UNVEILING THE NATURE OF THE UNIDENTIFIED GAMMA-RAY SOURCES. V.
ANALYSIS OF THE RADIO CANDIDATES WITH THE KERNEL DENSITY ESTIMATION

F. Massaro 1, R. D’Abrusco 2, A. Paggi 3, N. Masetti 3, M. Giroletti 4, G. Tosti 5, Howard A. Smith 2, and S. Funk 1
1 SLAC National Laboratory and Kavli Institute for Particle Astrophysics and Cosmology, 2575 Sand Hill Road, Menlo Park, CA 94025, USA; fmassaro@stanford.edu
2 Harvard-Smithsonian Astrophysical Observatory, 60 Garden Street, Cambridge, MA 02138, USA
3 INAF-Istituto di Astrofisica Spaziale e Fisica Cosmica di Bologna, via Gobetti 101, I-40129 Bologna, Italy
4 INAF Istituto di Radioastronomia, via Gobetti 101, I-40129 Bologna, Italy
5 Dipartimento di Fisica, Università degli Studi di Perugia, I-06123 Perugia, Italy

Received 2013 July 25; accepted 2013 August 27; published 2013 October 22

ABSTRACT

Nearly one-third of the γ-ray sources detected by Fermi are still unidentified, despite significant recent progress in this area. However, all of the γ-ray extragalactic sources associated in the second Fermi-LAT catalog have a radio counterpart. Motivated by this observational evidence, we investigate all the radio sources of the major radio surveys that lie within the positional uncertainty region of the unidentified γ-ray sources (UGSs) at a 95% level of confidence. First, we search for their infrared counterparts in the all-sky survey performed by the Wide-field Infrared Survey Explorer (WISE) and then we analyze their IR colors in comparison with those of the known γ-ray blazars. We propose a new approach, on the basis of a two-dimensional kernel density estimation technique in the single [3.4] − [4.6] − [12] μm WISE color–color plot, replacing the constraint imposed in our previous investigations on the detection at 22 μm of each potential IR counterpart of the UGSs with associated radio emission. The main goal of this analysis is to find distant γ-ray blazar candidates that, being too faint at 22 μm, are not detected by WISE and thus are not selected by our purely IR-based methods. We find 55 UGSs that likely correspond to radio sources with blazar-like IR signatures. An additional 11 UGSs that have blazar-like IR colors have been found within the sample of sources found with deep recent Australia Telescope Compact Array observations.

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

Online-only material: color figures

1. INTRODUCTION

The majority of the point sources detected by the Compton Gamma-ray Observatory in the 1990s (e.g., Hartman et al. 1999) still lack an association with a low-energy candidate counterpart, and given their sky distribution, a significant fraction of these unresolved objects are expected to have extragalactic origin (e.g., Thompson 2008; Abdo et al. 2010a). Unveiling the origin of the unidentified γ-ray sources (UGSs) is also one of the key scientific objectives of the recent Fermi mission that still lists about one-third of the γ-ray sources as unassociated in the second Fermi-LAT catalog (2FGL; Nolan et al. 2012).

A large fraction of UGSs is expected to be blazars, the largest known population of γ-ray active galaxies, not yet associated and/or recognized because of the lack of multifrequency observations (Ackermann et al. 2011a). Therefore, a better understanding of the nature of the UGSs is crucial to estimate accurately the blazar contribution to the extragalactic gamma-ray background (e.g., Mukherjee et al. 1997; Abdo et al. 2010b), and it is essential to constrain exotic high-energy physics phenomena (e.g., Zechlin et al. 2012).

Many attempts have been adopted to decrease UGSs number and to understand their composition. Pointed Swift observations (e.g., Mirabal 2009; Mirabal & Halpern 2009; Paggi et al. 2013; Tavecchio et al. 2013) to search for X-ray counterparts of UGSs as well as radio follow-up observations were already performed or are still in progress (e.g., Kovalev 2009a; Kovalev et al. 2009b; Petrov et al. 2013). Statistical approaches that are based on different techniques have also been developed and successfully used (e.g., Mirabal & Pardo 2010; Ackermann et al. 2012).

We recently addressed the problem of searching γ-ray blazar candidates as counterparts of the UGSs adopting two new approaches: the first is based on the Wide-field Infrared Survey Explorer (WISE) all-sky observations (Wright et al. 2010) aimed at recognizing γ-ray blazar candidates using their peculiar IR colors (Massaro et al. 2011b, 2012b; D’Abrusco et al. 2012, 2013), while the second uses the low-frequency radio observations (Massaro et al. 2013a). In particular, this second method was based on the combination of the radio observations Westerbork Northern Sky Survey (WENSS; Rengelink et al. 1997) at 325 MHz with those of the NRAO Very Large Array Sky Survey (NVSS; Condon et al. 1998) and of the Very Large Array Faint Images of the Radio Sky at Twenty-Centimeters (FIRST; Becker et al. 1995; White et al. 1997) at about 1.4 GHz.

It is worth noting that all of the Fermi extragalactic sources associated in the 2FGL catalog have a clear radio counterpart (Nolan et al. 2012); this is the basis of the radio-γ-ray connection, that has been found in the case of blazars (e.g., Ghirlanda et al. 2010; Mahony et al. 2010; Ackermann et al. 2011b). Thus, motivated by this observational evidence, we propose a different approach to search for the blazar-like counterparts of the UGSs. We combine the radio and IR information available for the sources lying within the positional uncertainty regions of the Fermi UGSs to select γ-ray blazar candidates.

With respect to our previous IR-based search for blazar-like counterparts (e.g., Massaro et al. 2012a; D’Abrusco et al. 2013), our new analysis relaxes the constraint on the 22 μm detection of the WISE-selected candidates and does not take into account their [12] − [22] μm color, replacing these features with the presence of a radio counterpart. The number of γ-ray blazars
Table 1

| Name                                      | Acronym          |
|-------------------------------------------|------------------|
| Multifrequency catalog of blazars         | ROMA-BZCAT       |
| Second Fermi Large Area Telescope catalog | 2FGL             |
| BL Lac object                             | BZB              |
| Flat spectrum radio quasar                | BZQ              |
| Blazar of uncertain type                  | BZU              |
| Unidentified gamma-ray source             | UGS              |
| Training blazar sample                    | TB               |
| Northern UGS sample                       | NU               |
| Southern UGS sample                       | SU               |
| Southern deep ATCA sample                 | SDA              |
| Kernel density estimation                 | KDE              |

undetected at 22 \( \mu m \) is only a small fraction (~8% of the total number of \( \gamma \)-ray blazars; D’Abrusco et al. 2013) but includes several high redshift sources that lying at larger distance than the whole population.

To perform our analysis, we search all of the radio sources detected in the NVSS (Condon et al. 1998) and in the Sydney University Molonglo Sky Survey (SUMSS; Mauch et al. 2003) surveys that lie within the positional uncertainty region, at 95% level of confidence, of the UGSs listed in the 2FGL. Then, we associate them with their \( WISE \) counterparts to compare their IR colors with those of the known \( \gamma \)-ray blazars in the \([3.4] – [4.6] – [12] \mu m\) plot using the kernel density estimation (KDE) technique (e.g., Richards et al. 2004; D’Abrusco et al. 2009; Massaro et al. 2012a). We also verified whether the radio sources found in the recent deep radio observations performed by Australia Telescope Compact Array (ATCA) and presented by Petrov et al. (2013) have an IR counterpart with \( WISE \) colors consistent with those of the \( \gamma \)-ray blazar population. Our analysis of the IR colors is restricted only to the \([3.4] – [4.6] – [12] \mu m\) color–color plot.

The paper is organized as follows: Section 2 is devoted to the definitions of the samples used while in Section 3, we describe the KDE technique used to perform our investigation; we then applied our selection in Section 4 to identify those radio sources that could be considered blazar-like counterpart of the UGSs listed in the 2FGL catalog. We also verified the presence of optical and X-ray counterparts for the selected \( \gamma \)-ray blazar candidates, and we compare our results with different approaches previously developed. Last, Section 5 is dedicated to our conclusions.

For our numerical results, we use cgs units unless stated otherwise. Spectral indices, \( \alpha \), are defined by flux density, \( S_\nu \propto \nu^{-\alpha} \) and \( WISE \) magnitudes at the \([3.4], [4.6], [12], \) and \([22] \mu m\) (i.e., the nominal \( WISE \) bands) are in the Vega system, respectively. All of the magnitudes and the IR colors reported in the paper have been corrected for the galactic extinction according to the formulae reported in Draine (2003) as also performed in our previous analysis (e.g., D’Abrusco et al. 2013; Massaro et al. 2013b). The most frequent acronyms used in this paper are listed in Table 1.

2. SAMPLE SELECTION

The first sample used in our analysis lists all of the blazars appearing in the Multiwavelength Blazar Catalog\(^6\) (ROMA-BZCAT; Massaro et al. 2009) that have been associated as counterparts of \( Fermi \) sources in the 2FGL (Nolan et al. 2012) with a \( WISE \) counterpart detected at least in the first three filters, regardless of the fact that they are detected at 22 \( \mu m \). The association radius between the ROMA-BZCAT catalog and the \( WISE \) all-sky survey adopted here was fixed to 3′3 (see D’Abrusco et al. 2013, for more details). This sample, named \textit{training blazar} (TB) sample, comprises a total of 737 blazars, excluding those classified as blazars of uncertain type (BZUs; see also Massaro et al. 2010, 2011a). The TB sample is used to build the isodensity contours for the KDE technique (see the following sections) and to test whether IR sources with radio counterparts have \( WISE \) colors consistent with the \( \gamma \)-ray blazar population.

Then, the UGSs sample considered is the one constituted by all the \( Fermi \) sources listed in the 2FGL with no assigned counterpart at low energies and without any \( \gamma \)-ray analysis flag listing 299 sources (Nolan et al. 2012). We further divided this sample in two subsamples: the northern UGS (NU) sample comprising only sources with declination above than ~40° and the southern UGS (SU) sample comprising sources with declination below ~30°. This subdivision has been chosen on the basis of the footprints of the radio surveys used for our analysis, since the NU sample is mainly covered by the NVSS survey (Condon et al. 1998), while the SU one by the SUMSS catalog (Mauch et al. 2003). The former sample lists 209 UGSs, while 115 sources belong to the latter one.

Last, we also considered the list of all the radio sources recently found by Petrov et al. (2013) using deep ATCA observations for the UGSs in the southern hemisphere. This sample is labeled as southern deep ATCA (SDA) sample.

3. KERNEL DENSITY ESTIMATION

The KDE technique is a non-parametric procedure to estimate the probability density function of a multivariate distribution without requiring any assumption about the shape of the parent distribution. The KDE technique also permits to reconstruct the density distribution of a population of points in a general \( N \)-dimensional space on the basis of a finite sample. This analysis depends on only one parameter—the bandwidth of the kernel of the density estimator (analogous to the window size for one-dimensional running average) that can be estimated locally (see, e.g., Richards et al. 2004; D’Abrusco et al. 2009; Laurino & D’Abrusco 2011, and reference therein).

We already applied the KDE technique in several cases to compare the IR colors of blazar candidates selected with different procedures with those of the known population of \( \gamma \)-ray blazars (see Massaro et al. 2011b, 2012a; Paggi et al. 2013, for more details). Thus, in the present analysis, we use the KDE method to compare the IR colors of the radio-selected counterparts with those of the \( \gamma \)-ray blazar population represented by the TB sample in the two-dimensional \([3.4] – [4.6] – [12] \mu m\) color–color plot. As already described in Massaro et al. (2012a), we provide an associated confidence \( \pi_{kde} \) drawn from the KDE density probabilities that a selected radio source as IR colors consistent with the blazars in the TB sample.

In Figure 1, we show the density profiles constructed for the whole blazar population (left panel) and used to estimate \( \pi_{kde} \) and those of the two subsamples of BL Lac objects (BZBs) and BZQs (right panel) belonging to the TB sample in order to highlight the dichotomy between the two subclasses.

\(^6\) http://www.asdc.asi.it/bzcat
4. UNIDENTIFIED $\gamma$-RAY SOURCES

4.1. Selection of $\gamma$-ray Blazar Candidates

For each UGS, we searched for all the radio sources that lie within their positional uncertainty regions at 95% level of confidence, and we found that there are 822 radio sources potential counterparts of 209 UGSs and 134 out of 115 for the NU and the SU samples, respectively. We then crossmatched all these radio sources with the WISE all-sky catalog\(^7\) (Wright et al. 2010) using the same radius of 3′′ and we selected only those with an IR counterpart detected at least in the first three WISE filters and not extended (i.e., extension flag, ext\_f1g < 1; Cutri et al. 2012). The 3′′ radius chosen to associated sources between the WISE and the radio catalogs is statistically justified on the basis of the analysis performed over the entire ROMA-BZCAT (see D’Abrusco et al. 2013, for more details). Thus, we obtained 374 out of 822 and 78 out of 134 radio sources in the NU and SU samples, respectively.

Subsequently, we applied the KDE technique described in Section 3 to find radio sources with WISE counterparts having IR colors consistent with the $\gamma$-ray blazar population. We considered reliable $\gamma$-ray blazar candidates only radio sources consistent within the isodensity contours, drawn from the KDE, at 90% level of confidence, correspondent to an association confidence ($\pi_{kde}$) greater than 10.0.

We found 41 and 14 radio sources WISE selected with $\pi_{kde}$ > 0.1 within the NU and the SU samples, respectively. In addition, only 11 out of 416 radio sources listed in the SDA sample have an IR counterpart consistent with the Fermi blazar population of the TB sample with $\pi_{kde}$ > 10.0. We also list two exceptions to the aforementioned criteria: the UGS 2FGLJ1223.3+7954 with its WISE blazar candidate WISE J122358.17+795327.8 in the NU sample and 2FGLJ0523.3–2530 with WISE J052313.07–253154.4 as potential counterpart in the SDA sample, having the $\pi_{kde}$ values equal to 9.6 and 9.5, respectively, marginally below our threshold. The total number of $\gamma$-ray blazar candidates is 66 all listed in Tables 2 and 3. It is worth noting that we do not have any multiple $\gamma$-ray blazar candidate within the positional uncertainty regions of the UGSs analyzed.

In Figure 2, we show the isodensity contours derived from the KDE analysis in the [3.4] – [4.6] – [12] $\mu$m color–color plot, together with the $\gamma$-ray blazar candidates selected in the UGS samples analyzed and in the SDA list. It is evident how the large fraction for the selected candidates are located within the isodensity contours drawn for the BZB class.

To establish if the $\gamma$-ray blazar candidate selected with our method have additional multifrequency properties that could confirm their nature and provide redshift estimates, we also searched for the counterpart of our radio-IR selected candidates in the following major surveys. For the near-IR we used only the

---

\(^7\) http://wise2.ipac.caltech.edu/docs/release/allsky/

---
| 2FGL Name | WISE Name       | Radio Name | [3.4] − [4.6] (mag) | [4.6] − [12] (mag) | \( \sigma_{\text{dE}} \) | Notes | \( \gamma \) | Compare |
|-----------|----------------|------------|---------------------|-------------------|----------------|-------|----------|---------|
| 2FGL0001.0+00724 | J000143.1+00175 | NVSSJ000143+00175 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |
| 2FGL0021.4+4048 | J002133.5+4048 | NVSSJ002133+4048 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |
| 2FGL0031.8+3054 | J003150.6+3054 | NVSSJ003150+3054 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |
| 2FGL0053.0+3154 | J005315.0+3154 | NVSSJ005315+3154 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |

**Table 2**

| Northern UGS Sample |  |  |  |  |  |  |  |  |  |
|---------------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 2FGL0014.4+3248 | J001430.6+3248 | NVSSJ001430+3248 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |
| 2FGL0015.2+3250 | J001523.5+3250 | NVSSJ001523+3250 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |
| 2FGL0016.0+3252 | J001627.4+3252 | NVSSJ001627+3252 | 0.80(0.04) | 2.40(0.10) | 29.3 | N, v | ? | 1, 2 |

**Notes.** Column 1: 2FGL name. Column 2: WISE name. Column 3: radio name. Columns 4 and 5: IR colors from WISE. Values in parentheses are 1σ uncertainties. Column 6: notes. Column 7: \( \gamma \). Column 8: Compare.
Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006, - M) since each WISE source is already associated with the closest 2MASS source by the default catalog (see Cutri et al. 2012, for more details). We then searched for optical counterparts, with possible spectra available, in the Sloan Digital Sky Survey (SDSS; e.g., Adelman-McCarthy et al. 2008; Paris et al. 2012, - s), in the Six-degree-Field Galaxy Redshift Survey (Jones et al. 2004, 2009, - 6), in The Muenster Red Sky Survey (MRSS; Ungruhe et al. 2003) and in the USNO-B Catalog (Monet et al. 2003) within 3′. These optical cross correlations are also useful to plan follow-up observations thus a complete list of sources together with their optical magnitudes is reported in Table 4. For the high energy we looked in the soft X-rays using the ROSAT All-sky Survey catalog (Voges et al. 1999, - X). Last, we investigated the NASA Extragalactic Database (NED)8 for any possible counterpart within 3′ for additional information. The results of this multifrequency investigation is presented and summarized in Tables 2 and 3.

4.2. Probability of Spurious Associations

We estimated the probability that our γ-ray blazar candidates can be spurious associations adopting the following approach, similar to that successfully used in our previous analyses (e.g., Massaro et al. 2013a; Paggi et al. 2013).

We created two fake γ-ray catalogs shifting the coordinates of the 41 γ-ray blazars in the NU sample and of the 25 in the SU one by 0:7 in a random direction of the sky within the footprints of the NVSS and the SUMSS radio surveys. Keeping the same values of σ0 of each fake UGS, we verified that there were no correspondences with real Fermi sources within a circular region of radius σ0 at the flux level of the 2FGL.

For each fake UGSs, we search for all the radio sources lying within the positional uncertainty region at 95% of confidence in both the NVSS and SUMSS radio surveys. We then checked the presence of an IR counterpart of each radio source selected above. For each radio source with a counterpart we applied our KDE technique selecting the radio sources detected by WISE at 3.4 μm, 4.5 μm, and 12 μm with πkde > 0.10 being fake γ-ray blazar candidates. Then we repeated the entire procedure 10 times for both the NU and the SU sample to establish the probability of spurious associations. Based on the above procedure, we expect that 4% and 3% of the γ-ray blazar candidates previously selected for the UGS in the NU and SU samples, respectively, could be contaminants.

Last, we emphasize that these estimates depend on the γ-ray background model, the detection threshold, and the flux limit of the 2FGL catalog (Nolan et al. 2012), in which no γ-ray emission arises from any of the positions listed in the fake γ-ray catalogs.

4.3. Comparison with Previous Investigations

We compare our results with those of previous analyses carried out in Massaro et al. (2013a), Massaro et al. (2013b), and Paggi et al. (2013). The results of our comparison is summarized below and presented in Tables 2 and 3.

We note that within the 41 γ-ray blazar candidates found in the NU sample, 16 sources were also selected on the basis of their three WISE colors in Massaro et al. (2013a), 7 that appeared consistent with the Fermi blazars. Thus, in the SDA sample, but they did not verified which have IR colors consistent with the Fermi blazars. Thus, in the SDA sample, we listed 11 radio sources detected thanks to the deeper radio survey performed with ATCA (Petrov et al. 2013) with IR colors consistent with those of the γ-ray blazar population.

---

Table 3

Identified Gamma-Ray Sources in the SDA Sample

| 2FGL Name | WISE Name | IAU Name | [3.4] − [4.6] (mag) | [4.6] − [12] (mag) | πkde | Notes | z | Compare |
|------------|-----------|----------|---------------------|---------------------|-------|-------|---|---------|
| 2FGL0200.4−4105 | J020020.94−410935.6 | J0200−4109 | 0.63(0.06) | 1.90(0.32) | 19.3 | 6:X | ? |
| 2FGL0340.7−2421 | J034022.89−242407.2 | J0340−2424 | 0.73(0.06) | 2.45(0.20) | 10.0 | N | ? |
| 2FGL0523.3−2530 | J052313.07−253154.4 | J0523−2531 | 1.33(0.06) | 2.90(0.09) | 9.5 | ? |
| 2FGL0547.5−0141c | J054720.85−013329.9 | J0547−0133 | 0.81(0.07) | 2.11(0.27) | 36.6 | N | ? |
| 2FGL0937.9−1434 | J093754.72−143350.3 | J0937−1433 | 0.71(0.04) | 2.15(0.08) | 35.1 | N | ? |
| 2FGL1135.6−0730 | J113552.98−073031.9 | J1135−0733 | 0.87(0.03) | 2.27(0.04) | 47.2 | N,F,M,v,BL | ? | ! |
| 2FGL1339.2−2348 | J133916.44−234829.4 | J1339−2348 | 0.75(0.05) | 2.06(0.19) | 35.0 | N | ? |
| 2FGL1345.8−3356 | J134543.05−335643.3 | J1345−3356 | 0.82(0.04) | 2.31(0.06) | 49.8 | N,S,M | ? | ! |
| 2FGL1203.7−4201 | J120351.08−420038.2 | J1203−4200 | 0.61(0.05) | 2.04(0.17) | 22.3 | ? |
| 2FGL2251.1−4927 | J225128.89−492910.6 | J2251−4929 | 0.76(0.04) | 2.47(0.10) | 12.1 | S | ? |
| 2FGL2234.3−4752 | J234022.9−475749.9 | J2343−4757 | 0.71(0.07) | 2.06(0.31) | 35.4 | S | ? |

Notes. Column 1: 2FGL name. Column 2: WISE name. Column 3: radio name. Columns 4 and 5: IR colors from WISE. Values in parentheses are 1σ uncertainties. Column 6: notes: N = NVSS, F = FIRST, M = 2MASS, s = SDSS dr9, 6 = 6dFG; X = ROSAT; QSO = quasar, BL = BL Lac; v = variable in WISE bands (var_flag > 5 in at least one band; see Cutri et al. 2012 for additional details); r = variable in the radio bands at 1.4 GHz. Column 7: estimate level of confidence derived from the KDE analysis. Column 8: redshift: ? = unknown. Column 9: results of the comparison with previous analyses. 1 = UGS analyzed in Massaro et al. (2013a), 2 = UGS analyzed in Massaro et al. (2013b), 3 = UGS analyzed in Paggi et al. (2013). Exclamation mark (!) indicates that the γ-ray blazar candidate is the same IR source found in the previous investigation.

---

8 http://ned.ipac.caltech.edu
Among these 11 γ-ray blazar candidates, two sources were already found in Massaro et al. (2013a) and only one UGS (i.e., 2FGLJ0547.5−0141c) previously investigated that appear to have a different potential counterpart.

We note that the comparison between the γ-ray blazar candidates found in the SU and in the SDA samples and those presented in Massaro et al. (2013b) that were based on the WENSS radio analysis was not possible because the footprints of the surveys used did not overlap. We also verified that the selected γ-ray blazar candidates having a SDSS counterpart exhibit optical color consistent with those of BL Lacs (i.e., \( u−r < 1.4 \); see Massaro et al., 2012, for more details). We found that with the exception of only NVSSJ154824+145702, all of them have the same optical properties of the BZB population.

Within the whole sample of UGSs analyzed, 25 sources were also unidentified in the 1FGL (Abdo et al. 2010a) and were analyzed on the basis of two different statistical approaches: the Classification Tree and the Logistic regression analyses (see Ackermann et al., 2012, and references therein). By comparing the results of our association method with those in Ackermann et al. (2012), we found that 19 out of 25 UGSs with a γ-ray blazar candidate recognized according to our method are also classified as active galactic nuclei (AGNs). All of them had a probability higher than 60%, with 14 higher than 80%. The remaining three sources were classified as pulsar candidates but with a very low probability (i.e., \(< 60\%\)) Consequently, our results are in good agreement with the classification suggested previously by Ackermann et al. (2012) and thus consistent with the γ-ray AGN nature.

Last, we remark that several γ-ray pulsars have been identified after the release of the 2FGL, where they are listed as UGSs. However, we did not exclude these UGSs from our sample to test if, as expected, we did not find any blazar-like counterpart associated to them. Thus, in agreement with our expectations, all of the UGSs for which we found a γ-ray blazar candidates do not have any pulsars associated according to the Public List of LAT-Detected Gamma-Ray Pulsars.9

### 5. SUMMARY AND CONCLUSIONS

In this paper, we presented a non-parametric method to search for γ-ray blazar candidates within two samples of UGSs. First, we identify all the optical sources in the two major surveys (i.e., NVSS and SUMSS; Condon et al. 1998; Mauch et al. 2003, respectively) that lie within the positional uncertainty region at 95% level of confidence, then we investigate the IR colors of their WISE counterparts to recognize those with similar spectral properties in the simple \([3.4]−[4.6]−[12]\) color–color plot. With respect to our previous WISE selection of γ-ray blazar candidates (e.g., Massaro et al. 2012a; D’Abrusco et al. 2013) the criteria adopted in the present analysis are less conservative, since the detection of the WISE counterpart at 22 \(\mu\)m is not required. A small fraction (\(~8\%) of the Fermi blazar are not detected at 22 \(\mu\)m. Thus, to compare the IR colors of the Fermi blazars with those of the radio sources selected, we adopted a KDE technique as already presented in Massaro et al. (2011a), Massaro et al. (2012a), and more recently in Paggi et al. (2013). Our new approach, being less restrictive than those adopted in our previous associations, permits us to search for faint γ-ray blazar candidates that were not previously selected because they were too faint at 22 \(\mu\)m. By relaxing the requirement

---

9. [https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars](https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars)
We thank the anonymous referee for useful comments on the probability of spurious associations that improved our paper. This work is supported by the NASA grants NNX12AO97G and NNX13AP20G. D’Abrusco 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. The work of G. Tosti is supported by the ASI/INAF contract I/005/12/0. Howard A. Smith acknowledges partial support from NASA-JPLRSA contract 717437. TOPCAT\footnote{http://www.star.bris.ac.uk/~mbt/topcat/} (Taylor 2005) for the preparation and manipulation of the tabular data and the images. The WENSS project was a collaboration between The Netherlands Foundation for Research in Astronomy and the Leiden Observatory. We acknowledge the WENSS team, which consisted of Ger de Bruyn, Yuan Tang, Roeland Rengelink, George Miley, Huub Rottgering, Malcolm Bremer, Martin Bremer, Wim Brouw, Ernst Raimond, and David Fullagar, for the extensive work aimed at producing the WENSS catalog. Part of this work is based on archival data, software, or online services provided by the ASI Science Data Center. This research has made use of data obtained from the High Energy Astrophysics Science Archive Research Center (HEASARC) provided by NASA’s Goddard Space Flight Center; the SIMBAD database operated at CDS, Strasbourg, France; the NASA/IPAC Extragalactic Database (NED) operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. Part of this work is based on the NVSS (NRAO VLA Sky Survey). The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation. This publication makes use of data products from the Two Micron All Sky Survey, which is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation. 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.

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, 720, 435
Ackermann, M., Ajello, M., Allafort, A., et al. 2011a, ApJ, 743, 171
Ackermann, M., Ajello, M., Allafort, A., et al. 2011b, ApJ, 741, 30
Ackermann, M., Ajello, M., Allafort, A., et al. 2012, ApJ, 753, 83
Adelman-McCarthy, J., Agueros, M. A., Allam, S. S., et al. 2008, ApJS, 175, 297
Becker, R. H., White, R. L., & Helfand, D. J. 1995, ApJ, 450, 559
Condon, J. J., Cotton, W. D., Greisen, E. W., et al. 1998, AJ, 115, 1693
Cutri, R. M., Wright, E. L., Conrow, T., et al. 2012, Explanatory Supplement to the WISE All-Sky Data Release Products
D’Abrusco, R., Longo, G., & Walton, N. A. 2009, MNRAS, 396, 223
D’Abrusco, R., Massaro, F., Ajello, M., et al. 2012, ApJ, 748, 68
D’Abrusco, R., Massaro, F., Paggi, A., et al. 2013, ApJS, 206, 12
Draine, B. T. 2003, ARA&A, 41, 241
Ghirlanda, G., Ghisellini, G., Tavecchio, F., & Foschini, L. 2010, MNRAS, 407, 791
Hartman, R. C., Bertics, D. L., Bloom, S. D., et al. 1999, ApJS, 123, 79
Jones, H. D., Saunders, W., Colless, M., et al. 2004, MNRAS, 355, 747
Jones, H. D., Read, M. A., Saunders, W., et al. 2009, MNRAS, 399, 683
Kovalev, Y. Y. 2009, ApJL, 707, L56
Kovalev, Y. Y., Adler, H. D., Aller, M. F., et al. 2009, ApJL, 696, L17
Laurino, O., & D’Abrusco, R. 2011, MNRAS, 418, 2165
Mahony, E. K., Sadler, E. M., Murphy, T., et al. 2010, ApJ, 718, 587
Massaro, E., Giommi, P., Leto, C., et al. 2009, A&A, 495, 691
Massaro, E., Giommi, P., Leto, C., et al. 2010, arXiv:1006.0922
Massaro, E., Giommi, P., & Leto, C. et al. (ed) 2011a, Multifrequency Catalogue of Blazars (3rd ed.; Rome: Aracne Editrice)
Massaro, F., D’Abrusco, R., Ajello, M., Grindlay, J. E., & Smith, H. A. 2011b, ApJL, 740, L48
Massaro, F., D’Abrusco, R., Tosti, G., et al. 2012a, ApJ, 750, 138
Massaro, F., D’Abrusco, R., Tosti, G., et al. 2012b, ApJ, 752, 61
Massaro, E., Nesci, R., & Piranomonte, S. 2012, MNRAS, 422, 2332
Massaro, F., D’Abrusco, R., Giorelli, M., et al. 2013a, ApJS, 207, 4
Massaro, F., D’Abrusco, R., Paggi, A., et al. 2013b, ApJS, 206, 13
Mauch, T., Murphy, T., Buttery, H. J., et al. 2003, MNRAS, 342, 1117
Mirabal, N. 2009, arXiv:0908.1389v2
Mirabal, N., & Halpern, J. P. 2009, ApJL, 701, 129
Mirabal, N., Nieto, D., & Pardo, S. 2010, A&A, submitted (arXiv:1007.2644v2)
Monet, D. G., Levine, S. E., Canzian, B., et al. 2003, AJ, 125, 984
Mukherjee, R., Bertsch, D. L., Bloom, S. D., et al. 1997, ApJ, 490, 116
Nolan, P. L., Abdo, A. A., Ackermann, M., et al. 2012, ApJS, 199, 31
Paggi, A., Massaro, F., D’Abrusco, R., et al. 2013, ApJS, 209, 9
Paris, I., Petitjean, P., Aubourg, E., et al. 2012, A&A, 548A, 66
Petrov, L., Mahony, E. K., Edwards, P. G., et al. 2013, MNRAS, 432, 1294
Rengelink, R., Tang, Y., de Bruyn, A. G., et al. 1997, A&AS, 124, 259
Richards, G. T., Nichol, R. C., Gray, A. G., et al. 2004, ApJS, 155, 257
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Takeuchi, Y., Kataoka, J., Maeda, K., et al. 2011, ApJS, 208, 25
Taylor, M. B. 2005, in ASP Conf. Ser. 347, Astronomical Data Analysis Software and Systems XIV, ed. P. Shobell, M. Britton, & R. Ebert (San Francisco, CA: ASP), 29
Thompson, D. J. 2008, RPPh, 71, 116901
Ungruhe, R., Seitter, W. C., & Duerbeck, H. W. 2003, IAU, S7, 1
Voges, W., Aschenbach, B., Boller, Th., et al. 1999, A&A, 349, 389
White, R. L., Becker, R. H., Helfand, D. J., Gregg, M. D., et al. 1997, ApJ, 475, 479
Wright, E. L., Eisenhardt, P. R. M., Mainzer, A. K., et al. 2010, AJ, 140, 1868
Zechlin, H.-S., Fernandes, M. V., Elsaesser, D., & Horns, D. 2012, A&A, 538A, 93