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Multi-wavelength selection and identification of gamma-ray blazar candidates

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Abstract. A significant fraction ($\sim 30\%$) of the gamma-ray sources detected by the *Fermi* Gamma-ray Space Telescope is still of unknown origin, being not yet associated with counterparts at lower energies. Many unidentified gamma-ray sources (UGSs) could be blazars, the largest identified population of extragalactic gamma-ray sources and the rarest class of active galactic nuclei. In particular, it has been found that blazars occupy a defined region in WISE three dimensional color space, well separated from that occupied by other sources in which thermal emission prevails. For farther sources with weaker IR emission, additional informations can be obtained combining WISE data with X-ray or radio emission. Alternatively, the low-frequency radio emission can be used for identifying potential gamma-ray candidate blazars. However, optical spectroscopic observations represent the tell-tale tool to confirm the exact nature of these sources. To this end, an extensive observational campaign has been performed with several optical telescopes, aimed at pinpointing the exact nature of gamma-ray candidate blazars selected with the different selection methods mentioned above. The results of this campaign lead to the discovery of 60 new gamma-ray blazars, thus confirming the effectiveness of these selection criteria.

Keywords. galaxies: active, BL Lacertae objects: general, galaxies: jets, radio continuum: galaxies, infrared: galaxies, X-rays: galaxies, gamma rays: observations

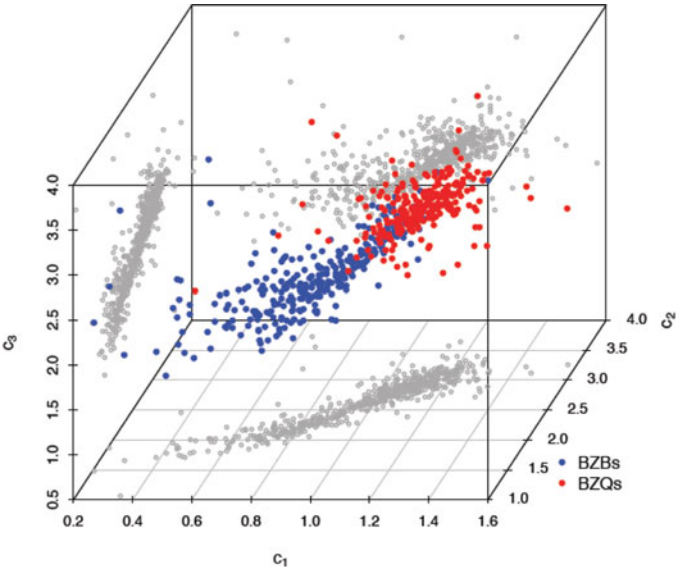

Figure 1. Scatterplot of the WFB sources in the three-dimensional WISE color space. The spectral class of the WFB sources is color-coded, while the three distributions of gray points represent the projections of the WFB sample in the three-dimensional color space onto the three two-dimensional color-color planes generated by the WISE colors c1=[3.4]-[4.6], c2=[4.6]-[12] and c3=[12]-[22], respectively.

1. Introduction

About 1/3 of the γ-ray sources listed in the 2nd *Fermi*-LAT catalog (2FGL, Nolan *et al.* 2012) have not yet been associated with counterparts at lower energies. A precise knowledge of the number of unidentified gamma-ray sources (UGSs) is extremely relevant since for example it could help to provide the tightest constraint on the dark matter models ever determined (Berlin & Hooper 2014). Many UGSs could be blazars, the largest identified population of extragalactic γ-ray sources, but how many are actually blazars is not yet known due in part to the incompleteness of the catalogs used for the associations (Ackermann *et al.* 2011). The first step to reduce the number of UGSs is therefore to recognize those that could be blazars.

Blazars are the rarest class of active galactic nuclei, dominated by variable, non-thermal radiation over the entire electromagnetic spectrum (e.g., Urry & Padovani 1995; Giommi, Padovani & Polenta 2013). Their observational properties are generally interpreted in terms of a relativistic jet aligned within a small angle to our line of sight (Blandford & Rees 1978).

Blazars have been classified as BL Lacs and FSRQs (or BZBs and BZQs according to the nomenclature proposed by Massaro *et al.* 2013), with the latter showing similar optical spectra except for the stronger emission lines, as well as higher radio polarization. In particular, if the only spectral features observed are emission lines with rest frame equivalent width $EW \leqslant 5$ Å the object is classified as a BZB (Sickel *et al.* 1991; Stocke & Rector 1997), otherwise it is classified as BZQ (Lurent-Muehleisen *et al.* 1999; Massaro *et al.* 2013). Systematic projects aimed at obtaining optical spectroscopic observations of blazars are currently carried out by different groups (see, e.g., Sbarufatti *et al.* 2006; Sbarufatti *et al.* 2009; Landoni *et al.* 2012; Landoni *et al.* 2013; Shaw *et al.* 2013a).

Here we present the main results of an extensive campaign of optical spectroscopic observations carried on during 2013 and 2014 with different facilities (both in the northern

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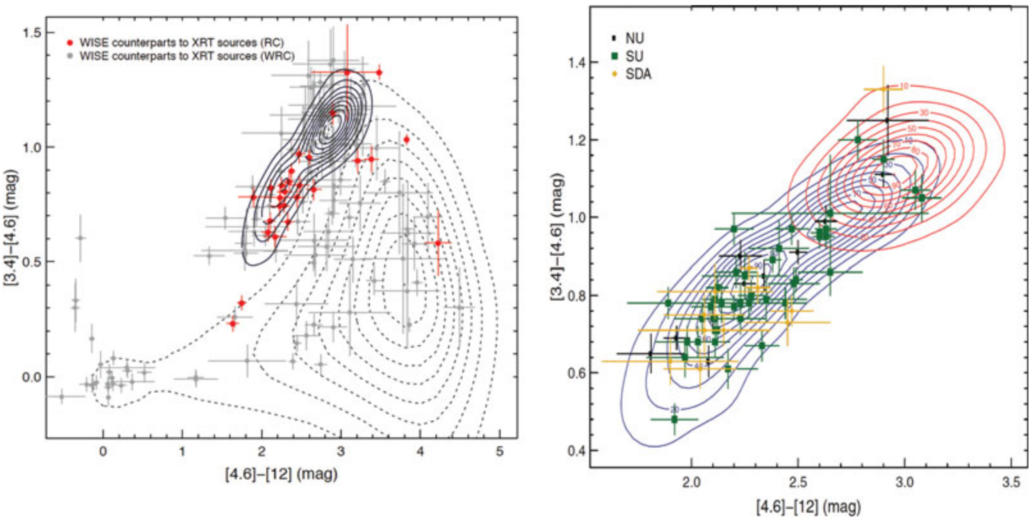

Figure 2. (Left panel) Projection of the three-dimensional WISE color space on the two-dimensional[3.4]-[4.6] [4.6]-[12] color-color plane for *Swift*-XRT sources with a WISE counterpart. Black lines represent the two-dimensional densities of WISE counterparts to know γ-ray blazars evaluated using the KDE technique, with the outermost line indicating the 90% density contour normalized to the peak density. Grey circles represent XRT-PC sources without a radio counterpart (WRC), and red circles represent the XRT-PC sources with a radio counterpart (RC). Black dashed lines represent isodensity contours of generic WISE sources. (Right panel) Isodensity contours generated by the KDE technique in the [3.4]-[4.6] [12] color color diagram for the BZBs (blue) and the BZQs (red). Points overlaid to the contours show the location of the selected radio candidates with IR colors consistent with the γ-ray blazar population for the sources in the three different samples analyzed: NU (NVSS survey, black circles), SU (SUMSS survey, green squares), and SDA (ATCA survey, yellow diamonds).

and southern hemisphere) aimed at pinpointing the exact nature of gamma-ray candidate blazars selected with different methods described in Sect. 2. The results of this campaign lead to the discovery of 60 new gamma-ray blazars, thus confirming the effectiveness of these selection criteria.

2. Selection methods

Recently, D'Abrusco *et al.* (2013) proposed an association procedure to recognize γ-ray blazar candidates on the basis of their positions in the three-dimensional WISE color space. As a matter of fact, blazars – whose emission is dominated by beamed, non thermal emission – occupy a defined region in such a space (the WISE Fermi Blazar locus, WFB, see Fig. 1), well separated from that occupied by other sources in which thermal emission prevails (Massaro *et al.* 2011; D'Abrusco *et al.* 2012). Applying this method, Cowperthwaite *et al.* (2013) recently identified thirteen gamma-ray emitting blazar candidates from a sample of 102 previously unidentified sources selected from Astronomer's Telegrams and the literature.

Massaro *et al.* (2013a) applied the classification method proposed by D'Abrusco *et al.* (2013) to 258 UGSs and 210 active galaxies of uncertain type (AGUs) listed in the 2FGL finding candidate blazar counterparts for 141 UGSs and 125 AGUs. The classification method proposed by D'Abrusco *et al.* (2013), however, can only be applied to sources detected in all 4 WISE bands, i.e., 3.4, 4.6, 12 and 22 μm.

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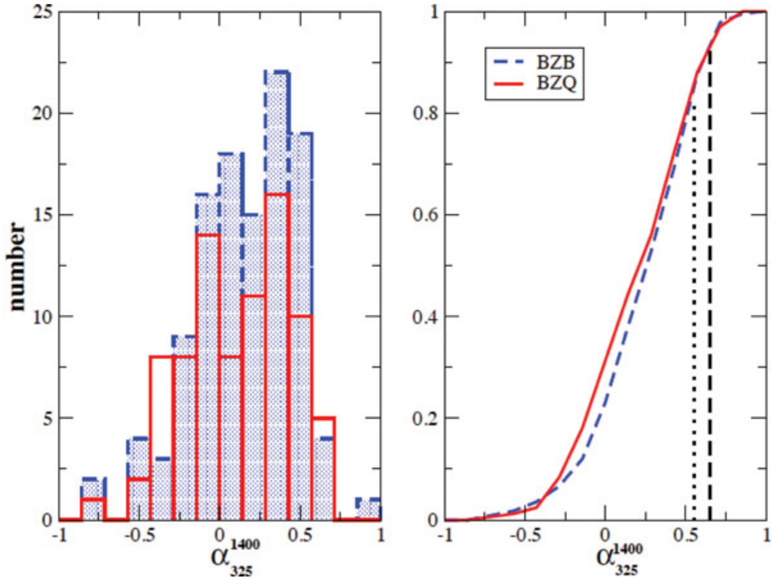

Figure 3. The distributions of the radio spectral index between 325 and 1400 GHz (α_{325}^{1400}) of all the identified blazars in the low radio frequency Gamma-ray Blazar sample sample, BZBs (blue) and BZQs (red). The two vertical lines mark the 0.55 (dotted) and 0.65 (dashed) values of α_{325}^{1400}.

Using the X-ray emission in place of the 22 μm detection, Paggi *et al.* (2013) proposed a method to select γ-ray blazar candidates among *Swift*-XRT sources considering those that feature a WISE counterpart detected at least in the first 3 bands, and with IR colors compatible with the 90% two-dimensional densities of known γ-ray blazar evaluated using the Kernel Density Estimation (KDE) technique (Richards *et al.* 2004; D'Abrusco, Longo & Walton 2009; Laurino *et al.* 2011 and reference therein), so selecting 37 new γ-ray blazar candidates (Fig. 2, left panel). Similarly, using the radio emission as additional information, Massaro *et al.* (2013b) investigated all the radio sources in NVSS and SUMSS surveys that lie within positional uncertainty region of *Fermi* UGSs and, considering those sources with IR colors compatible with the 90% two-dimensional KDE densities of known γ-ray blazar, selected 66 additional γ-ray blazar candidates (Fig. 2, right panel).

Finally, Massaro *et al.* (2013c) investigated the low-frequency radio emission of blazars and searched for sources with similar features combining the information derived from the WENSS and NVSS surveys, identifying 26 γ-ray candidate blazars in the *Fermi* LAT the positional uncertainty region of 21 UGSs.

3. Observations and Results

During 2013 and 2014 we carried on an extensive campaign of optical spectroscopic observations of candidate γ-ray blazar candidates selected with the methods described in Sect. 2, mainly thanks to a joint Fermi-NOAO proposal approved in 2013 (PI: D'Abrusco), making use of MMT, OAN, SOAR and KPNO telescopes. The results of these campaign are presented in several published and submitted papers (Paggi *et al.* 2014; Landoni *et al.* 2014; Massaro *et al.* 2014; Ricci *et al.* 2014), and here we recap the main points.

So far we observed 60 γ-ray blazar candidates, and all of them show featureless BZB optical spectra or QSO-like spectra typical of BZQs, thus confirming the reliability of our

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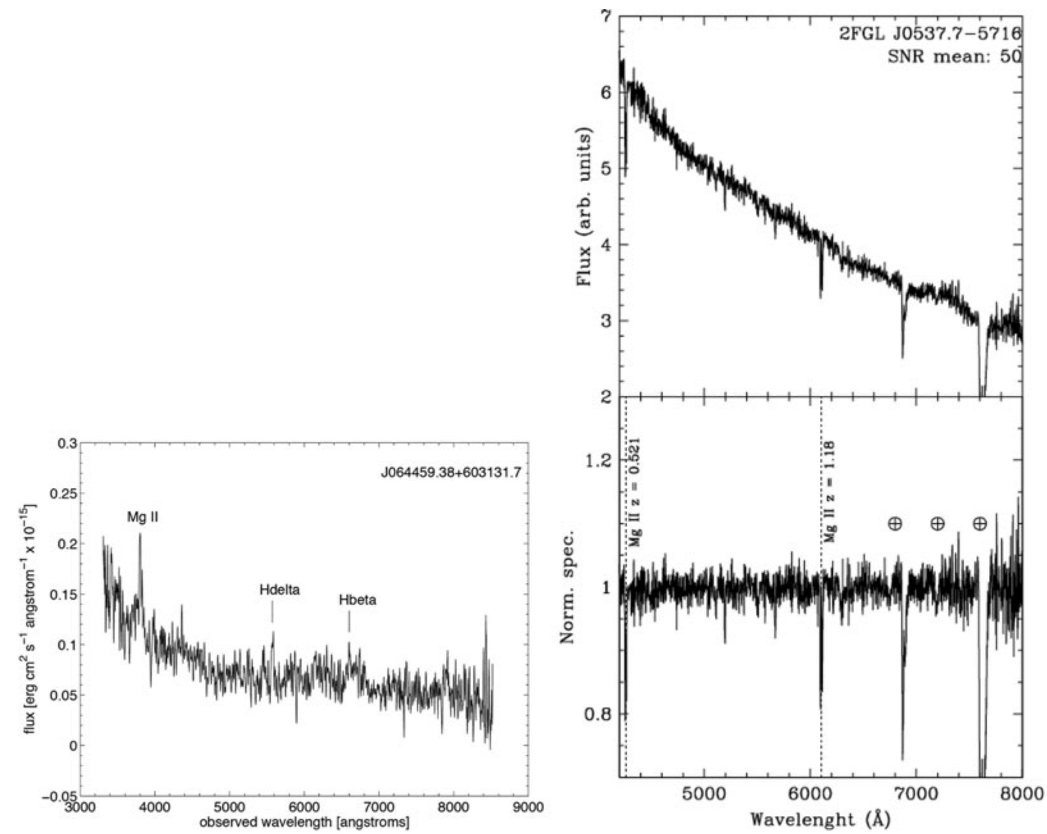

Figure 4. (Left panel). Optical spectra of the WISE γ-ray blazar candidate WISE J064459.38+603131.7 associated with *Fermi*-LAT UGS 2FGL J0644.6+6034 obtained with MMT Blue Channel Spectrograph. (Right panel). 2FGL J0537.7–5716 optical spectrum obtained at SOAR with Goodman High Throughput Spectrograph. Top: Flux calibrated (relative units) spectrum of the source. Bottom: Normalised spectrum.

different approaches in selecting γ-ray candidate blazars. In particular, the spectrum of WISEJ064459.38+603131.7 (Fig. 4, left panel), is somewhat reminiscent of weak emission line quasar spectra Shemmer *et al.* (2006), Shemmer *et al.* (2009), but the blazar identification for this source appears problematic. In fact the WISEJ064459.38+603131.7 is not detected by NVSS survey, so we can only put an upper limit on its flux ~ 2.5 mJy. Even if it is possible that deeper radio observations will detect emission from the source, blazars are traditionally defined as radio-loud sources basing on present radio data. All confirmed blazar from BZCAT are in fact detected at 1.4 GHz with fluxes $\gtrsim 1$ mJy, and radio-quiet blazars are extremely rare objects Londish *et al.* (2004). We have been also able to evaluate redshifts for a number of our sources. In particular, we highlight the lower limit redshift that we put for the BZB source 2FGL J0537.7–5716 where multiple Mg II absorption system are detected. The first one is found to be at redshift $z = 0.521$ while the second one is at $z = 1.18$ making this source the third the most distant BZB ever observed.

In conclusion the results of our observing campaign seem confirm the reliability of our multi-wavelength methods in selecting selecting γ-ray candidate blazars. There could be possible contamination by different source classes in these selection procedures (e.g., Stern & Assef 2013) and such degeneracy can be only removed with optical spectroscopic observations (Masetti *et al.* 2013; Shaw *et al.* 2013a,b). Therefore additional observations are needed in order to obtain a significant sample that allows a detailed statistical analysis to firmly assess the completeness and efficiency of our selection methods.

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