$$U = F_{225} - F_{675},$$
$$I = (F_{000} + F_{450} + F_{225} + F_{675})/2,$$
$$P_{\text{raw}} = 100 \times \frac{(Q^2 + U^2) / \Delta I}{I}.$$  

Here $Q$ and $U$ are the Stokes parameters and $I$ is the total intensity. A source with strong polarization stands out in $Q/I$ or $U/I$ images as demonstrated in the right panel of Figure 1.

Since $F_{000}$, $F_{225}$, $F_{450}$, and $F_{675}$ are not observed simultaneously, temporal variation of the atmospheric conditions causes polarimetry errors in addition to those from the standard sky background noise. Hence we estimated the polarization error $\Delta P$ in a given field from the median $P_{\text{raw}}$ value of all of the detected sources, assuming that most of those sources at high Galactic latitudes have no intrinsic polarization. Then, true polarization degrees were derived by de-biasing the measured $P_{\text{raw}}$ (Wardle & Kronberg 1974) following

$$P = (P_{\text{raw}}^2 - \Delta P^2)^{1/2}. $$

Thus the presented values of polarization and its error should be regarded as the lower and upper limits, respectively, considering the above assumption of no intrinsic polarization for most of the detected sources. We provide upper limits of polarization for objects with $P_{\text{raw}} < \Delta P$ or $P < \Delta P$.

3. RESULTS AND DISCUSSION

We present the results of photometry and polarimetry measurements for the blazars in Table 1. Their polarization and variation since the 2MASS observations, as well as those for all other sources detected in the blazar fields, are plotted in Figure 2.

Strong variability of the blazars is evident; 22 out of 26 blazars (85%) have $|H_{\text{IRSF}} - H_{\text{2MASS}}| > 0.25$ mag, whereas only one of the other detected sources shows such variation (≈0.3 mag; it is likely a contaminating normal star). The blazars are also characterized by pronounced polarization; 10 out of 25 blazars (40%; polarization was not measured for a blazar associated with J0038.4−2504) due to a large (>0.05 mag) photometry...
Table 3
2FGL Identification (Association) of 1FGL “Unidentified” Sources in Our Sample

| 1FGL ID | Associated Source | Object Type            |
|---------|------------------|------------------------|
| J0001.9 | 1RXS J000135.5−4155 | Active galaxy of uncertain type |
| J0101.0 | PSR J0101−6422     | Pulsar                |
| J0223.0 | 1RXS J022314.6−11174 | Active galaxy of uncertain type |
| J0335.5 | 1RXS J033514.5−44592 | Active galaxy of uncertain type |
| J0614.1 | PSR J0614−3330     | Pulsar                |
| J1124.4 | PSR J1124−36       | Pulsar                |
| J1141.8 | 1RXS J114142.2−14075 | Active galaxy of uncertain type |
| J1231.1 | PSR J1231−1411     | Pulsar                |
| J1312.6 | PSR J1312+00       | Pulsar                |
| J2241.9 | PSR J2241−5236     | Pulsar                |
| J2330.3 | PKS 2326−477       | Blazar                |

Figure 2. Polarization and variation of 326 sources detected in the blazar fields. The diamonds represent the blazars associated with 1FGL sources whereas the dots represent all other objects. The arrows denote upper limits of polarization.

From the above results, we can derive an expected number of blazars that should be discovered by their high polarization and/or variation in the fields of unidentified sources if they are similar but unknown blazars. In total, 23 out of 26 blazars (88%) have pronounced polarization ($P > 10\%$) or variation ($\left| H_{\text{IRSF}} - H_{\text{2MASS}} \right| > 0.25$ mag). Since 39 unidentified sources were observed, we would have $\sim 35$ objects with such distinguishable properties under the above assumption. However, $\sim 35\%$ of them would be fainter than our limiting magnitude $H_{\text{lim}} \approx 16.0$ mag based on the 2MASS magnitude distribution of 1FGL blazars. Furthermore, $\sim 32\%$ of them would be outside the SIRPOL field of view ($7.7 \times 7.7$) when $\gamma$-ray positions are used as the telescope pointing center, based on the distribution of distance between $\gamma$-ray positions and associated blazars. Considering these restrictions, we expect to find 15 blazars in 39 fields of unidentified sources if their $\gamma$-rays are indeed emitted by a population similar to 1FGL blazars.

Figure 3 shows the polarization and variation of 608 objects detected in all of the fields of unidentified sources. While three objects are found to have high variation ($\left| H_{\text{IRSF}} - H_{\text{2MASS}} \right| > 0.25$ mag), two of them with $P < 7\%$ and $\left| H_{\text{IRSF}} - H_{\text{2MASS}} \right| \sim 0.3$ mag are likely contaminations; this is consistent with one contamination out of 326 objects in the blazar fields (Figure 2). On the other hand, the object at $P \sim 9\%$ and $\left| H_{\text{IRSF}} - H_{\text{2MASS}} \right| \sim 1.2$ mag is a promising candidate for a new $\gamma$-ray blazar. It is found in the J1315.6−0729 field, at R.A. $13^h15^m52^s98$, decl. $−07^d33^m01^s99$ (J2000.0) with $H$-band brightness $H_{\text{IRSF}} = 14.1$ mag and $H_{\text{2MASS}} = 15.3$ mag. Its counterparts are found in the NED:5 the optical variable source PQV1 J131553.00−073302.0 (Bauer et al. 2009) and the radio source NVSS J131552−073301. We plan to carry out a spectroscopic follow-up observation of this object in the near future.

5 The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.
Except for the above blazar candidate, we found no clear sign of variable or polarized objects in the fields of unidentified sources. The apparent inconsistency between the expected number of blazar candidates as estimated above (15) and the actual number observed (1) indicates that γ-ray emission of the unidentified sources arises from types of objects other than known 1FGL blazars. They could be non-blazar active galaxies, starburst galaxies, or Galactic objects such as pulsars and supernova remnants at relatively high Galactic latitudes, as well as active galaxies with jets but without strong polarization and variability at near-IR wavelengths. In this regard, it is noteworthy that some of them are already identified in (or associated with) the latest 2FGL catalog and the Fermi-LAT second AGN catalog (2LAC; Ackermann et al. 2011) as summarized in Table 3. Many of them are pulsars, which is consistent with our observation results. While J2330.3−4745 is associated with the blazar PKS 2326−477, their separation is relatively large and the blazar is outside the field of view of our SIRPOL observation.

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REFERENCES

Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010a, ApJS, 188, 405
Abdo, A. A., Ackermann, M., Ajello, M., et al. 2010b, ApJ, 715, 429
Ackermann, M., Ajello, M., Allafort, A., et al. 2011, ApJ, 743, 171
Ackermann, M., Ajello, M., Allafort, A., et al. 2012, ApJ, 753, 83
Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al. 2006, Nature, 440, 1018
Bauer, A., Baltay, C., Coppi, P., et al. 2009, ApJ, 705, 46
Bertin, E., & Arnouts, S. 1996, A&AS, 117, 393
Kandrari, R., Kusakabe, N., Tamura, M., et al. 2006, Proc. SPIE, 6269, 626951
Matsumoto, T., Matsuura, S., Murakami, H., et al. 2005, ApJ, 626, 31
Matsuoka, Y., Ienaka, N., Kawara, K., & Oyabu, S. 2011, ApJ, 736, 119
Matsuoka, Y., Kawara, K., & Oyabu, S. 2008, ApJ, 673, 62
Matsuoka, Y., Oyabu, S., Tsuzuki, Y., & Kawara, K. 2007, ApJ, 663, 781
Matsuoka, Y., Yuan, F.-T., Takeuchi, Y., & Yanagisawa, K. 2012, PASJ, 64, 44
Nagashima, C., Nagayama, T., Nakajima, Y., et al. 1999, Star Formation 1999, ed. T. Nakamoto (Nobeyama: Nobeyama Radio Observatory), 397
Nagayama, T., Nagashima, C., Nakajima, Y., et al. 2003, Proc. SPIE, 4841, 459
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Wardle, J. F. C., & Kronberg, P. P. 1974, ApJ, 194, 249