The Multimessenger Chakra of Blazar Jets
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A *WISE* perspective of the blazar hunt in the γ-ray sky

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Abstract. Thanks to the data of the *WISE* all-sky survey we discovered that the non-thermal infrared emission of blazars, the largest population of associated γ-ray sources, has peculiar spectral properties. Here we provide a summary of all results achieved on the *infrared–γ-ray connection*. We also show results on the latest statistical analysis of the tight correlation between the mid-infrared colors and the γ-ray spectral index for *Fermi* blazars, a connection that links both emitted powers and spectral shapes of particles accelerated in blazar jets over ten decades in frequency of the electromagnetic spectrum. Finally, we outline all developments performed in the last decade achieved using the infrared–γ-ray connection to discover hundreds of new blazars within the sample of unidentified γ-ray sources thanks to optical spectroscopic observations.

Keywords. active galactic nuclei, blazars, relativistic jets, surveys, gamma-rays

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1. Introduction

Blazars are a class of radio-loud active galaxies showing an extreme behavior. Their emission spans the whole electromagnetic spectrum from radio to TeV energies exhibiting variability at all wavelengths with timescales ranging from weeks to minutes coupled with evidence of superluminal motions, high and variable polarization and flat radio spectra (see e.g. Urry & Padovani 1995; Massaro et al. 2009, for a review), even observed below $\sim$1 GHz (i.e., Massaro et al. 2013a,b).

Discoveries on the blazar population in the last decade where mainly achieved thanks by the survey carried out with the *Fermi* satellite (Atwood et al. 2009), since blazars constitute the dominant class of γ-ray sources. Blazars account for more than 1/3 of the *Fermi* detected sources (Acero et al. 2015). Thus we could also expect that a significant fraction of the unidentified/unassociated γ-ray sources (UGSs; Massaro et al. 2012, 2013c), in particular at high Galactic latitudes, also belong to this class.

Moreover, together with star forming galaxies (e.g. Ackermann et al. 2012) and radio galaxies (e.g. Di Mauro et al. 2014; Massaro & Ajello 2011), blazars produce a significant contribution to the extragalactic γ-ray background (Ajello et al. 2012, 2014; Massaro et al. 2016b, and references therein).

Blazars historically come in two flavors, mainly distinguished on the basis of their optical properties: BL Lac objects and flat spectrum radio quasars. According to the nomenclature introduced by the *Roma-BZCAT* (Massaro et al. 2015b) The former subclass is generally labelled as BZBs while the latter as BZQs. In particular, BZBs show featureless optical spectra and/or with weak absorption lines of equivalent width lower than 5$\AA$, while the BZQs have a typical quasar-like optical spectra (Stickel et al. 1991; Falomo et al. 2014).

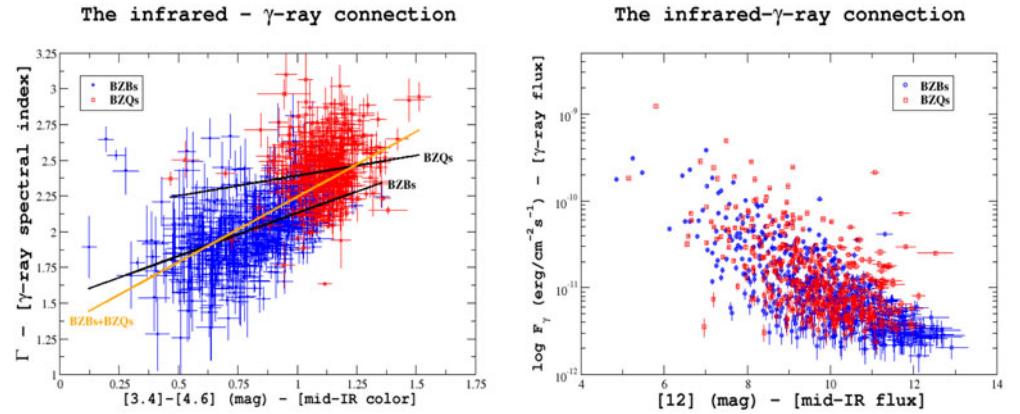

Figure 1. (Left panel) The γ-ray spectral index Γ *vs* the mid-IR color [3.4]-[4.6] μm for the blazars belonging to the *WISE locus*. BZBs are shown in blue open circles while BZQs in red open squares. Linear correlations between the γ-ray spectral and the mid-IR shaped are highlighted by regression lines in black for BZBs and BZQs while in orange for the whole population, respectively. This is the observational evidence of the infrared–γ-ray connection. **(Right panel)** The *WISE* magnitude at [12] μm *vs* the γ-ray flux density for all blazars included in the to the *WISE locus*. Here we report the trend between fluxes using the magnitude at [12] μm, being less contaminated by the emission arising from the host galaxy than that measured at 3.4 μm, and the γ-ray flux. Similar trends/correlations exists also using all other *WISE* magnitudes (see e.g., Massaro & D'Abrusco 2016, for all details about the analysis).

Starting from 2010, the NASA Wide-field Infrared Survey Explorer (*WISE*; Wright et al. 2010) mapped the sky at mid-infrared (mid-IR) frequencies, in 4 bands at nominal wavelenghts: 3.4, 4.6, 12, and 22 μm, making possible the statistical investigation of the mid-IR properties of the blazar population.

In 2011, we discovered that *Fermi* blazars inhabit a region of the mid-IR color-color diagram (i.e., [3.4]-[4.6]-[12] μm), built with the *WISE* magnitudes, well separated from the location of other extragalactic sources (Massaro et al. 2011; D'Abrusco et al. 2012). This 2-dimensional region of the mid-IR color-color diagram was originally labelled as the *WISE Gamma-ray Strip*. Then we found that the *WISE Gamma-ray Strip* is the projection of a 3-dimensional volume, in the mid-IR color space, today known as the *WISE locus* of γ-ray blazars (D'Abrusco et al. 2013, 2014). Here we show the results achieved on the link found between the *WISE* mid-IR colors and the γ-ray photon index as well as between fluxes measured in these energy ranges (Massaro & D'Abrusco 2016).

We use cgs units unless stated otherwise. Gamma-ray photon index, Γ is defined by the usual convention on the flux density, $N(E) \propto E^{-\Gamma}$, being $N(E)$ the number of γ-ray photons detected per unit of time, area and energy. *WISE* magnitudes are in the Vega system and are not corrected for the Galactic extinction since such correction affects significantly only the magnitude at 3.4 μ for sources lying at low Galactic latitudes (see e.g. D'Abrusco et al. 2014).

2. On the infrared–γ-ray connection

To assess the significance of the *infrared–*γ*-ray connection*, we searched a correlation between the γ-ray photon index Γ and their *WISE* mid-IR colors, a surrogate of the mid-IR spectral index, for all *Fermi* blazars. We discovered a strong correlation, the first evidence of the existence of the *infrared–*γ*-ray connection*, between these two parameters, as reported in Fig. 1 (see Massaro & D'Abrusco 2016, for whole details about the statistical analysis).

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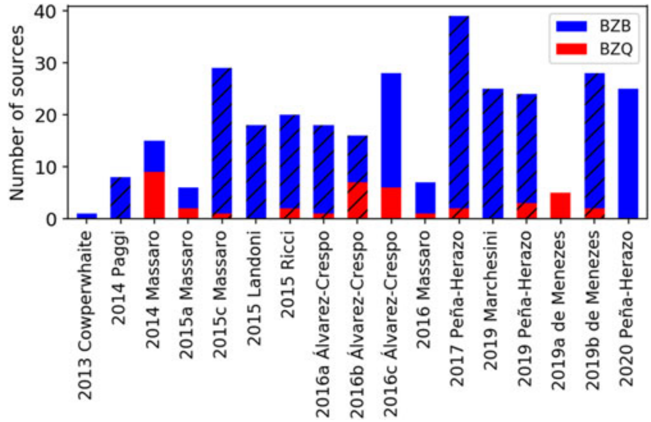

Figure 2. Number of blazars discovered during the optical spectroscopic campaign carried out pointing γ-ray blazar candidates that lie within the positional γ-ray uncertainty region and have mid-IR colors similar to that of blazars (hatched bars). We also show blazars discovered thanks to archival searches on spectroscopic surveys (non-hatched bars). BZBs are shown in blue while BZQs in red as previously labelled.

We first searched for a correlation between spectral shapes in the Γ *vs* [3.4]-[4.6] μm plane. The correlation we found appears to be more statistically significant for BZBs rather than for BZQs with a linear correlation coefficient $\rho = 0.47$ for the former ones and a negligible probability to be spurious, given the large datasets used. We obtained $\rho = 0.15$ for the BZQs computed using a sample of 419 γ-ray sources that also in this case led to a negligible chance probability. When combining datasets of both classes, for a total of 1022 *Fermi* blazars, the linear correlation coefficient, unsurprisingly, increases to $\rho = 0.65$. Thus the slope of the best fit regression lines, as expected, is mainly driven by the stronger correlation found on the sources belonging to the BZB class.

A similar situation occurs in the Γ *vs* [4.6]-[12] μm plane, where the correlation coefficients for the 595 BZBs and the 419 BZQs separately are $\rho = 0.48$ and $\rho = 0.13$, respectively. Then the correlation coefficient computed for the whole *Fermi* blazar sample, in this case listing 1014 γ-ray sources is $\rho = 0.60$, lower than the previous one due to the larger scatter induced by the uncertainties of mid-IR magnitudes at 12μm larger than those at 3.4 μm and 4.6 μm.

For the sake of comparison, it is worth stressing that the *radio–γ-ray connection* is based on the correlation between the radio and γ-ray flux densities. A similar trend also exists for the mid-IR emission as shown in Fig. 1, which displays the 12 μm magnitude vs γ-ray flux density for both *Fermi* BZBs and BZQs.

3. Summary and conclusions

Several years after the discovery that the non-thermal emission of γ-ray blazars can be traced using mid-IR colors obtained from the photometry of the *WISE* all-sky survey, we report the latest results on the existence of a *infrared–γ-ray connection* for the *Fermi* blazars that appears to be at least as strong as the well-known radio–γ-ray one.

We found statistically significant correlations between the γ-ray photon index and the mid-IR colors for both the whole sample of *Fermi* blazars and the BZBs and BZQs spectral classes separately, the basis of the *infrared–γ-ray connection*. This correlation appears "stronger" than the well known radio–γ-ray connection because it involves the spectral shapes of the *Fermi* blazars over $\sim$10 orders of magnitude and not only their flux densities.

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Taking advantage of the overwhelming fraction of *Fermi* blazars detected in the *WISE* all-sky survey (i.e., ∼99%) in the first two mid-IR filters, we suggested a comprehensive investigation of their IR properties at the light of the *infrared–γ-ray connection* since it has been a powerful tool to reveal the real fraction of *Fermi* blazars hidden within the sample of UGSs. To emphasize its use we finally, report in Fig. 2, a summary of the spectroscopic campaign carried out in the last decade to observed γ-ray blazar candidates that lie within the positional γ-ray uncertainty region and have mid-IR colors similar to that of blazars. This was also augmented by an extensive archival search in the databases of the major optical surveys that significantly helped to discover new γ-ray blazars as also shown in Fig. 2.

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