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

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ABSTRACT

Nearly one-third of the γ-ray sources detected by *Fermi* are still unidentified, despite significant recent progress in this effort. On the other hand, all 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 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, based on a 2-dimensional kernel density estimation (KDE) 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 22μm 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 22μm, are not detected by *WISE* and thus are not selected by our purely IR based methods. We find fifty-five UGS's likely correspond to radio sources with blazar-like IR signatures. Additional eleven UGSs having, blazar-like IR colors, have been found within the sample of sources found with deep recent ATCA observations.

Subject headings: galaxies: active - galaxies: BL Lacertae objects - radiation mechanisms: non-thermal

1. INTRODUCTION

The large majority of the point sources detected by the Compton Gamma-ray Observatory in the 1990s (e.g., Hartman et al. 1999) are still lacking 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 1/3 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 due to 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) 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). In addition, statistical approaches based on different techniques have been also 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) aiming at recognizing γ-ray blazar candidates using their peculiar IR colors (Massaro et al. 2011a; D'Abrusco et al. 2012; Massaro et al. 2012b; D'Abrusco et al. 2013) while the second employs the low-frequency radio observations (Massaro et al. 2013b). In particular, this second method was indeed 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 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

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combine the radio and the 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 22μm 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 undetected at 22μm is only a small fraction (~8%of the total number of γ-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 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 γ-ray blazars in the [3.4]-[4.6]-[12] μm 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 if 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 γ-ray blazar population. Our analysis of the IR colors is restricted only to the [3.4]-[4.6]-[12] μm 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 γ-ray blazar candidates and we compare our results with different approaches previously developed. Finally, Section 5 is dedicated to our conclusions.

For our numerical results, we use cgs units unless stated otherwise. Spectral indices, α, are defined by flux density, $S_\nu \propto \nu^{-\alpha}$ and *WISE* magnitudes at the [3.4], [4.6], [12], [22] μm (i.e., the nominal *WISE* bands) are in the Vega system respectively. All 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. 2013a). The most frequent acronyms used in the paper are listed in Table 1.

2. SAMPLE SELECTION

The first sample used in our analysis lists all the blazars listed 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 22μm. 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 *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; Massaro et al. 2011b). The TB sample is used to build the isodensity contours for the KDE technique (see following sections) and to test if IR sources with radio counterparts have *WISE* colors consistent with the γ-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 γ-ray analysis flag listing 299 sources (Nolan et al. 2012). We further divided this sample in two subsamples: the northern UGS (NU) sample where only sources with Declination above than -40 deg and the southern UGS (SU) sample selecting those at Declination below -30 deg. 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.

Finally, 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.

TABLE 1
List of most frequent acronyms.

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

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 based on 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).

[6] http://www.asdc.asi.it/bzcat/

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 γ-ray blazars (see Massaro et al. 2011a; Massaro et al. 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 γ-ray blazar population represented by the TB sample in the 2-dimensional [3.4]-[4.6]-[12] μm color-color plot. As already described in Massaro et al. (2012a), we provide an associated confidence π_{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 π_{kde} and those of the two subsamples of BZBs and BZQs (right panel) belonging to the TB sample, to highlight the dichotomy between the two subclasses.

4. UNIDENTIFIED γ-RAY SOURCES

4.1. *Selection of γ-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′′.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, $ext\_flg \leq 1$) (Cutri et al. 2012). The 3′′.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 γ-ray blazar population. We considered reliable γ-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 (π_{kde}) grater than 10.0.

We found 41 and 14 radio sources *WISE* selected with π_{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 π_{kde} >10.0. We also list two exceptions to the above 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 π_{kde} values equal to 9.6 and 9.5, respectively, marginally below our threshold. The total number of γ-ray blazar candidates is 66 all listed in Table 2 and Table 3. It is worth noting that we do not have any multiple γ-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] μm color color plot, together with the γ-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 with the isodensity contours drawn for the BZB class.

To establish if the γ-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 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 (6dFGS; Jones et al. 2004; Jones et al. 2009, - 6), in the The Muenster Red Sky Survey (MRSS; Ungruhe et al. 2003) and in the USNO-B Catalog (Monet et al. 2003) within 3′′.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 (RASS; Voges et al. 1999, - X). Finally, we also considered the NASA Extragalactic Database (NED) [8] for any possible counterpart within 3′′.3 for additional information. The results of this multifrequency investigation is presented and summarized in Table 2 and Table 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. 2013b; 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 θ_{95} of each *fake* UGS, we verified that there were no correspondences with real *Fermi* sources within a circular region of radius θ_{95} 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 crossmatching the *WISE* all-sky catalog with their NVSS and SUMSS positions within a radius of 3′′.3. The value of this IR-to-radio association radius has been chosen on the basis

[7] http://wise2.ipac.caltech.edu/docs/release/allsky/

[8] http://ned.ipac.caltech.edu/

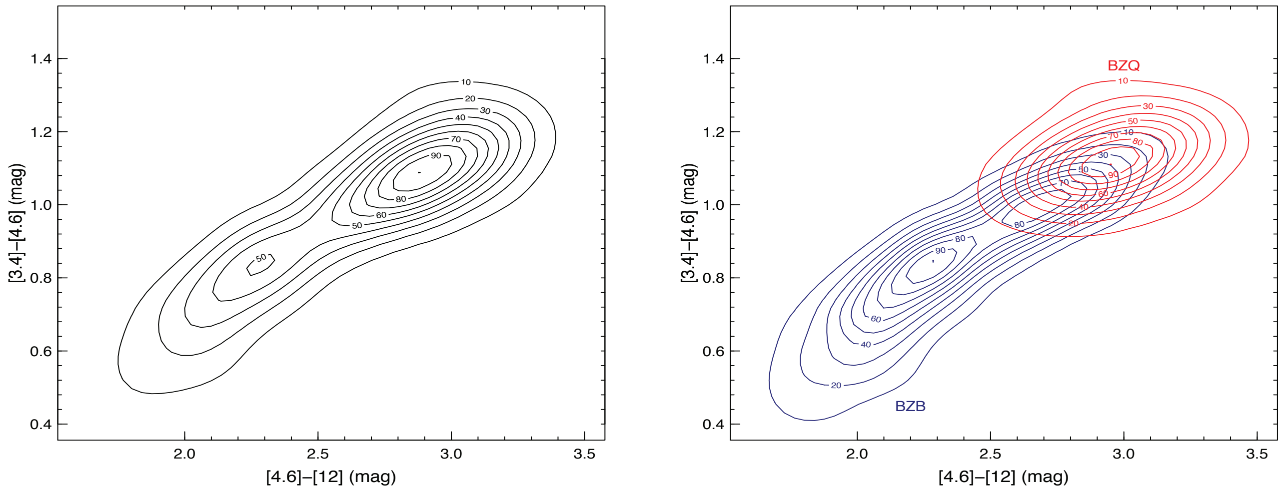

FIG. 1.— Left) The isodensity contours generated by KDE technique in the [3.4]-[4.6]-[12] μm color-color diagram for the whole γ-ray blazar population represented by the sources in the TB sample. Right) The KDE isodensity contours built separately for the BZB (blue) and the BZQ (red) classes in the TB sample. The numbers appearing close to each contour corresponds to the values of π_{kde} in both panels.

of our previous statistical analyses (see Section 2 and D'Abrusco et al. 2013, for more details).

For each radio source with a *WISE* counterpart we applied our KDE technique selecting the radio sources detected by *WISE* at 3.4μm, 4.5μm and 12μm with $\pi_{kde} > 0.10$ 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.

Finally, 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 is arising from any of the positions listed in the *fake* γ-ray catalogs.

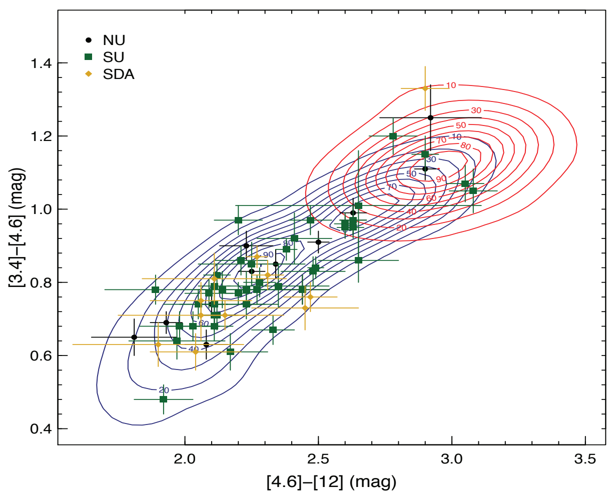

FIG. 2.— The isodensity contours generated by KDE technique in the [3.4]-[4.6]-[12] μm color-color diagram for the BZBs (blue) and the BZQs (red) in the TB sample. Points overlaid to the contours show the location of the selected radio candidates with IR colors consistent with the γ-ray blazar population within π_{kde} >10 for the sources in the three different samples analyzed: NU (black circles), SU (green squares) and SDA (yellow diamonds). The numbers appearing close to each contour corresponds to the values of π_{kde}.

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 Table 2 and Table 3.

We note that within the 41 γ-ray blazar candidates found in the NU sample there are 16 sources that were also selected on the basis of their three *WISE* colors in Massaro et al. (2013a) 7 that appeared as potential counterpart in Massaro et al. (2013b) found with the low-frequency radio observations and 14 listed with an X-ray properties in Paggi et al. (2013). In addition, 12 UGS were also investigated in our previous analyses but for them we found a different γ-ray blazar candidate. The number of new candidates counterparts in the NU sample is 5. On the other hand, within the SU sample, we found that 8 radio sources were also selected in Massaro et al. (2013a) and 4 in Paggi et al. (2013), in addition to 4 new γ-ray blazar candidates.

Petrov et al. (2013) already found the *WISE* counterparts of their 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. Among these 11 γ-ray blazar candidates, there are two sources already found in Massaro et al. (2013a) and only one

TABLE 2
Unidentified Gamma-ray Sources in the Northern and in the Southern samples.

2FGL name	WISE name	Radio name	[3.4]-[4.6] mag	[4.6]-[12] mag	π_{kde}	notes	z	compare
NORTHERN UGS SAMPLE								
2FGLJ0031.0+0724	J003119.70+072453.6	NVSSJ003119+072456	0.83(0.04)	2.48(0.12)	29.3	N	?	3
2FGLJ0039.1+4331	J003908.14+433014.6	NVSSJ003907+433015	0.97(0.04)	2.20(0.09)	10.3	N,v	?	1,2,3
2FGLJ0103.8+1324	J010345.73+132345.4	NVSSJ010345+132346	0.68(0.04)	2.03(0.10)	31.3	N,M	?	3
2FGLJ0158.4+0107	J015852.76+010132.9	NVSSJ015852+010133	0.85(0.06)	2.25(0.20)	49.1	N,F,s,rv	?	-
2FGLJ0158.6+8558	J015248.80+855703.6	NVSSJ015248+855706	1.07(0.05)	3.05(0.07)	65.6	N,M	?	1,2
2FGLJ0227.7+2249	J022744.35+224834.3	NVSSJ022744+224834	0.95(0.03)	2.60(0.03)	53.1	N,v	?	1!,3!
2FGLJ0312.8+2013	J031240.54+201142.8	NVSSJ031240+201141	0.79(0.06)	2.35(0.19)	36.4	N	?	-
2FGLJ0332.1+6309	J033153.90+630814.1	NVSSJ033153+630814	0.96(0.03)	2.60(0.04)	54.5	N,M	?	1!,2!
2FGLJ0353.2+5653	J035309.54+565430.8	NVSSJ035309+565431	0.78(0.04)	1.89(0.19)	10.9	N,M,rv	?	2!,3!
2FGLJ0409.8-0357	J040946.57-040003.4	NVSSJ040946-040003	0.89(0.03)	2.38(0.04)	46.4	N,M	?	1!,3!
2FGLJ0420.9-3743	J042025.09-374445.0	NVSSJ042025-374443	0.78(0.04)	2.44(0.10)	20.2	N,S	?	3!
2FGLJ0600.9+3839	J060102.86+383829.2	NVSSJ060102+383828	0.97(0.04)	2.47(0.08)	38.3	N	?	2!,3!
2FGLJ0644.6+6034	J064435.72+603851.2	NVSSJ064435+603849	0.64(0.05)	1.97(0.18)	24.6	N	?	1,2!,3
2FGLJ0658.4+0633	J065845.02+063711.5	NVSSJ065844+063711	0.68(0.04)	1.98(0.15)	27.4	N	?	3
2FGLJ0723.9+2901	J072354.83+285929.9	NVSSJ072354+285930	1.15(0.05)	2.90(0.05)	81.0	N,F	?	1!,2!,3!
2FGLJ0746.0-0222	J074627.03-022549.3	NVSSJ074627-022549	0.68(0.04)	2.11(0.07)	31.3	N,M	?	1!,3!
2FGLJ0928.8-3530	J092849.83-352948.9	NVSSJ092849-352947	0.97(0.04)	2.63(0.05)	57.8	N,S,M	?	-
2FGLJ1016.1+5600	J101544.44+555100.7	NVSSJ101544+555100	1.05(0.06)	3.08(0.09)	48.0	N,F,s	?	1!,2!
2FGLJ1115.0-0701	J111511.74-070239.9	NVSSJ111511-070238	0.86(0.06)	2.65(0.15)	17.2	N	?	3
2FGLJ1123.3-2527	J112325.38-252857.0	NVSSJ112325-252858	0.84(0.03)	2.49(0.03)	30.0	N,M,6,QSR	0.146	-
2FGLJ1129.5+3758	J112903.25+375657.4	NVSSJ112903+375655	0.92(0.07)	2.41(0.14)	42.3	N,F,M,s,BL?	?	3
2FGLJ1223.3+7954	J122358.17+795327.8	NVSSJ122358+795329	0.48(0.04)	1.92(0.11)	9.6	N,M	?	2!,3
2FGLJ1254.2-2203	J125422.47-220413.6	NVSSJ125422-220413	0.67(0.04)	2.33(0.08)	11.4	N,M,v	?	1!,3!
2FGLJ1259.8-3749	J125949.80-374858.1	NVSSJ125949-374856	0.71(0.04)	2.11(0.08)	36.8	N,S,M,v	?	1!,3!
2FGLJ1340.5-0412	J134042.02-041006.8	NVSSJ134042-041006	0.71(0.04)	2.12(0.08)	36.6	N,M,v	?	1!
2FGLJ1347.0-2956	J134706.89-295842.3	NVSSJ134706-295840	0.79(0.03)	2.11(0.06)	39.8	N,S,M,v	?	1!,3!
2FGLJ1513.5-2546	J151303.66-253925.9	NVSSJ151303-253924	1.01(0.15)	2.65(0.46)	65.9	N	?	3
2FGLJ1517.2+3645	J151649.26+365022.9	NVSSJ151649+365023	0.95(0.03)	2.63(0.04)	54.5	N,F,s,v	?	1!,2,3
2FGLJ1548.3+1453	J154824.39+145702.8	NVSSJ154824+145702	0.74(0.05)	2.11(0.19)	39.6	N,F,M,s	?	-
2FGLJ1647.0+4351	J164619.95+435631.0	NVSSJ164619+435631	0.77(0.04)	2.09(0.09)	38.1	N,F,s,X	?	1!
2FGLJ1704.3+1235	J170409.59+123421.7	NVSSJ170409+123421	0.74(0.04)	2.05(0.07)	35.4	N,M	?	3
2FGLJ1704.6-0529	J170433.84-052840.6	NVSSJ170433-052839	0.78(0.05)	2.14(0.16)	43.0	N,M,v	?	3
2FGLJ2004.6+7004	J200506.02+700439.3	NVSSJ200506+700440	0.77(0.03)	2.20(0.05)	45.7	N,v	?	1!,3
2FGLJ2021.5+0632	J202155.45+062913.7	NVSSJ202155+062914	0.82(0.03)	2.12(0.05)	35.3	N,M	?	1!,3!
2FGLJ2115.4+1213	J211522.00+121802.8	NVSSJ211522+121802	0.78(0.05)	2.23(0.18)	46.2	N,M	?	3!
2FGLJ2132.5+2605	J213253.05+261143.8	NVSSJ213252+261143	1.20(0.05)	2.78(0.09)	25.9	N	?	3
2FGLJ2133.9+6645	J213349.21+664704.3	NVSSJ213349+664706	0.80(0.04)	2.28(0.06)	49.0	N,v	?	1!,2,3
2FGLJ2134.6-2130	J213430.18-213032.6	NVSSJ213430-213032	0.78(0.04)	2.27(0.08)	44.3	N,M	?	1!,3
2FGLJ2228.6-1633	J222830.19-163642.8	NVSSJ222830-163643	0.74(0.04)	2.23(0.12)	37.9	N,M	?	3!
2FGLJ2246.3+1549	J224604.98+154435.3	NVSSJ224604+154437	0.61(0.05)	2.17(0.14)	16.0	N,M	?	3!
2FGLJ2358.4-1811	J235836.83-180717.3	NVSSJ235836-180718	0.86(0.04)	2.21(0.10)	43.2	N,M,6,X,BL	0.058?	1
SOUTHERN UGS SAMPLE								
2FGLJ0116.6-6153	J011619.59-615343.5	SUMSSJ011619-615343	0.85(0.04)	2.34(0.06)	49.9	S,M	?	1!,3!
2FGLJ0133.4-4408	J013306.35-441421.3	SUMSSJ013306-441422	0.83(0.03)	2.25(0.05)	51.0	S,M	?	1!,3!
2FGLJ0143.6-5844	J014347.39-584551.3	SUMSSJ014347-584550	0.69(0.03)	1.93(0.06)	23.0	S,M	?	1!,3
2FGLJ0316.1-6434	J031614.31-643731.4	SUMSSJ031614-643732	0.74(0.03)	2.10(0.06)	38.9	S,M	?	1!,3
2FGLJ0416.0-4355	J041605.81-435514.6	SUMSSJ041605-435516	1.11(0.03)	2.90(0.04)	97.2	S,M	?	1!
2FGLJ0420.9-3743	J042025.09-374445.0	MRSS303-096250	0.78(0.04)	2.44(0.10)	20.2	N,S	?	3!
2FGLJ0555.9-4348	J055618.74-435146.1	SUMSSJ055618-435146	0.91(0.03)	2.50(0.04)	43.9	S,M	?	1!
2FGLJ0928.8-3530	J092849.83-352948.9	SUMSSJ092849-352947	0.97(0.04)	2.63(0.05)	57.8	N,S,M	?	-
2FGLJ1032.9-8401	J103015.35-840308.7	SUMSSJ103014-840307	0.99(0.04)	2.63(0.05)	62.1	S,v	?	1!
2FGLJ1259.8-3749	J125949.80-374858.1	SUMSSJ125949-374856	0.71(0.04)	2.11(0.08)	36.8	N,S,M,v	?	1!,3!
2FGLJ1328.5-4728	J132840.61-472749.2	SUMSSJ132840-472748	0.63(0.04)	2.08(0.08)	24.4	S,M,v	?	3!
2FGLJ2042.8-7317	J204201.92-731913.5	SUMSSJ204201-731911	0.65(0.05)	1.81(0.16)	12.1	S,M	?	-
2FGLJ2131.0-5417	J213208.28-542036.4	SUMSSJ213208-542037	1.25(0.09)	2.92(0.19)	29.0	S	?	-
2FGLJ2213.7-4754	J221330.33-475425.0	SUMSSJ221330-475426	0.90(0.04)	2.23(0.10)	33.4	S,M	?	-

Col. (1) 2FGL name.
Col. (2) WISE name.
Col. (3) Radio name.
Cols. (4,5) IR colors from *WISE*. Values in parentheses are 1σ uncertainties.
Col. (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); rv = variable in the radio bands at 1.4 GHz.
Col. (7) Estimate level of confidence derived from the KDE analysis.
Col. (8) Redshift: ? = unknown.
Col. (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.

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) 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 only exception of NVSSJ154824+145702 all of them have the same optical properties of the BZB population.

Within the whole sample of UGSs analyzed, there are 25 sources that were also unidentified in the 1FGL (**?**) 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

TABLE 3
UNIDENTIFIED GAMMA-RAY SOURCES IN THE SDA SAMPLE.

2FGL name	WISE name	IAU name	[3.4]-[4.6] mag	[4.6]-[12] mag	π_{kde}	notes	z	compare
2FGLJ0200.4-4105	J020020.94-410935.6	J0200-4109	0.63(0.06)	1.90(0.32)	19.3	6,X	?	
2FGLJ0340.7-2421	J034022.89-242407.2	J0340-2424	0.73(0.06)	2.45(0.20)	10.0	N	?	
2FGLJ0523.3-2530	J052313.07-253154.4	J0523-2531	1.33(0.06)	2.90(0.09)	9.5	-	?	
2FGLJ0547.5-0141c	J054720.85-013329.9	J0547-0133	0.81(0.07)	2.11(0.27)	36.6	N	?	1
2FGLJ0937.9-1434	J093754.72-143350.3	J0937-1433	0.71(0.04)	2.15(0.08)	35.1	N	?	
2FGLJ1315.6-0730	J131552.98-073301.9	J1315-0733	0.87(0.03)	2.27(0.04)	47.2	N,F,M,v,BL?	?	1!
2FGLJ1339.2-2348	J133916.44-234829.4	J1339-2348	0.75(0.05)	2.06(0.19)	35.0	N	?	
2FGLJ1345.8-3356	J134543.05-335643.3	J1345-3356	0.82(0.04)	2.31(0.06)	49.8	N,S,M	?	1!
2FGLJ2034.7-4201	J203451.08-420038.2	J2034-4200	0.61(0.05)	2.04(0.17)	22.3	-	?	
2FGLJ2251.1-4927	J225128.69-492910.6	J2251-4929	0.76(0.04)	2.47(0.10)	12.1	S	?	
2FGLJ2343.3-4752	J234302.29-475749.9	J2343-4757	0.71(0.07)	2.06(0.31)	35.4	S	?	

Col. (1) 2FGL name.
Col. (2) WISE name.
Col. (3) Radio name.
Cols. (4,5) IR colors from *WISE*. Values in parentheses are 1σ uncertainties.
Col. (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); rv = variable in the radio bands at 1.4 GHz.
Col. (7) Estimate level of confidence derived from the KDE analysis.
Col. (8) Redshift: ? = unknown.
Col. (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.

candidate recognized according to our method are also classified as AGNs. All of them with 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. $\leq$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.

Finally, 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 associable to them. Thus, in agreement with our expectations, all 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 an non-parametric method to search for γ-ray blazar candiates within two samples of UGSs. First we identify all the radio 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 22μm is not required. A small fraction ($\sim$8%) of the *Fermi* blazar are in fact not detected at 22μm. 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 to search for faint γ-ray blazar candidates that were not previously selected because too faint at 22μm. By relaxing the requirement on the detection at 22μm and thus on the [12]-[22] color, this method would select candidate blazars at the cost of a larger contamination, mitigated by the requirement on the presence of a radio counterpart.

We found 41 and 14 radio sources with IR similar to those of the *Fermi* blazars within the NU and the SU samples, respectively. In addition, we investigated the sample of radio sources discovered with recent deep ATCA observations performed to search for radio counterparts of the UGS in the southern hemisphere. Among 416 radio objects listed in Petrov et al. (2013) only 11 sources have an IR counterpart consistent with the γ-ray blazars. The total number of γ-ray blazar candidates is 66 all listed in Table 2 and Table 3. without no multiple candidates within the positional uncertainty regions of the UGSs analyzed. **We estimate a probability of spurious association for the γ-ray blazar candidates selected according to our method of the order of 4% and 3% for the NU and SU samples, respectively.**

It is worth noting that the large majority of our candidates show IR colors more consistent with the region occupied by the BZBs in the [3.4]-[4.6]-[12] μm color-color diagram rather than that of BZQs. Thus they could be potential faint and so distant BZBs that were not previously selected with different methods because lacking of the IR flux at 22μm. More detailed investigations based on ground-based, optical and near IR, spectroscopic follow up observations will be planned for the selected γ-ray blazar candidates to confirm their nature and to obtain their redshifts.

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[9] https://confluence.slac.stanford.edu/display/GLAMCOG/Public+List+of+LAT-Detected+Gamma-Ray+Pulsars
[10] http://www.star.bris.ac.uk/~mbt/topcat/

TABLE 4
Optical magnitudes for the *WISE* counterparts.

WISE name	B1 mag	R1 mag	B2 mag	R2 mag	I mag	θ arcsec
J003119.70+072453.6	19.03	18.17	19.84	18.63	18.67	0.14
J003908.14+433014.6	19.9	19.61	21.42	20.77		0.14
J010345.73+132345.4	17.98	17.73	18.69	17.38	17.24	0.07
J011619.59-615343.5		17.72	18.22	17.78	17.91	0.27
J013306.35-441421.3		18.38	19.7	18.12	18.76	0.26
J014347.39-584551.3		16.7	18.48	16.64	17.04	0.04
J015248.80+855703.6	20.57	18.84	19.63	18.71	17.82	0.38
J020020.94-410935.6		19.84	21.1	18.79	18.75	0.6
J022744.35+224834.3			20.82	20.22	19.28	0.35
J031240.54+201142.8		19.34	21.22	19.42	19.07	2.63
J031614.31-643731.4		16.59	18.19	16.57	16.82	0.22
J033153.90+630814.1			20.66	19.92	18.35	0.35
J034022.89-242407.2		19.56	20.07			0.21
J035309.54+565430.8	20.09	19.24	20.43	18.76	18.53	0.55
J040946.57-040003.4	19.45	19.18	17.53	16.98	16.86	0.07
J041605.81-435514.6		18.49	18.7	18.17	18.0	0.18
J042025.09-374445.0		20.44	20.73	19.71	18.17	0.38
J052313.07-253154.4		19.2	20.83	20.07	18.95	0.17
J055618.74-435146.1		19.23	18.88	19.08	18.08	0.31
J060102.86+383829.2		19.11		19.84	18.48	0.04
J064435.72+603851.2	20.01	19.58	20.7	18.75	18.37	0.3
J065845.02+063711.5	20.25			19.12	18.3	0.39
J072354.83+285929.9	19.78	19.05	19.97	18.72		0.19
J074627.03-022549.3	19.03		18.59	18.43	16.53	0.31
J092849.83-352948.9		18.56	19.64	18.07	18.23	0.23
J093754.72-143350.3	18.82	17.92	18.64	17.73	17.56	0.1
J101544.44+555100.7	19.69	19.42	20.61	19.35		0.37
J103015.35-840308.7		19.36	19.26	18.84	18.03	0.15
J111511.74-070239.9		19.86	20.68	19.05	18.66	0.14
J112325.38-252857.0	16.9	15.76	15.87	15.56	15.51	0.19
J112903.25+375657.4	19.9	19.23	19.35	19.48	18.58	0.65
J122358.17+795327.8		17.6	20.18	18.46	17.63	1.04
J125422.47-220413.6		19.88	18.67	19.11	18.22	0.41
J125949.80-374858.1		17.44	18.07	16.78	17.35	0.17
J131552.98-073301.9	19.78	18.68	18.75	17.75	17.56	0.16
J132840.61-472749.2		17.75	18.23	16.8		0.98
J133916.44-234829.4	20.3	19.3	20.43	19.79	18.5	0.31
J134042.02-041006.8	18.21	17.21	17.59	16.46	17.08	0.19
J134543.05-335643.3		17.98	19.58	18.65	18.12	0.38
J134706.89-295842.3	17.85	17.09	18.8	17.14	17.09	0.41
J151303.66-253925.9	19.92	18.96	19.77	20.35		0.5
J151649.26+365022.9	20.9		21.49	20.07	19.16	1.58
J154824.39+145702.8	20.51	18.29	19.86	17.74	17.45	0.41
J164619.95+435631.0	20.43	19.73	20.42	19.67		0.34
J170409.59+123421.7	19.86	18.04	18.62	17.63	17.46	0.47
J170433.84-052840.6	19.62	18.97	18.42	17.28	17.98	0.45
J200506.02+700439.3	20.73	19.25	19.24	18.65		0.45
J202155.45+062913.7	17.27	16.13	17.01	16.67	16.03	0.43
J203451.08-420038.2		18.97	19.34	18.87	18.27	0.44
J204201.92-731913.5		17.46	17.9	18.36	18.04	0.29
J211522.00+121802.8	18.15	18.15	17.68	17.31	17.58	0.16
J213253.05+261143.8	20.04	19.29	19.14	19.62	18.44	0.07
J213430.18-213032.6	19.77	18.65	18.96	16.8	17.7	0.09
J213349.21+664704.3				19.37	18.8	0.45
J221330.33-475425.0		18.12	18.6	18.34	18.33	0.05
J222830.19-163642.8	18.57	19.34	19.95	19.04	17.91	0.29
J224604.98+154435.3	19.14	18.27	19.57	18.53	17.65	0.13
J225128.69-492910.6		18.8	19.21	18.45	18.03	0.42
J234302.29-475749.9		19.84	18.92	21.3	18.32	0.29
J235836.83-180717.3	19.14	18.45	18.28	17.22	17.53	0.3

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