UNIDENTIFIED $\gamma$-RAY SOURCES: HUNTING $\gamma$-RAY BLAZARS

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Received 2012 February 5; accepted 2012 March 24; published 2012 May 25

ABSTRACT

One of the main scientific objectives of the ongoing Fermi mission is unveiling the nature of unidentified $\gamma$-ray sources (UGSs). Despite the major improvements of Fermi in the localization of $\gamma$-ray sources with respect to the past $\gamma$-ray missions, about one-third of the Fermi-detected objects are still not associated with low-energy counterparts. Recently, using the Wide-field Infrared Survey Explorer (WISE) survey, we discovered that blazars, the rarest class of active galactic nuclei and the largest population of $\gamma$-ray sources, can be recognized and separated from other extragalactic sources on the basis of their infrared (IR) colors. Based on this result, we designed an association method for the $\gamma$-ray sources to recognize if there is a blazar candidate within the positional uncertainty region of a generic $\gamma$-ray source. With this new IR diagnostic tool, we searched for $\gamma$-ray blazar candidates associated with the UGS sample of the second Fermi $\gamma$-ray LAT catalog (2FGL). We found that our method associates at least one $\gamma$-ray blazar candidate as a counterpart to each of 156 out of 313 UGSs analyzed. These new low-energy candidates have the same IR properties as the blazars associated with $\gamma$-ray sources in the 2FGL catalog.

Key words: BL Lacertae objects: general – galaxies: active – gamma rays: galaxies – radiation mechanisms: non-thermal

Online-only material: color figures, machine-readable table

1. INTRODUCTION

More than half of the $\gamma$-ray sources detected by the Compton Gamma-Ray Observatory (CGRO) and present in the third EGRET (3EG) catalog were not associated with known counterparts seen at low energies (Hartman et al. 1999). Whatever the nature of the unidentified $\gamma$-ray sources (UGSs), these objects could provide a significant contribution to the isotropic $\gamma$-ray background (IGRB, e.g., Abdo et al. 2010a). Solving the puzzle of the origin of the UGSs and gaining better knowledge of other IGRB contributions estimated from known sources are also crucial to constraining exotic high-energy physics phenomena, such as dark matter signatures or new classes of sources.

With the advent of the Fermi mission, the localization of $\gamma$-ray sources has significantly improved with respect to past $\gamma$-ray missions, thus simplifying the task of finding statistically probable counterparts at lower energies. New association methods also have been developed and applied, so that the number of UGSs has decreased significantly with respect to the 3EG catalog (Hartman et al. 1999); however, according to the second Fermi $\gamma$-ray LAT catalog (2FGL), about one-third of detected $\gamma$-ray sources in the energy range above 100 MeV are still unassociated (Nolan et al. 2012). It is worth noting that the most commonly detected sources in the $\gamma$-ray sky since the epoch of CGRO are blazars, one of the most enigmatic classes of active galactic nuclei (AGNs, e.g., Hartman et al. 1999). Within the 2FGL, there are 576 UGSs out of a total number of 1873 sources detected; among the 1297 associated sources, ~1000 have been associated with AGNs (Nolan et al. 2012; Ackermann et al. 2011a).

Blazar emission extends over the whole electromagnetic spectrum and is generally interpreted as non-thermal radiation arising from particles accelerated in relativistic jets closely aligned to the line of sight (Blandford & Rees 1978). They are divided into two classes: BL Lac objects, with featureless optical spectra or only with absorption lines of galactic origin and weak and narrower emission lines, and flat spectrum radio quasars, with optical spectra showing broad emission lines. In the following, we indicate the former as BZBs and the latter as BZQs according to the ROMA-BZCAT$^6$ nomenclature (Massaro et al. 2009, 2010, 2011a).

The first step to improving our knowledge about the origin of the UGSs and of their associations with low-energy counterparts is to recognize those that could have a blazar within their $\gamma$-ray positional uncertainty regions.

Recently, we developed a procedure of identifying blazars using their infrared (IR) colors within the preliminary data release of the Wide-field Infrared Survey Explorer (WISE) survey (Wright et al. 2010). In particular, we discovered that the IR color space distribution of the extragalactic sources dominated by non-thermal emission, such as blazars, can be used to distinguish such sources from other classes of galaxies and/or AGNs and/or galactic sources (Massaro et al. 2011b, hereafter Paper I). We also found that $\gamma$-ray-emitting blazars delineate a narrow, distinct region of the IR color–color plots, denominated as the WISE $\gamma$-ray blazar Strip (WGS; D’Abrusco et al. 2012, hereafter Paper II). There is a peculiar correspondence between the IR and $\gamma$-ray spectral properties of the blazars detected in the 2FGL (Paper II). On the basis of our previous investigation of these IR–$\gamma$-ray properties of blazars, we built a parameterization of the WGS to evaluate how many AGNs of uncertain type (AGUs) have a counterpart associated with a $\gamma$-ray blazar candidate in the 2FGL (Massaro et al. 2012, hereafter Paper III).

In this paper, we present a new association method based on the IR colors of the $\gamma$-ray-emitting blazars and the WGS parameterization. Then, we apply this new association procedure to

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$^6$ http://www.asdc.asi.it/bzcat/
$^7$ http://wise2.ipac.caltech.edu/docs/release/prelim/
search for γ-ray blazar candidates within the γ-ray positional error regions of the UGSs. One of the main advantages of our method is that it reduces the number of potential counterparts for the UGSs and provides their positions with arcsecond resolution, thus restricting the search regions for future follow-up observations necessary to confirm their blazar nature. Unfortunately, only a restricted number of UGSs fall within the portion of the sky currently covered by the IR observations of the WISE Preliminary Data Release, corresponding to ~57% of the whole sky. When the WISE survey is completely released in 2012 March, it will be possible to apply the method to the whole sky, even in regions not covered by radio, optical, and X-ray frequencies, where the other methods for establishing counterpart associations for the 2FGL cannot be used.

This paper is organized as follows: In Section 2, we describe the samples used in our investigation; in Section 3, we illustrate the new association method; in Section 4 we apply the new association technique to the UGSs and describe the subset of sources that has been associated with γ-ray blazar candidates. In Section 5, we also compare our results with those found by adopting different statistical approaches for a subsample of UGSs. Finally, we present conclusions in Section 6.

2. THE SAMPLE SELECTION

To build our association procedure, we considered a sample of blazars selected from the combination of ROMA-BZCAT (Massaro et al. 2009, 2010) and 2FGL (Nolan et al. 2012), as described and used in Paper II and used in Paper III to parameterize the WGS, denoted by the 2FB sample. It contains 284 γ-ray blazars (135 BZBs and 149 BZQs) that have optical and radio counterparts as reported in the ROMA-BZCAT and also have a WISE counterpart within 2′′ radius (see Papers I and III). The blazars in the 2FB sample are detected by WISE with a signal-to-noise ratio higher than 7 in at least one band and do not have any upper limits in all of the WISE bands. We excluded from our analysis all the blazars with a Fermi analysis flag, according to the 2FGL and the 2LAC (Nolan et al. 2012; Ackermann et al. 2011a). The blazars of uncertain type (BZUs) were excluded from our analysis, while the BL Lac candidates have been considered to be BZBs. More details on the 2FB sample and the source selections are given in Papers II and III. We applied our association procedure to the sample of the defined UGSs as follows: The number of UGSs in the 2FGL is 576, but only 410 of these γ-ray sources lie in the region of the sky available in the WISE Preliminary Data Release. These sources can be analyzed according to our method based on the IR WISE colors. We adopted a more conservative selection, restricting our sample to 313 UGSs out of 410, excluding sources with a Fermi analysis flag since these sources might not be real and/or could be affected by analysis artifacts (see, e.g., Nolan et al. 2012, for more details).

3. THE WGS ASSOCIATION METHOD

In Paper III, working on the AGUs, we built the WGS parameterization to verify if the low-energy counterparts of the AGUs, associated in 2FGL, are consistent with the WGS and are therefore γ-ray blazar candidates. With respect to the previous analysis, the following proposed association procedure aims at providing new γ-ray blazar candidates, possible counterparts of the UGSs, that lie within their γ-ray positional uncertainty regions, on the basis of our previous results concerning the IR–γ-ray blazar properties. In this section, we report the basic details of our WGS parameterization together with the definition of different classes of γ-ray blazar candidates. Then, we describe our new association procedure.

3.1. The WGS Parameterization

In Paper II, we found that γ-ray-emitting blazars (i.e., those in the 2FB sample) cover a narrow region in the three-dimensional color space built with the WISE magnitudes delineating the so-called WGS.

In Paper III, using the 2FB sample, we presented the parameterization of the WGS based on the strip parameter s. This parameter, ranging between 0 and 1, provides a measure of the distance between the WGS and the location of a WISE source in the three-dimensional IR color parameter space. For example, sources with high values of s (e.g., ≥0.50) are consistent with the WGS. We also distinguished between WISE sources that lie in the subregion of the WGS occupied by the BZBs and BZQs using the s and sq parameters separately (Paper III).

The IR color space has been built using the archival data available in the 2011 WISE Preliminary Data Release, in four different bands centered at 3.4, 4.6, 12, and 22 μm with an angular resolution of 6′′, 6′′, 6′′, and 12′′, respectively, and achieving 5σ point source sensitivities of 0.08, 0.11, 1, and 6 mJy. In addition, the absolute (radial) differences between WISE source peaks and “true” astrometric positions anywhere on the sky are no larger than ~0.′′50, 0.′′26, 0.′′26, and 1′′4 in the four WISE bands, respectively (Cutri et al. 2011).

3.2. γ-Ray Blazar Candidate Definition

Based on the s and sq distributions of all WISE sources in different random regions of the sky, at both high and low Galactic latitudes (Paper III), the critical threshold of the s parameters used to define the above classes has been arbitrarily determined on the basis of the following considerations:

1. class A—WISE sources with 0.24 < sb < 1.00 and 0.38 < sq < 1.00;
2. class B—WISE sources with 0.24 < sb < 1.00 or 0.38 < sq < 1.00; and
3. class C—WISE sources with 0.10 < sb < 0.24 and 0.14 < sq < 0.38.

All the WISE sources with sb < 0.10 or sq < 0.14 are considered outliers of the WGS and are therefore discarded. All the above thresholds are then used to select the WISE sources that are associated with the UGSs and that can be considered potential γ-ray blazar candidates.

The above choice of threshold have been adopted for the analysis of the γ-ray blazar content within the AGUs (Paper III). From the distributions of the sb and sq parameters for the generic IR WISE sources, we note that 99.9% of them have sb < 0.24 and sq < 0.38. Then, for the BZBs in the 2FB sample only 6 sources out of 135 have sb < 0.24; in the case of the BZQs only 33 sources out of 149 show sq values lower than 0.38. We also note that 99.0% of the generic IR WISE sources have sb < 0.10 and only 2 BZBs are below this value, while 97.2% of the generic IR WISE sources together with only 5 BZQs out of 149 have sq < 0.14.

The WISE objects of class A are the most probable blazar counterparts of the UGSs, because their WISE colors are more

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8 http://wise2.ipac.caltech.edu/docs/release/allsky/

9 http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/sec2_3g.html
consistent with the WGS in both the BZBs and BZQs subregions than are the colors of sources of class B or C. Based on the distributions of the $s_b$ and $s_q$ parameters for WISE sources in a random region of the sky, the sources of class A are, as expected, rarer than the sources belonging to the other two classes (see Section 4 for more details).

3.3. The Association Procedure

For each UGS we defined a searching region (SR) corresponding to a circular region of radius $R = \theta_{999}$, centered on the position given in the 2FGL, where $\theta_{999}$ is the major axis of the elliptical source location region corresponding to the 99.9% level of confidence. In addition, we also considered a region of comparison (ROC) defined as a circular region of the same radius $R$, but lying at $2.5\sqrt{2}$ deg angular distance from the 2FGL position. A schematic view of the locations of the SR and the ROC is shown in Figure 1.

Successively, for every unassociated $\gamma$-ray source in the 2FGL catalog, we ranked all the WISE sources within the $\gamma$-ray source’s SR on the basis of the classification described above, and we selected as $\gamma$-ray blazar candidates the positionally closest sources with the highest classes. In our analysis, we considered only sources of the WISE preliminary catalog detected in all four WISE bands, without any upper limit.

The ROCs are used to assess the association confidence that a WISE source in a random region in the sky, where no $\gamma$-ray source is located, has IR colors compatible with the WGS. To provide an estimate of the association confidence, we considered the distribution of the strip parameters $s_b$ and $s_q$ for all the WISE sources within each ROC associated with a UGS. For these WISE sources, we estimated the confidence $\pi$ that a generic WISE source belongs to the same class as the $\gamma$-ray blazar candidate selected within the SR. Thus, the $\pi$ value will be expressed as the ratio between the number of WISE sources of a particular class and the total number of WISE sources that lie in the ROC.

3.4. Testing the Association Method with Blazars

We performed a test to evaluate the completeness of our association method, searching for the $\gamma$-ray blazar candidates that are potential counterparts of the 2FB sample and verifying whether our procedure correctly finds the same associations as in the 2FB sample.

Assuming that the 284 blazars in the 2FB sample have been associated with the real low-energy counterparts, we ran our association procedure considering the IR colors for all the WISE sources within the SRs for all these sources. We found that for the population of BZBs, consisting of 135 BL Lac objects, our association procedure was able to recognize 123 sources as 2FGL, 62 as class A, and 61 as class B. Within the remaining 12 BZBs, 3 objects are associated with WISE sources of higher class than the original 2FL associated sources, while for 9 sources we only found outliers of the WGS within their SRs.

For the BZQs, our method finds the same associations as in the 2FGL catalog for 124 of the sources, with 85 sources classified as class A, 32 as class B, and 7 as class C. For the remaining 25 sources, we found 11 outliers and 14 $\gamma$-ray sources associated with a WISE source with higher classes.

Our procedure re-associated 247 out of 284 $\gamma$-ray blazars of the 2FB sample in agreement with the 2FGL analysis, with a completeness of 87.0% (91.0% for the BZBs and 83.0% for the BZQs). We found that 7.1% are outliers of the WGS, but this number can be expected because the WGS parameterization was built to require at least 90% of the 2FB sources inside each two-dimensional WGS projection (see Paper III for more details).

It is interesting to note that 17 out of 284 $\gamma$-ray sources in 2FGL have, on the basis of our method, a “better” $\gamma$-ray blazar candidate within the SR. These associations need to be verified with follow-up observations, for example in the X-rays, and a deeper analysis to check their reliability relative to the 2FGL association method will be performed in a forthcoming paper (F. Massaro et al. 2012, in preparation).

4. RESULTS

The application of our association procedure to the 313 UGSs selected from 2FGL (see Section 2 for more details) led to the association of 156 UGSs with a low-energy candidate $\gamma$-ray blazar counterpart within their SRs. According to our criteria (see Section 3.2), these 156 new associations consist of 44 sources of class A, 74 of class B, and 38 of class C. Thus, our procedure finds associations with likely $\gamma$-ray blazar candidates for 49.8% of the UGSs analyzed. We also list all of the $\gamma$-ray blazar candidates with lower classes for each UGSs, if more than one is present within the SRs. Among these 156 new associations, for 86 sources, 12 of class A, 43 of class B, and 31 of class C have only a single $\gamma$-ray blazar candidate within the SR. In Figure 2, we show the WISE colors of the 156 $\gamma$-ray blazar candidates in comparison with those of the blazars in the 2FB sample for the [3.4]–[4.6]–[12] $\mu$m two-dimensional projection of the WGS.

By restricting our sample of UGSs to those at high Galactic latitudes, i.e., $|b| > 15^\circ$, we found a $\gamma$-ray blazar candidate for 72 UGSs, 16 of class A, 29 of class B, and 27 of class C; for 34 out of these 74, the low-energy counterpart associated with our method is univocal. In Figure 3, we show the distribution of the Galactic latitude (i.e., sin $b$) for all the UGSs analyzed in comparison with those 156 associated with our method. At high Galactic latitude, the method seems to be less efficient given the ratio between the number of UGSs analyzed and those associated. This could be due to the non-uniform exposure of the archival
Figure 2. The [3.4]–[4.6]–[12] μm two-dimensional projection of the WGS is shown. Red dashed lines show the boundaries of the WGS used in our analysis (see Paper III for more details). The orange background filled circles are the blazars associated with the 2FGL constituting the 2FB sample, while the black filled circles indicate the 156 γ-ray blazars that have been associated in our procedure.

(A color version of this figure is available in the online journal.)

Figure 3. Distribution of the Galactic latitude for all the UGSs analyzed in comparison with that for the 156 associated in our procedure.

(A color version of this figure is available in the online journal.)

WISE observations in the WISE Preliminary Data Release\(^{10}\) and will be re-analyzed once the whole WISE archive will be available. In addition, we note that our association method could be more efficient at low Galactic latitudes where the blazar catalogs, such as ROMA-BZCAT, are less complete (Massaro et al. 2009).

We also remark that within the 313 regions of comparison chosen for the UGSs there are 55,195 WISE sources, but only 49 of class A, 213 of class B, and 129 of class C, all of them detected in all four WISE bands and with a signal-to-noise ratio higher than 7 in at least one band, as for the blazars in the 2FB sample. The distributions of the \(s_b\) and \(s_q\) parameters for all 55195 WISE sources within the 313 ROCs are shown in Figure 4. A blind search of all the possible γ-ray blazar candidates in the WISE archive on the basis of the WGS properties will be performed once it is completely available (F. Massaro et al. 2012, in preparation). However, the \(s_b\) and \(s_q\) distributions reported in Figure 4 strongly suggest that the density of WISE blazar candidates is low over the sky.

In Table 1, we show three cases of WISE sources that have been associated with three UGSs using our procedure.

\(^{10}\) http://wise2.ipac.caltech.edu/docs/release/prelim/figures/prelim_3x3-w1-equ.jpg
We report both the $s_b$ and $s_q$ values, the WGS class, and the association confidence $\pi$. In this example, the source 2FGL J0038.8+6259 is associated with one WISE class A source, J003818.70+630605.0, that has been selected as a single $\gamma$-ray blazar candidate out of 791 WISE sources within its SR. The corresponding association confidence $\pi$, expressed in terms of number of sources with a higher $s_b$ or $s_q$ value than J003818.70+630605.0 within the ROC and estimated considering 830 WISE sources, is 2/830.

Similarly, the source 2FGL J0616.6+2425 has been associated with the WISE source J061609.79+241911.0 that belongs to class B with a low association confidence estimated on 5465 WISE sources in the ROC. The 2FGL source 2FGL J0312.8+2013 has a WISE class C source that has been associated following our procedure, with a lower confidence of finding a similar source in an ROC where there are 512 WISE sources.

Within the 313 UGS analyzed there are 14 sources that have a variability index (Nolan et al. 2012) higher than the value of 41.6 corresponding to the 99% of confidence that the source is variable. It is worth noting that 13 out of these 14 variable UGSs have been successfully associated here with a $\gamma$-ray blazar candidate, strongly supporting the blazar nature.

The entire list of the UGSs analyzed can be found in Table 2. For each UGS, we report all the $\gamma$-ray blazar candidates with their IR colors (i.e., $c_{12} = [3.4]–[4.6]$ $\mu$m, $c_{23} = [4.6]–[12]$ $\mu$m, and $c_{34} = [12]–[22]$ $\mu$m, together with their errors, $\sigma_{12}$, $\sigma_{23}$, $\sigma_{34}$, respectively), the distances in arcseconds between the $\gamma$-ray position and the selected WISE source, the $s_b$ and $s_q$ values, the class, and the association confidence $\pi$ that there is a WISE source of the same class within the ROC (see Section 3.2).

In addition, we found that there are 157 UGSs that do not have clear $\gamma$-ray blazar counterparts within their SRs and are classified as outliers of the WGS. The lack of association for these sources could be due to a lower accuracy of the $\gamma$-ray position that might occur close to the Galactic plane or to the systematic uncertainties of the diffuse emission model used in the 2FGL analysis. The whole UGS sample is reconsidered for associations with $\gamma$-ray blazar candidates when the all-sky WISE survey is available.

Assuming that all the 2FB blazar associations are correct on the basis of our test (see Section 3.4), we can argue that within our sample we would expect about 41 ($\sim$13.0%) unrecognized low-energy counterparts, for a total of 197 $\gamma$-ray blazar candidates within the 313 UGSs analyzed.

Finally, it is worth stressing that our association procedure also provides interesting information about the sources that do not have a $\gamma$-ray blazar candidate in the SR. The absence of $\gamma$-ray blazar candidates selected according to our association procedure could direct us to better use the follow-up resources for identifying other $\gamma$-ray source candidates. For example, in the case of the UGS 2FGL J1446.8−4701 within the 1604 WISE sources that lie in its SR, we did not find any $\gamma$-ray blazar candidates. This source recently has been identified with the pulsar PSR 1446−4701 (see the Public List of LAT-Detected $\gamma$-Ray Pulsars).

5. COMPARISON WITH OTHER METHODS

We note that among the 313 UGSs analyzed, there are 70 sources that were also unidentified according to the investigation performed in the first Fermi $\gamma$-ray catalog (1FGL; Abdo et al. 2010b); 48 of them were associated with a $\gamma$-ray blazar candidate in our analysis. In particular, a recent analysis of the 1FGL UGSs was carried out using two different statistical...
approaches: the classification tree and the logistic regression analyses (see Ackermann et al. 2011b and references therein).

For 44 of the 48 UGSs that have been analyzed on the basis of the above statistical methods, it is also possible to perform a comparison with our results to verify if the 2FGL sources that we associated with a γ-ray blazar candidate also have been classified as AGNs following the procedures in Ackermann et al. (2011b). By comparing the results of our association method with those in Ackermann et al. (2011b), we found that 27 out of 44 UGSs that we associate with a γ-ray blazar candidate are also classified as AGNs, all of them with a probability higher than 71% and 18 of them higher than 80%. Among the remaining 17 sources, 7 have been classified as pulsars, with a very low probability with respect to the whole sample; in particular, 3 of these pulsar candidates are classified with a probability lower than 71% and all of them are lower than 71%, making these classifications less reliable than those of the AGNs. The last 10 UGSs did not have a classification in Ackermann et al. (2011b). Consequently, we emphasize that our results are in good agreement with the classification suggested previously by Ackermann et al. (2011b), consistent with the γ-ray blazar nature of the WISE candidates proposed in our analysis.

6. SUMMARY AND CONCLUSIONS

Recently, we discovered that blazars have peculiar mid-IR colors with respect to other galactic sources or different classes of AGNs. In particular, we found that within the three-dimensional IR parameter space they delineate a distinct, well-defined, region known as the WISE Blazar Strip (Paper I). Moreover, this distinction, mostly due to the non-thermal emission that dominates the IR radiation of blazars, appears to be more evident when considering those blazars selected on the basis of their γ-ray properties (Paper II) so defining the WGS. Then, in Paper III, we built the WGS parameterization to test the consistency of the low-energy counterpart of the AGUs associated in 2FGL with the WGS.

On the basis of these results, in the present work we developed a new association method to search for blazar counterparts of γ-ray sources, and we applied this method to the blazars of the 2FGL sample. We also provided new γ-ray blazar candidates, potential counterparts of the UGSs, that lie within their γ-ray positional error region and have the same mid-IR colors as the γ-ray blazars already associated. We also tested our new procedure a posteriori, trying to re-associate all the blazars in the 2FB sample, and we found that our results are in good agreement with different association procedures.

The application of our association procedure to the UGSs has led to the selection of possible blazar counterparts for 156 of the 313 UGSs analyzed.

As noted in Section 4, our association procedure also provides interesting information about the sources that do not have a γ-ray blazar candidate in the SRs as in the case of the UGS 2FGL J1446.8–4701, recently identified with the pulsar PSR 1446–4701.

Several developments will be considered to improve our association procedure, such as taking into account not only the IR colors, corresponding to flux ratios, but also the IR fluxes as well as the IR–γ-ray spectral index correlation (Paper II) and the sky distribution of the γ-ray blazar candidates, once the whole WISE data archive is released. Then, it will be also possible to calibrate our association procedure choosing different thresholds for the s parameters at different Galactic latitudes to take into account the WISE background.

Moreover, our association method is complementary with those adopted in the 2FGL catalog analysis, because it is based on different multifrequency information. For this reason, these methods could in principle be combined to increase the fraction of associated UGSs and the efficiency of the association. Further developments of this new association method will be investigated in a forthcoming paper (F. Massaro et al. 2012, in preparation).

We thank the anonymous referee for his or her comments. F. Massaro is grateful to S. Digel for fruitful discussions and for all the comments helpful toward improving our presentation. We also thank A. Cavaliere, D. Harris, J. Grindlay, J. Knodlseder, P. Giommi, N. Omodei, H. Smith, and D. Thompson for their suggestions. The work at SAO and at Stanford University is supported in part by the NASA grants NNX10AD50G, NNH09ZDA001N, and NNX10AD68G. R.D. gratefully acknowledges the financial support of the US Virtual Astronomical Observatory, which is sponsored by the National Science Foundation and the National Aeronautics and Space Administration. F.M. acknowledges the Fondazione Angelo Della Riccia for the grant awarded him to support his research at SAO during 2011 and the Foundation BLANCEFLOR Boncompagni-Ludovisi (formerly Bildt) for the grant awarded him in 2010 to support his research. TOPCAT12 (Taylor 2005) was used extensively in this work for the preparation and manipulation of the tabular data. Part of this work is based on archival

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Table 2

| Name          | Distance (arcsec) | c_12 | σ_12 | c_23 | σ_23 | c_34 | σ_34 | s_b | s_q | Class | π |
|---------------|-------------------|------|------|------|------|------|------|-----|-----|-------|---|
| 2FGL J0038.8+6259 |                   |      |      |      |      |      |      |     |     |       |   |
| J003818.70+630650.2 | 443.08            | 1.15 | 0.03 | 2.59 | 0.03 | 2.52 | 0.03 | 0.89 | 0.99 | A     | 2/830 |
| J003756.80+630459.2 | 492.33            | 0.67 | 0.04 | 2.09 | 0.06 | 2.36 | 0.12 | 0.40 | 0.00 | B     | 3/830 |
| J003834.17+630621.7 | 413.68            | 0.95 | 0.06 | 2.55 | 0.09 | 2.69 | 0.16 | 0.22 | 0.19 | C     | 0/830 |
| 2FGL J0158.6+8558 |                   |      |      |      |      |      |      |     |     |       |   |
| J014847.32+860345.3 | 707.33            | 1.21 | 0.03 | 3.10 | 0.03 | 2.66 | 0.05 | 0.29 | 0.73 | A     | 1/2439 |
| J015619.63+855634.6 | 173.64            | 1.11 | 0.04 | 3.49 | 0.04 | 2.71 | 0.05 | 0.00 | 0.70 | B     | 0/2439 |
| J014935.28+860115.3 | 603.41            | 0.73 | 0.03 | 2.34 | 0.05 | 2.06 | 0.16 | 0.44 | 0.21 | B     | 0/2439 |
| J015550.14+854745.1 | 644.48            | 1.15 | 0.04 | 2.51 | 0.06 | 2.20 | 0.19 | 0.26 | 0.37 | B     | 0/2439 |
| J015248.81+855703.5 | 376.98            | 1.11 | 0.05 | 2.96 | 0.08 | 1.87 | 0.29 | 0.21 | 0.22 | C     | 0/2439 |

(This table is available in its entirety in a machine-readable form in the online journal. A portion is shown here for guidance regarding its form and content.)

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12 http://www.star.bris.ac.uk/~mbt/topcat/
data, software, or online services provided by the ASI Science Data Center. This publication makes use of data products from the Wide-field Infrared Survey Explorer, which is a joint project of the University of California, Los Angeles, and the Jet Propulsion Laboratory/California Institute of Technology, funded by the National Aeronautics and Space Administration.

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