ABSTRACT

We searched for γ-ray blazar candidates among the 382 unidentified hard X-ray sources of the third Palermo BAT Catalog (3PBC) obtained from the analysis of 66 months of Swift Burst Alert Telescope (BAT) survey data and listing 1586 sources. We adopted a recently developed association method based on the peculiar infrared colors that characterize the γ-ray blazars included in the second catalog of active galactic nuclei detected by the Fermi Large Area Telescope. We used this method exploiting the data of the all-sky survey performed by the Wide-field Infrared Survey Explorer (WISE) to establish correspondences between unidentified 3PBC sources and WISE γ-ray blazar candidates located within the BAT positional uncertainty region at a 99% confidence level. We obtained a preliminary list of candidates for which we analyzed all the available data in the Swift archive to complement the information in the literature and in the radio, infrared, and optical catalogs with the information on their optical–UV and soft X-ray emission. Requiring the presence of radio and soft X-ray counterparts consistent with the infrared positions of the selected WISE sources, as well as a blazar-like radio morphology, we finally obtained a list of 24 γ-ray blazar candidates.

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

Online-only material: color figures

1. INTRODUCTION

One of the biggest challenges of X-ray astronomy is understanding the origin of the cosmic X-ray background (Giacconi et al. 1962; Mushotzky et al. 2000). A key issue in addressing this open question is the association of unidentified X-ray sources with their low- or high-energy counterparts, which is a crucial step toward their identification and classification. The Burst Alert Telescope (BAT; Barthelmy et al. 2005) on board the Swift observatory (Gehrels et al. 2004), thanks to its wide field of view (∼1.4 sr) coupled with a large collecting area (∼5200 cm²), has performed an all-sky survey in the 15–150 keV energy range since its launch. This survey provides an unprecedented view of hard X-ray-detected active galactic nuclei (AGNs; e.g., Burlon et al. 2011), corresponding to a significant fraction (i.e., ∼60%; Ajello et al. 2012) of the BAT-detected sources, so increasing our knowledge on their contribution to the cosmic X-ray background (e.g., Gilli et al. 2007; Ajello et al. 2009).

The third Palermo BAT Hard X-ray Catalog6, obtained from the analysis of 66 months of BAT all-sky data with the BATIMAGER software (Segreto et al. 2010) and covering 50% of the sky down to a 15–150 keV flux limit of $7.4 \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$, lists 1586 sources. In past years, thanks to follow-up observations performed by the Swift mission itself, the fourth INTEGRAL catalog7 (Bird et al. 2010) of the all-sky survey performed with the IBIS/ISGRI (Ubertini et al. 2003; Lebrun et al. 2003) instrument lists 723 sources detected in the 17–100 keV energy range, ∼30% of which are unidentified. The largest fraction of the associated INTEGRAL sources (i.e., ∼35%) are AGNs, with respect to ∼31% of identified Galactic sources. The fraction of unidentified sources is probably larger in INTEGRAL IBIS/ISGRI compared to Swift-BAT because the former spends more time on the Galactic plane, where source identification is naturally more challenging. A limited fraction (∼15%) of the AGNs detected by BAT and included in the 3PBC is constituted by blazars which represent, in turn, the largest known population of γ-ray sources detected by the Fermi Large Area Telescope (LAT; Atwood et al. 2009). Blazars are peculiar AGNs whose emission is dominated by non-thermal radiation over the entire electromagnetic spectrum. They belong to the radio-loud class of AGNs and are characterized by flat radio spectra, peculiar infrared (IR) colors (Massaro et al. 2011b), apparent superluminal motion, and a typical double-humped spectral energy distribution (SED; e.g., Urry & Padovani 1995). Blandford & Rees (1977) proposed interpreting the blazar emission as arising from particles accelerated in relativistic jets observed at a small angle with respect to the line of sight. Thus, their SED has been described in terms of synchrotron radiation from radio through the soft X-rays, and of inverse Compton scattering of low-energy photons from the hard X-rays to the γ-ray band (Marscher & Gear 1985);

6 http://bat.ifa.inaf.it
7 http://irfu.cea.fr/Sap/IGR-Sources/
Blazars are divided into two sub-classes: the BL Lac objects (BL Lacs) characterized by weak or absent optical emission lines, and the flat spectrum radio quasars (FSRQs) showing broad emission lines in their optical spectrum (e.g., Stickel et al. 1991; Stocke et al. 1991). The \textit{Roma-BZCAT Multi-Frequency Catalog of Blazars} (Massaro et al. 2009, 2011a) is, at present, the most complete list of blazars including certified BL Lacs and FSRQs as well as blazars with uncertain classification.

Using the recent all-sky survey performed by the \textit{Wide-field Infrared Survey Explorer} (WISE; Wright et al. 2010), D’Abrusco et al. (2012) showed that $\gamma$-ray-emitting blazars detected by Fermi-LAT and included in the second LAT AGN Catalog (2LAC; Ackermann et al. 2011) can be well separated from other Galactic and extragalactic sources on the basis of their IR properties. This analysis confirmed and strengthened the results obtained previously by Massaro et al. (2011b) on the basis of the \textit{WISE} preliminary data release (Cutri et al. 2011) and constituted the first step to developing a new association procedure for the unidentified $\gamma$-ray sources (Massaro et al. 2012c). Applying this association method, which is able to recognize if there is a $\gamma$-ray blazar candidate within their Fermi location uncertainty, Massaro et al. (2012d) assigned a $\gamma$-ray blazar candidate counterpart to 156 out of 313 unidentified $\gamma$-ray sources analyzed, having the same IR properties of the $\gamma$-ray emitting blazars. Several methods have been used in the past to identify blazars in radio and X-ray surveys such as, for example, those proposed by Perlman et al. (1998) for the Deep X-Ray Radio Blazar Survey (DXRBS) or by Laurent-Muehleisen et al. (1999) in the case of the RASS/Green Bank sample as well as the more recent case of Beckmann et al. (2003) for the HRX-BL Lac sample. In these cases, the combination of the radio-to-optical and/or the optical-to-X-ray spectral indices was a good indicator of blazar-like sources (see also Giommi et al. 1999; Turriziani et al. 2007). However, the new approach based on the IR peculiar colors of blazars (Massaro et al. 2012c) can be applied to the whole sky when the lack of multifrequency information, mostly in the radio and in the optical bands, does not allow one to adopt the above criteria.

The main scientific objective of this paper is the search for \textit{WISE} $\gamma$-ray blazar candidates that could be possible counterparts of unidentified BAT objects listed in the third Palermo BAT Catalog (3PBC). For this purpose we applied the association method developed by Massaro et al. (2012c); then, for the established 3PBC–\textit{WISE} correspondences we searched for \textit{Swift} pointed observations to reveal the presence of an optical–UV and/or soft X-ray counterpart to each \textit{WISE} $\gamma$-ray blazar candidate that are crucial to addressing a correct classification. A similar investigation has been carried out (Massaro et al. 2012c) searching among the unidentified sources of the fourth \textit{INTEGRAL} catalog, leading to the definition of 18 $\gamma$-ray blazar candidates.

This paper is organized as follows: the application of the \textit{WISE} association method to blazars detected by both \textit{Swift}-BAT and Fermi-LAT, as well as to the unidentified 3PBC objects, is illustrated in Section 2; the multifrequency properties of the obtained \textit{WISE} candidates, including details about the \textit{Swift} data reduction for both the UVOT and XRT telescopes, are described in Section 3. The final list of the 3PBC–\textit{WISE} correspondences, obtained after establishing more restrictive selection criteria based on the peculiar emission of blazars, is presented in Section 4 together with additional comments and details on some selected candidates. Finally, Section 5 is devoted to our summary and conclusions.

The nominal \textit{WISE} bands are [3.4], [4.6], [12], and [22] $\mu$m; \textit{WISE} colors are [3.4]–[4.6] mag, [4.6]–[12] mag, and [12]–[22] mag. Unless stated otherwise, we use cgs units throughout.

2. THE \textit{WISE GAMMA-RAY STRIP ASSOCIATION PROCEDURE AND THE 3PBC SOURCES

In this section we describe the application of the \textit{WISE} association procedure to some opportually selected samples of BAT sources included in the 3PBC. Some basic details of this procedure can be found in the Appendix; a complete description is given in Massaro et al. (2012c, 2012d) and additional details are also illustrated in D’Abrusco et al. (2013).

The method is based on the parameterization of the Gamma-ray Strip, the very narrow region of the IR color–color space in which the \textit{WISE} counterparts, detected in all of the four \textit{WISE} bands, of the $\gamma$-ray blazars included in the 2LAC (Ackermann et al. 2011) are located. The position of a generic \textit{WISE} source in the IR color–color space with respect to the strip is represented by a parameter $s$, normalized to vary in the range between 0 (\textit{WISE} source definitely outside the strip) and 1. Three classes (A, B, and C) have been opportune defined on the basis of the values of the $s$ parameter: high values are typical of class A, while low values correspond to class C. For each \textit{WISE} source a circular searching region centered at its position as provided in the 3PBC and with a radius equal to the positional uncertainty at a 99% confidence level is defined. This uncertainty varies in the range 0.8–8.4 according to the signal-to-noise ratio of the source, with a mean value of 5.2 $\pm$ 1.4. Then, all the \textit{WISE} sources within this searching region are ranked according to their $s$ parameter: of the obtained list of candidates we indicate, as a rule, our best choice as the \textit{WISE} source of higher class with the smallest angular separation from the BAT position.

First, we report the results of the application of the above-described procedure to the \textit{Roma-BZCAT} certified blazars detected by both \textit{Swift}-BAT and Fermi-LAT. We computed how many of these blazars are found within the boundaries of the Gamma-ray Strip, as expected; in this way, we could evaluate the reliability of the association method. The number of \textit{Roma-BZCAT} certified blazars that are present in the 3PBC is 125, which corresponds to a modest fraction ($\sim$10%) of the 1204 identified 3PBC objects. According to the 2LAC (Ackermann et al. 2011), 67 out of these 125 are associated with a Fermi-LAT source. We treated these 67 BAT–LAT blazars as if they were unidentified and applied our procedure; in particular, we verified that the positionally closest source belonging to the highest class was the same associated with the 3PBC. Their location with respect to the \textit{WISE} Gamma-ray Strip is shown in Figure 1; for this particular two-dimensional (2D) projection of the \textit{WISE} color–color space, only two sources are completely outside the \textit{WISE} Gamma-ray Strip ($s_{12} = 0$). Considering also the remaining two 2D projections, the method was able to confirm 62 out of 67 BAT–LAT blazars; this implies a high capability ($\sim$93%) of validating $\gamma$-ray blazars through our association procedure. These 62 blazars are divided into 17 sources of class A ($\geq$28%), 20 of class B ($\geq$32%), and 25 of class C ($\geq$40%).

Then, we applied our association procedure to the unidentified sources included in the 3PBC. From a general point of view, hard X-ray sources like those constituting the 3PBC can be considered identified when a counterpart at some other energy...
band (radio, IR, soft X-rays), whose coordinates are provided with arcsecond precision, has been associated with them and when this counterpart has been opportunely classified so that the nature of these sources is well established. Therefore, the 382 3PBC unidentified objects can be further divided into two groups: 222 unassociated sources, for which a counterpart has not been found, and 160 unclassified objects that are generic radio, soft X-ray, and γ-ray sources for which a lower energy counterpart has been assigned in the 3PBC but no classification has been yet provided. Applying our association procedure to all the 382 unidentified objects, we obtained a WISE γ-ray blazar candidate for 22 unassociated and 39 unclassified 3PBC sources.

3. MULTIFREQUENCY PROPERTIES OF THE WISE γ-RAY BLAZAR CANDIDATES

Once a WISE γ-ray blazar candidate was found for a 3PBC source by the application of our method, we investigated its possible emission in energy ranges other than the IR and the hard X-rays by searching for the available information in the literature and for observations in the Swift database to cover the optical–UV as well as the soft X-ray bands.

The values of the radio flux density $F_r$ were extracted from the main radio surveys such as FIRST (White et al. 1997), NVSS (Condon et al. 1998), PMN (Wright et al. 1994), and SUMSS (Mauch et al. 2003). We searched for radio sources included in a circle centered at the position of the WISE candidate and with a conservative radius of 30″ to take into account the possibly low sensitivity of some surveys as well as the intrinsic weakness of some radio sources. When available, we also checked the radio morphology of the source to discard radio galaxies with an evident FR I/FR II morphology (Fanaroff & Riley 1974) and focus on sources with a compact core or with a core/single-sided jet structure characteristic of blazars.

Moreover, we searched for candidates in the field of the Sloan Digital Sky Survey Data Release 9 (SDSS-DR9; Páris et al. 2012) to obtain the values of the photometry in the $u$, $g$, $r$, $i$, and $z$ filters. As recently shown by Massaro et al. (2012a), the $u$–$r$ color index is a simple and well-suited parameter to measure the AGN contribution to the source emission with respect to the host galaxy. Therefore, it can be used to introduce a new classification scheme for blazars distinguishing between galaxy-dominated blazars ($u < r < 1.4$ mag) and nuclear-dominated blazars ($u > r > 1.4$ mag). We calculated the intrinsic $u$–$r$ values adopting their formula

$$ (u - r) = (u - r)_{\text{obs}} - 0.81A_r, $$

where $A_r$ is the extinction in the $r$ band provided in the SDSS database.

3.1. Swift UVOT and XRT Observations

We searched in the Swift archive at the position of each WISE γ-ray blazar candidate within a circular region with a radius of 15″, wide enough to take into account the eventuality that the source of interest is not necessarily close to the center of the field of the Swift observation.

We carried out the photometry of UVOT data adopting the following procedure: we summed the available frames with the uvotimsum task and obtained a single image in FITS format in the corresponding filter. We defined for each source a circular region with the recommended radius of 5″ adopted for the calibration of counts to magnitudes (Poole et al. 2008). For the background region a much larger value of the radius, typically 20″, was considered. Then, we used the task uvotsource adopting a 3σ level of significance to compute the background limit, and obtained the values of the photometry in the Vega System; we took into account both statistic and systematic errors.

We analyzed X-ray data with the aim of determining with the best possible accuracy the position of the X-ray source. In the case of several observations for the same source, we downloaded the data corresponding to the longer XRT exposure time. However, when a longer exposure time was needed to establish the position of the X-ray source with sufficient accuracy due to a modest count rate, we downloaded all the available observations and summed the corresponding event files to obtain a single frame. We reduced XRT data with the XRT Data Analysis Software (XRTDAS v2.8.0) included and distributed within the HEASoft v6.12 package. Cleaned event files, as well as the other analysis products, were obtained with the xrtpipeline task. Multiple event files from different observations were summed with the xselect task. Then, the event files were examined with ximage and a preliminary source detection was carried out with a sliding-cell method to reveal significant X-ray sources in the field. The coordinates of the eventual X-ray source closest to the WISE source were instead determined using the xrtcentroid task, providing in this way an error radius to the X-ray position. We found that the position of XRT sources is known with a precision of a few arcseconds, ranging from 3.5″ up to 8″, depending on the count rate of the source and on the exposure time of the observation.

We used the images acquired in the UVOT filters to verify the consistency of the WISE and the XRT source with each other and with the optical–UV counterpart, when detected. We examined the images with DS9 and defined the region files to locate the position, with their errors, of both WISE sources and relevant, previously detected, XRT sources in the field. For the position of the WISE sources we adopted, for the sake of simplicity, a conservative error radius of 2″ (see Cutri et al. 2012 for further details).
4. RESULTS AND SOURCE DETAILS

4.1. More Stringent Criteria on the Selection of Blazar Candidates

Due to the presence of multifrequency observations for several unidentified BAT sources, we established more restrictive criteria with respect to those adopted for the Fermi unidentified $\gamma$-ray sources (Massaro et al. 2012d) to select our list of $\gamma$-ray blazar candidates.

First, we required that the positions of the WISE $\gamma$-ray blazar candidates were included in the uncertainty region corresponding to the soft X-ray emission by Swift-XRT or by other X-ray telescopes. Second, in addition to peculiar IR colors like those of the $\gamma$-ray blazars, we required the $\gamma$-ray blazar candidates to have a radio counterpart. Moreover, we checked the radio morphology of the source in the NVSS map, when available, and confirmed candidates with a compact core or with a core/single-sided jet structure as shown in Figure 2. In the case of WISE J010930.21+085748.1, we found a multicomponent structure compatible with the signature of the jet on a kiloparsec scale; such occurrence has been already evidenced for other well-studied sources like 3C 273 or 3C 454.3, where the jet has also been imaged in the X-rays (Massaro et al. 2011c) with the Chandra X-ray satellite.

The adoption of these criteria severely reduced the number of candidates with respect to our preliminary list, particularly among those provided for unassociated 3PBC sources. In fact, the largest part of candidates that fulfilled the criteria corresponds to unclassified objects, with only a single candidate given for an unassociated 3PBC source. This is mainly due to the large difference between unassociated and unclassified objects in the relative fraction of objects for which at least a Swift observation is available. This gap is, in turn, the natural consequence of the fact that a large fraction of the counterparts to the hard X-ray sources in the 3PBC has been found thanks to dedicated Swift observational campaigns.

We report in Table 1 three candidates included in our preliminary list with a core-dominated radio counterpart in the NVSS but, unfortunately, no available detection in the soft X-ray band, either by Swift or by other X-ray satellites. The observation of this small number of objects by Swift or by other soft X-ray telescopes would be a very simple and helpful step for addressing their correct classification.

### 4.2. The List of $\gamma$-Ray Blazar Candidates

From the application of our association procedure and the further adoption of our selection criteria, we obtained 24 $\gamma$-ray blazar candidates. The list of 3PBC–WISE correspondences, sorted following the right ascension of the 3PBC sources, is presented in Table 2. For each correspondence, we report (1) the name of the 3PBC source and (2) one of the names with which the 3PBC counterpart is addressed in the main astronomical databases (NED, SIMBAD), (3) the name of the WISE $\gamma$-ray blazar candidate, (4) the class designated by our association procedure, and (5) its angular separation $d$ from the 3PBC counterpart. The redshift of the WISE source as found in the literature with the corresponding reference is reported in Column 6; the origin of the redshift is spectroscopic in all the cases with the exception of WISE J174201.50–605512.1 (Burgess & Hunstead 2006) for which it is photometric. The values of the radio flux density $F_r$ from the main radio surveys are reported in Column 7. The distance between the coordinates of the WISE candidate and the radio source is typically lower than 3$''$; for three WISE candidates (J044047.72+273947.1, J192630.21+413305.0, and J221409.17–255749.1) we found a higher value, in any case lower than 15$''$, but we considered the possibility that this discrepancy is due to the low flux of the radio source, of the order of a few mJy. The intrinsic $u$–$r$ color index, calculated adopting Equation (1), is available for eight of these candidates and is reported in Column 8. Six of these values are lower than 0.9 mag, configuring the sources as nuclear-dominated blazar candidates (see Section 3). In Column 9 the comparison between the position of the WISE source, represented by a small inner circle, and the position of the closest X-ray source in the field of the available XRT observations, represented by a circle with a larger radius, is summarized. Two concentric circles indicate that the position of the WISE source with its error is completely included in the uncertainty region of the XRT source. This agreement occurs for all the selected candidates, including the three sources with no Swift observation but included in the ROSAT All-Sky Survey Bright Source Catalog (1RXS; Voges et al. 1999). In these cases, the larger circle has been replaced by a square in the symbols adopted in Column 9.

#### Table 1

| 3PBC Name | WISE Name | Class | $d''$ | $F_r$ (mJy) |
|-----------|-----------|-------|-------|-------------|
| J0744.7–2348 | J074450.96–235014.8 | C | 110.6 | 3.0 |
| J1922.9+2648 | J192300.98+265504.8 | C | 148.5 | 45.5 |
| J2131.3+6100 | J213130.14+605752.2 | A | 202.9 | 11.7 |

Note. Columns: (1) the 3PBC name, (2) the WISE name, (3) the class of the candidate, (4) its distance $d''$ from the 3PBC source, and (5) its radio flux density $F_r$. |
Table 2: List of Correspondences between Unidentified 3PBC Hard X-Ray Sources and WISE γ-Ray Blazar Candidates

| 3PBC Name | 3PBC Counterpart | WISE Name | Class | $d$ (arcmin) | $z$ | $F_{\gamma}$ (mJy) | $u-r$ color (mag) | IR/X |
|-----------|-----------------|-----------|-------|-------------|-----|-----------------|-----------------|------|
| J0056.9+6401 | NVSS J005712+635942 | J005712.84+635942.8 | B | 0.2 | - | - | 16.3 n | ⊙ |
| J0109.3+0859 | IRXS J010929.7+08573 | J010930.21+085748.1 | A | 12.6 | - | - | 11.2 n | ⊙ |
| J0137.4+5814 | RX J0137.4+5811 | J013750.47+581411.3 | C | 0.2 | - | - | 170.7 n | ⊙ |
| J0207.9+8410 | CRATES J0207+8411 | J020713.45+841119.1 | C | 0.1 | - | - | 100.1 n | ⊙ |
| J0312.0+5059 | 4C 50.11 | J031202.97+502914.6 | A | 0.9 | - | - | 12.6 n | ⊙ |
| J0356.2−6252 | 2MASX J035619.96−625139.2 | J035619.96−625139.2 | B | 0.5 | 0.108 | - | 20.4 s | ⊙ |
| J0359.6+5059 | 4C 50.11 | J035929.74+502957.0 | B | 0.1 | 1.52 | - | 4296.6 n | 0.34 |
| J0413.2+1659 | CRATES J0413+1659 | J041322.32+165951.1 | A | 0.1 | - | - | 94.0 n | ⊙ |
| J0421.1+2602 | IRXS J042054.9+26050 | J042056.00+260450.1 | A | 19.7 | - | - | 5.4 n | 1.91 |
| J0440.8+2739 | 2MASX J04404770+2739467 | J044047.72+273947.1 | B | 0.1 | - | - | 3.1 n | ⊙ |
| J0459.9+2704 | 4C 27.14 | J045956.08+270602.1 | B | 1.1 | - | - | 927.0 n | ⊙ |
| J0612.2−4645 | IRXS J061227.3−464725 | J061226.91−464718.5 | B | 8.0 | - | - | 216.2 s | ⊙ |
| J1240.1+3501 | IRXS J124020.3+35023 | J124021.14+350259.0 | C | 3.1 | 1.199 | - | 230.8 n | 0.20 |
| J1448.7−4007 | CRATES J1448−4008 | J144850.99−400845.6 | A | 19.4 | - | - | 49.0 n | ⊙ |
| J1508.7−0952 | IRXS J150839.0−495304 | J150838.93−495302.2 | C | 2.4 | - | - | 595.0 p | ⊙ |
| J1540.1+1414 | CRATES J1540+1411 | J154007.85+141137.2 | B | 30.6 | 0.119 | - | 21.5 f | 0.35 |
| J1742.0−6053 | IRXS J174205.1−605514 | J174201.50−605512.1 | B | 1.8 | 0.41 | - | 97.7 s | ⊙ |
| J1745.6−2907 | SWIFT J1745.6−2906 | J174538.26+290822.2 | B | 0.2 | 0.111 | - | 13.3 n | ⊙ |
| J1812.3−0648 | PMN J1812−0648 | J181250.94−064825.4 | B | 1.6 | - | - | 1342.2 n | ⊙ |
| J1926.5+1432 | IRXS J192630.6+413314 | J192630.21+413305.0 | B | 10.4 | - | - | 2.8 n | ⊙ |
| J2010.3−2524 | IRXS J201020.0−252359 | J201019.76−252359.1 | C | 4.2 | - | - | 58.9 n | ⊙ |
| J2030.1+7609 | NVSS J203019.76+761139.2 | J202952.72+761139.2 | C | 159.7 | - | - | 100.0 n | 0.36 |
| J2117.5+5138 | IGR J21178+5139 | J211747.70+513856.8 | B | 4.2 | - | - | 9.1 n | ⊙ |
| J2214.0−2557 | 2MASX J22140917−2557487 | J221409.17−255749.1 | B | 0.2 | 0.052 | - | 3.4 n | ⊙ |

Notes. Columns: (1) the name of the source and (2) the counterpart provided in the 3PBC; (3) the WISE name, (4) the class of the candidate as designated by our association procedure, and (5) its distance $d$ from the 3PBC counterpart; (6) the redshift $z$; (7) the radio flux density $F_{\gamma}$; (8) the $u-r$ color index as derived from SDSS-DR9; (9) the comparison between the positions of the WISE (small inner circle) and of the soft X-ray source. Further details are given in Section 2, in Section 4.2, and in the Appendix.

Redshift. (1) 6dF; Jones et al. 2009; (2) Agudo et al. 2007; (3) SDSS-DR9, Pâris et al. 2012; (4) Burgess & Hunstead 2006; (5) Tueller et al. 2008.

Radio flux density. (f) White et al. 1997; (m) NVSS, Condon et al. 1998; (p) PMN, Wright et al. 1994; (n) SUMSS, Mauch et al. 2003.

* This value represents the distance of the WISE source from the 3PBC source.

Colors of ~600 generic IR sources detected within the positional uncertainty regions of the unidentified 3PBC sources which are not selected as γ-ray blazar candidates by our method. We note that a few sources have IR colors similar to those of γ-ray blazars but are not selected by our method as, in the other two color–color planes, they lie outside the boundaries corresponding to the projections of the WISE Gamma-ray Strip or the values of their strip parameters $s_{23}$ or $s_{34}$ are very low.

A comparison of the maps in the IR, in one of the UVOT filters, and in the soft X-ray band for one of these candidates is shown in Figure 4. For the same source we also show the SED in Figure 5; a log-parabolic model fits the radio and the IR data while the data in the optical filters, which are above the fit and are not simultaneous with the IR ones, can be explained as the signature of the intrinsic source’s variability. The X-ray data in the soft (XRT) and in the hard (BAT) bands are consistent with each other and can be interpreted as the rising branch of the inverse Compton component.

We note among these candidates the presence of two sources already included in the Fermi catalogs. WISE J013750.47+581411.3 has been detected in both the 1FGL (Abdo et al. 2010b) and the 2FGL (Nolan et al. 2012). It was already proposed, among others, by Maselli et al. (2011) as a blazar source and in particular as a high-energy synchrotron-peak (HSP; Abdo et al. 2010a) blazar after analysis of its SED.
source in the 1FGL. The analysis of the spectral index in different energy bands like the radio (Massardi et al. 2008), microwaves (Planck Collaboration 2011), and soft X-rays (Landi et al. 2012) configures this object as a low-energy synchrotron-peak (LSP; Abdo et al. 2010a) source. The fact that only two of our candidates have already been included in the Fermi catalogs is not unexpected and may be justified considering the extreme variability of blazar sources. Similar cases have already been shown by the two recently discovered γ-ray sources Fermi J1350−1140 (Torresi & D’Ammando 2011) and Fermi J1717−5156 (Schinzel & Cheung 2012), detected in a flaring state well above the flux limit of the 2FGL on the day timescale but not present in the 2FGL itself; these sources have been associated using the WISE IR colors as reported in Massaro et al. (2012b) and Paggi et al. (2012), respectively.

All the 21 candidates that have been observed by Swift, with only one exception, have been detected in at least one of the optical–UV Swift–UVOT filters; details about their photometry are given in Table 3. Several objects have been found with a very low value of Galactic latitude; for this reason, we preferred to report in Table 3 the value of the magnitude not corrected for Galactic extinction together with the corresponding $E(B − V)$

value as derived by the Infrared Science Archive11 (IRSA). The lack of a detection in any of the UVOT filters for WISE J181250.94−064825.4 is most probably due to the combined effect of its intrinsic weakness, the low value of its Galactic latitude, and an insufficient exposure time of the observations.

Among the candidates not observed by Swift we address WISE J124021.14+350259.0 which benefits from quite rich information such as a considerable radio emission (230.8 mJy in the NVSS), a very low value of color index ($u − r = 0.20$ mag), and an optical spectrum as shown in Figure 6. With its large and strong emission lines and its continuum blueward emission, this candidate indeed has many requirements for classification as an FSRQ.

4.3. Spurious Associations

The number of generic IR sources lying within the positional uncertainty region at the 99% level of confidence of each unidentified 3PBC source is definitely larger than one, since the source density of WISE sources is very large (Wright et al. 2010). However, to estimate the probability that our associations are spurious we need to verify the chance to have an IR source not only of class A, B, or C (therefore with

11 http://irsa.ipac.caltech.edu/applications/DUST/
Table 3
Optical–UV Photometry of WISE γ-Ray Blazar Candidates Observed by Swift-UVOT

| WISE Name                  | Name                        | \( b \) (deg) | \( E(B - V) \) (mag) | Error (mag) | ObsID      | Date       | Filter | Exposure (s) | Magnitude (mag) | Error (mag) |
|----------------------------|-----------------------------|---------------|----------------------|-------------|------------|------------|--------|--------------|----------------|-------------|
| J005712.84+635942.8        | J005712.84+635942.8         | +1.13         | 1.46                 | 0.03        | 00041144001| 2010 Aug 30| M2     | 6562         | 21.6           | 0.3         |
|                            | J005712.84+635942.8         |              |                      |             |            |            |        |              |                |             |
|                            | J013750.47+581411.3         | −4.09         | 0.53                 | 0.01        | 00041273001| 2010 Sep 04| W1     | 2698         | 20.1           | 0.3         |
|                            | J013750.47+581411.3         |              |                      |             |            |            |        |              |                |             |
|                            | J020713.45+841119.1         | +21.62        | 0.11                 | 0.01        | 00039241001| 2009 Sep 12| M2     | 5345         | 17.7           | 0.1         |
|                            | J020713.45+841119.1         |              |                      |             |            |            |        |              |                |             |
|                            | J031202.97+502914.6         | −6.38         | 0.71                 | 0.01        | 00038026001| 2008 Oct 11| M2     | 1557         | 20.3           | 0.3         |
|                            | J031202.97+502914.6         |              |                      |             |            |            |        |              |                |             |
|                            | J035619.96−625339.2        | −43.37        | 0.05                 | 0.01        | 00037304002| 2008 Oct 10| M2     | 5044         | 18.5           | 0.1         |
|                            | J035929.74+505750.1        | −1.60         | 1.51                 | 0.05        | 00038079001| 2007 Jan 25| U      | 3449         | 21.5           | 0.2         |
|                            | J035929.74+505750.1        |              |                      |             |            |            |        |              |                |             |
|                            | J041322.32+165951.1        | −24.10        | 0.66                 | 0.03        | 00090151002| 2009 Aug 02| W2     | 5717         | 19.3           | 0.1         |
|                            | J041322.32+165951.1        |              |                      |             |            |            |        |              |                |             |
|                            | J044047.72+273947.1        | −12.34        | 0.73                 | 0.02        | 00040910001| 2010 Jul 22| W1     | 5836         | 18.9           | 0.1         |
|                            | J044047.72+273947.1        |              |                      |             |            |            |        |              |                |             |
|                            | J050838.93−495302.2        | +7.18         | 0.38                 | 0.01        | 00037996001| 2010 Jun 21| U      | 2312         | 18.8           | 0.1         |
|                            | J050838.93−495302.2        |              |                      |             |            |            |        |              |                |             |
|                            | J154007.85+141337.2        | +8.70         | 0.05                 | 0.01        | 00039843001| 2009 Oct 01| W2     | 6723         | 15.8           | 0.1         |
|                            | J154007.85+141337.2        |              |                      |             |            |            |        |              |                |             |
|                            | J174201.50−605512.1        | −15.63        | 0.08                 | 0.01        | 00041273002| 2011 Nov 10| W1     | 823          | 15.5           | 0.1         |
|                            | J174201.50−605512.1        |              |                      |             |            |            |        |              |                |             |
|                            | J174538.26+290822.2        | +26.24        | 0.05                 | 0.01        | 00035273001| 2005 Dec 11| V      | 989          | 15.7           | 0.1         |
|                            | J174538.26+290822.2        |              |                      |             |            |            |        |              |                |             |
opportunite color indices) but also with a radio counterpart in a random region of the sky. Thus, we considered the following approach.

We created a list of 100 “fake” hard X-ray positions randomly selecting 100 unidentfied 3PBC sources that lie in the northern hemisphere (i.e., decl. > 5°) and shifting their positions by 30' in a random direction of the sky; the adoption of this threshold on the declination guarantees that NVSS radio data are potentially available for all of them. We assigned to each “fake” hard X-ray source an error radius randomly chosen from the distribution of those corresponding to the unidentified BAT sources. We verified that no 2FGL source was included within this error radius. Applying our association procedure to search for “fake” hard X-ray sources.

We repeated the above-described procedure 1000 times and we concluded that the probability of a chance coincidence is of the order of 1% for class B and class C sources, while it is lower than 0.1% for class A sources. We emphasize that these probability estimates are only upper limits; a detailed Fermi analysis is indeed necessary to verify that no significant γ-ray emission is due to the “fake” class B source and to that of a class C source with a radio counterpart obtained from the application of our procedure to the list of “fake” positions. This might occur since the 2FGL catalog was not built using a blind all-sky search (Nolan et al. 2012) and intrinsic source variability, or artifacts due to the γ-ray background, could affect the above estimates making them lower.

5. SUMMARY AND CONCLUSIONS

We applied an association procedure based on the peculiar IR properties of γ-ray-emitting blazars to search for γ-ray blazar candidates among the 382 unidentified BAT sources in the 3PBC. Using this method, we obtained a preliminary list of WISE candidates distributed between unclassified and unassociated 3PBC sources. We searched the literature for information about their multifrequency emission properties and complemented it with the analysis of Swift observations, when available. Consequently, we established more restrictive selection criteria requiring the existence of consistent radio emissions.
and soft X-ray emission for the candidates selected by our association procedure; moreover, we excluded candidates with an extended radio emission.

We obtained a list of 24 $\gamma$-ray blazar candidates: 5 class A ($\sim$21\%), 13 class B ($\sim$54\%), and 6 class C (25\%) sources. Only one of them corresponds to a 3PBC unassociated source. Three candidates are promising as compact radio emission, which is essential for blazar classification according to the Roma-BZCAT criteria, has been reported in the NVSS, but they have never been observed in the X-rays. We consider a very low probability of a chance coincidence for our list of candidates, of the order of 0.1\% for class A candidates and 1\% for class B and class C candidates.

We note that the fraction of blazars included in the 3PBC and detected by Fermi-LAT is $\sim$6\% of the identified 3PBC objects. Assuming, in a first approximation, the same fraction of $\gamma$-ray blazars among the unidentified 3PBC sources we would obtain 21 objects, which is in very good agreement with the number of candidates that we selected. At the same time, we also note that our results cannot rule out the possibility that the hard X-ray emission from unidentified BAT sources is due to a Seyfert galaxy or some other obscured AGN, rather than to the blazar candidate provided by our method.

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**APPENDIX**

**SOME DETAILS ABOUT THE ASSOCIATION METHOD**

We provide here the basic details of the association method adopted in our analysis to search for $\gamma$-ray blazar candidates among the unidentified BAT sources. A complete description is given in Massaro et al. (2012c, 2012d) and additional details are also illustrated in D’Abrusco et al. (2013).

Our procedure is based on the peculiar IR properties of the $\gamma$-ray blazars that allow one to distinguish them, at a high confidence level, from other Galactic and extragalactic sources dominated by thermal emission (see D’Abrusco et al. 2012). The IR counterparts, detected in all of the four WISE bands, of the Fermi-LAT blazars included in the 2LAC (Ackermann et al. 2011) locate in a very narrow region of the IR color–color space that has been named as the WISE Gamma-ray Strip. We developed a parameterization of the strip that can be used to search for $\gamma$-ray blazar candidates. This parameterization is described in terms of the projections of the strip in each of the three independent 2D planes of the IR color–color space. For each projection, we defined the boundaries that include at least 90\% of the corresponding $\gamma$-ray blazars. Then, we defined a parameter to characterize the position of a generic IR source with respect to these boundaries. For example, in the $[3.4]–[4.6]–[12]$ $\mu$m diagram we defined the $s_{12}$ parameter: its value ranges in the 0–1 interval, with 0 corresponding to a source definitely outside these boundaries. In an analogous way, we defined $s_{23}$ in the $[4.6]–[12]–[22]$ $\mu$m and $s_{34}$ in the $[3.4]–[4.6]–[12]–[22]$ $\mu$m diagrams, respectively. Finally, these values are combined to define a single strip parameter in the three-dimensional WISE color–color space:

$$s = (s_{12} s_{23} s_{34})^{1/3}.$$  \hspace{1cm} (A1)

Thus, IR sources that lie out of the boundaries of the WISE Gamma-ray Strip have still $s = 0$ as they do not have blazar-like IR colors, while sources with $s$ close to 1 are likely $\gamma$-ray blazar candidates. By definition, $s$ is weighted for the errors on all the IR colors and is normalized to range in the 0–1 interval. Moreover, BL Lacs and FSRQs cluster in distinct subregions of the IR color–color space: for this reason it is possible to compute, for each source, the $sb$ parameter that is relevant to the part of the strip including the majority of BL Lacs, and $sg$ relevant to the region that mostly includes FSRQs (see also Massaro et al. 2012d for further details).

We selected random regions of the sky, at high Galactic latitude with a total area of $\sim$19 deg$^2$, and considered a sample of 10,311 generic IR sources detected in all the four WISE bands like the blazars in the Gamma-ray Strip. We evaluated the $sb$ and $sg$ parameters for both the generic IR sources and these $\gamma$-ray blazars, and computed the corresponding distributions. From their comparison, we established the thresholds to define three classes of $\gamma$-ray blazar candidates:

\[^{12}\text{http://www.star.bris.ac.uk/~mbt/topcat/}\]
All the WISE sources with $s_b < 0.15$ and $s_q < 0.15$ are considered outliers of the WISE Gamma-ray Strip. The above definition of the thresholds corresponds to an improvement with respect to the previous one (Massaro et al. 2012d) and is based on the larger sample of WISE counterparts (610 versus 284) associated with Fermi-LAT-detected blazars after the release of the WISE full archive available since 2012 March (see also Cutri et al. 2012) and containing the attributes for 563,921,584 point-like and resolved objects. The association method takes into account the correction for the Galactic extinction for all the WISE magnitudes according to Draine (2003). As shown in D’Abrusco et al. (2013) this affects only, and in a marginal way, the [3.4]–[4.6] color index; in particular, for more than 95% of the blazars on the WISE Gamma-ray Strip the correction is less than ~3%.

We note that class A sources, with relatively higher values of the $s_b$ and $s_q$ parameters, are in the innermost region of the WISE Gamma-ray Strip and in this sense can be considered more reliable candidates compared to class C sources (Massaro et al. 2012d). However, this does not imply that class C sources are bad candidates. In fact, 559 out of 610 (99.6%) 2LAC blazars with an IR counterpart detected in all of the four WISE bands have been confirmed by our method. Among them there are 134 class A sources (~24%), 170 class B sources (~30%), and 255 class C sources (~46%).

On the basis of the described parameterization and the definition of the threshold that establishes the three different classes for the γ-ray blazar candidates, the method (Massaro et al. 2012c) defines for each high-energy source a circular searching region centered at its position with a radius equal to the positional uncertainty at the 99% confidence level; then, all the WISE sources within this searching region are ranked according to their $s$ parameter. Of the obtained list of candidates we indicate, as a rule, our best choice as the WISE source of higher class with the smallest angular separation from the position of the high-energy source.

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