Unveiling the nature of the unidentified gamma-ray sources

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One of the main scientific objectives of the recent *Fermi* mission is investigating the origin of the unidentified gamma-ray sources (UGSs). Despite the large improvements of Fermi in the gamma-ray source localization with respect to the past gamma-ray missions, about 1/3 of the gamma-ray objects detected do not have yet an assigned counterpart a low energies. We recently developed a new association method to identify if there is a γ-ray blazar candidate within the positional uncertainty region of a generic γ-ray source. This method is entirely based on the discovery that blazars, the largest known class of gamma-ray sources, can be recognized and separated from other extragalactic sources on the basis of their infrared colors. Here we summarize the results obtained by applying our association procedure to the unidentified γ-ray sources (UGSs) and to the active galaxies of uncertain type (AGUs) listed in the Second *Fermi* Large Area Telescope (LAT) catalog.

1. Intorduction

Unveiling the nature of the Unidentified Gamma-ray Sources (UGSs) [Abdo et al. 2009] is one of the biggest challenges in contemporary gamma-ray astronomy. In particular, according to the Second *Fermi* Large Area Telescope (LAT) catalog [2FGL; Nolan et al. 2012], $\sim$1/3 of the γ-ray detected sources are still unassociated with their low energy counterparts. A large fraction of the UGSs are likely to be blazars, the rarest class of active galaxies, because their emission dominates the γ-ray sky [e.g., Mukherjee et al. 1997, Abdo et al. 2010].

However, due to the incompleteness of the current radio and X-ray surveys on the basis of the usual γ-ray association method is not always possible to find the blazar-like counterpart of an UGS. Additional attempts have also been recently developed to associate or to characterize the UGSs using either pointed *Swift* observations [e.g., Mirabal 2009, Mirabal & Halpern 2009] or statistical approaches [e.g. Mirabal et al. 2010, Ackermann et al. 2012].

Blazar emission is characterized by high and variable polarization, apparent superluminal motions, and high luminosities, coupled with a flat radio spectrum that steepens toward the infrared-optical bands and together with rapid flux variability at all frequencies [e.g., Urry & Padovani 1995]. Their broad band spectral energy distributions show two main components: the low-energy one with power peaking in the range from the IR to the X-ray band, and the high-energy showing its maximum in the MeV – TeV energy range [e.g., Giommi et al. 2005].

Blazars come in two flavors: the BL Lac objects, characterized by featureless optical spectra and lower luminosity with respect to the second class composed of flat-spectrum radio quasars showing quasar-like optical spectra [Stickel et al. 1991, Stoke et al. 1991]. In the following we label the BL Lac objects as BZBs and the flat-spectrum radio quasars as BZQs, following the nomenclature of the Multifrequency Catalogue of Blazars [ROMA-BZCAT, Massaro et al. 2009, Massaro et al. 2010, Massaro et al. 2011a].

On the basis of the preliminary data release of the Wide-field Infrared Survey Explorer [*WISE*, see Wright et al. 2010, for more details], we discovered that in the 3-dimensional IR color space γ-ray emitting blazars lie in a distinct region, well separated from other extragalactic sources whose IR emission is dominated by thermal radiation [e.g., Massaro et al. 2011b, D'Abrusco et al. 2012]. According to D'Abrusco et al. (2013) we refer to the 3-dimensional region occupied by γ-ray emitting blazars as the *locus*, to its 2-dimensional projection in the [3.4]-[4.6]-[12] μm color-color diagram still maintain its historical definition as the *WISE* Gamma-ray Strip.

This *WISE* analysis led to the development of a new association method to recognize γ-ray blazar candidates for the unidentified γ-ray sources listed in the 2FGL [Massaro et al. 2012a, Massaro et al. 2012b], as well as in the 4th *INTEGRAL* catalog [Massaro et al. 2012c].

Here we present the results achieved by applying a more conservative approach and several improvements recently made on the association procedure [see

D'Abrusco et al. 2013, for more details], mostly based on the availability of the *WISE* full archive [1], available since March 2012 [see also Cutri et al. 2012]. We analyzed all the UGSs listed in the 2FGL as well as the sample of the active galactic nuclei of uncertain type (AGUs) that have still unclear classification [Nolan et al. 2012]. We also performed an extensive literature search looking for multifrequency information on the γ-ray blazar candidates selected on the basis of their *WISE* colors to confirm their nature.

We remark that a detailed description of our multifrequency analysis and of the association procedure adopted, together with the lists of γ-ray blazar candidates, is presented in details in Massaro et al. (2013) and D'Abrusco et al. (2013), while here we only highlight the major results achieved.

2. RESULTS

A new association method has been recently developed based on the discovery that γ-ray emitting blazars lie in a distinct region in the *WISE* 3-dimensional color space, separated from that occupied by other extragalactic and galactic sources [Massaro et al. 2011b, D'Abrusco et al. 2012]. According to D'Abrusco et al. (2013) the 3-dimensional region occupied by γ-ray emitting blazars is the *locus*; its 2-dimensional projection in the [3.4]-[4.6]-[12] μm parameter space, retains its historical definition of *WISE* Gamma-ray Strip [Massaro et al. 2011b]. Additional improvements, mostly based on the *WISE* all-sky data release, available since March 2012 [Cutri et al. 2012], and on a new parametrization of the *locus* in the parameter space of its principal components have been subsequently developed [D'Abrusco et al. 2013].

Then we applied our new association procedure searching for new γ-ray blazar candidates in the two samples: the unidentified gamma-ray sources (UGSs), and the active galaxies of uncertain type (AGUs), **as** listed in the 2FGL [Nolan et al. 2012]. We also perform an extensive archival search to see if the sources associated with our method, show additional blazar-like characteristics; as, for example, the presence of a radio counterpart and/or of a spectrum that could be featureless as for BZBs or similar to those of broad-line quasars as generally occurs in BZQs.

We found 62 γ-ray blazar candidates for the UGSs without any γ-ray analysis flag and 49 for those with γ-ray analysis flag, out of a total of 590 sources investigated. For the AGU sample, we confirmed the blazar-like nature of 87 out 210 of AGUs analyzed on the basis of their IR colors. Figure 1 shows the 3-dimensional color plot comparing the IR colors of the selected γ-ray blazar candidates with the blazar population that constitutes the *locus*.

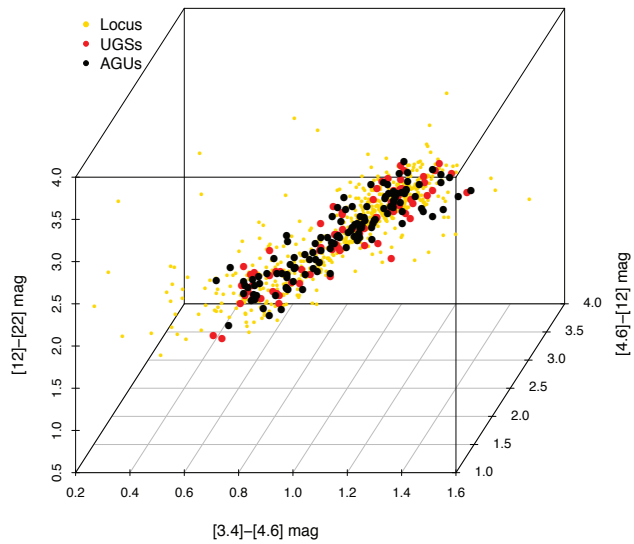

Figure 1: The 3D representation of the *locus* (known γ-ray blazars are indicated in yellow) in comparison with the selected γ-ray blazar candidates: UGSs (red) and AGUs (black).

We searched in the following major radio,infrared, optical and X-ray surveys as well as in the NASA Extragalactic Database (NED) [2] for possible counterparts of our γ-ray blazar candidates, selected with the *WISE* association method, to verify if additional information could confirm their blazar-like nature. For the radio counterparts we used the NRAO VLA Sky Survey [NVSS; Condon et al. 1998, - N], the VLA Faint Images of the Radio Sky at Twenty-Centimeters [FIRST; Becker et al. 1995, White et al. 1997, - F], the Sydney University Molonglo Sky Survey [SUMSS; Mauch et al. 2003, - S] and the Australia Telescope 20 GHz Survey [AT20G; Murphy et al. 2010, - A]; for the infrared we used 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]. Then, we also 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 Sur-

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

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

vey [6dFGS; Jones et al. 2004, Jones et al. 2009, -6]; while for the high energy we looked in the soft X-rays using the ROSAT all-sky survey [RASS; Voges et al. 1999, - X]. We also searched in the USNO-B Catalog [Monet et al. 2003] for the optical counterparts of our γ-ray blazar candidates

A significant fraction (i.e., $\sim$ 36%) of the *WISE* sources associated with our method with UGSs have a radio counterpart, more than 50% are also detected in the 2MASS catalog as generally occurs for blazars, and more than $\sim$10% appear to be variable according to the *WISE* analysis flags [Cutri et al. 2012]. Notably, more than 90% sources for which an optical spectrum was available in literature clearly show blazar-like features, being either featureless or having broad emission lines typical of quasars. As generally expected for γ-ray blazars a handful of the selected candidates are also detected in the X-rays. A deeper investigation of their X-ray counterparts will be addressed in a forthcoming paper [Paggi et al. 2013].

Our results are in good agreement with those based on different statistical approaches like the Classification Tree and the Logistic regression analyses [Ackermann et al. 2012]. In particular, 23 out of 28 UGSs that we associate to a γ-ray blazar candidate are also classified as active galaxies by the above methods at high level of confidence.

Finally, we emphasize that additional investigations of different samples of active galactic nuclei, such as Seyfert galaxies, are necessary to study the problem of the contamination of our association method by extragalactic sources with infrared colors similar to those of γ-ray blazars. Moreover extensive ground-based spectroscopic follow up observations in the optical and in the near IR would be ideal to verify the nature of the selected *WISE* sources and to estimate the fraction of non-blazar objects, similar to the recent studies performed for the unidentified INTEGRAL sources [e.g., Masetti et al. 2008, Masetti et al. 2009, Masetti et al. 2010, Masetti et al. 2012].

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[3] http://www.star.bris.ac.uk/~mbt/topcat/

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