IDENTIFICATION OF THE INFRARED NON-THERMAL EMISSION IN BLAZARS

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ABSTRACT
Blazars constitute the most interesting and enigmatic class of extragalactic $\gamma$-ray sources dominated by non-thermal emission. In this Letter, we show how the Wide Infrared Survey Explorer (WISE) infrared data make it possible to identify a distinct region of the [3.4]–[4.6]–[12] $\mu$m color–color diagram where the sources dominated by the thermal radiation are separated from those dominated by non-thermal emission, in particular the blazar population. This infrared non-thermal region, which we indicate as the WISE blazar strip (WBS), will constitute a new powerful diagnostic tool when the full WISE survey data are released. The WBS can be used to extract new blazar candidates, to identify those of uncertain type and also to search for the counterparts of unidentified $\gamma$-ray sources. We show one example of the value of the use of the WBS identifying the TeV source VER J0648+152, recently discovered by VERITAS.

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

1. INTRODUCTION
Blazars are one of the most enigmatic and rare classes of active galactic nuclei (AGNs). Their continuum emission is dominated by non-thermal radiation from radio to $\gamma$-ray energies, making them the most frequently detected class of extragalactic sources at GeV–TeV energies. Their observational features also include high and variable polarization, superluminal motions, very high observed luminosities coupled with a flat radio spectrum that steepens in the IR–optical bands, and a rapid variability from the radio to X-ray bands with weak or absent emission lines. In 1978, Blandford & Rees suggested that radiation of blazars could be described as arising from a relativistic jet closely aligned with the line of sight (Blandford & Rees 1978). In short, blazars constitute the purest non-thermal kind of AGNs.

The spectral energy distributions (SEDs) of blazars include two main components: a low-energy component with power peaking in the range from the IR to the X-ray band and a substantial high-energy component often dominated by $\gamma$-rays. Blazars come in two types: the BL Lac objects (BZBs) and flat spectrum radio quasars (BZQs), with the latter having strong emission lines, generally higher radio to optical polarization, higher redshift, and more prominent $\gamma$-ray bumps in their SEDs, than the former population. The BL Lac population is in turn divided in two subclasses: the “low-frequency-peaked BL Lacs” (LBLs) in which the peak of the first component falls in the IR–optical range, and the “high-frequency-peaked BL Lacs” (HBLs) when it falls in the range between the UV and the X-ray bands (Padovani & Giommi 1995). Recently, HBLs detected at TeV energies have been reclassified as TBLs (Massaro et al. 2008, Massaro et al. 2011b).

In this Letter, we present a color–color diagram using infrared (IR) magnitudes that allows us to distinguish between extragalactic sources dominated by non-thermal emission, like blazars, and other classes of galaxies and/or AGNs. We construct the diagram using the archival data of the recent Wide Infrared Survey Explorer (WISE) facility (Wright et al. 2010). The WISE mission mapped the sky at 3.4, 4.6, 12, and 22 $\mu$m in 2010 with an angular resolution of 6′.1, 6′.4, 6′.5, and 12′0 in the four bands, achieving 5$\sigma$ point source sensitivities of 0.08, 0.11, 1, and 6 mJy in unconfused regions on the ecliptic, respectively. Regarding the WISE astrometry, we note that the absolute (radial) differences between WISE source peaks and “true” astrometric positions anywhere on the sky are no larger than $\sim$0′.50, 0′.26, 0′.26, and 1′.4 for the four WISE bands, respectively (Cutri et al. 2011).

We show how in the [3.4]–[4.6]–[12] $\mu$m color–color diagram the blazar population, which is dominated by non-thermal emission in the infrared, covers a distinct region well separated from the locus of other extragalactic sources dominated by the IR thermal radiation. We suggest how this infrared non-thermal region (hereinafter the WISE blazar strip, WBS) could be used as a diagnostic tool for identifying the blazar population over the entire sky when the final data release of the WISE survey will be available. Finally, we discuss the possible implications of our results on efforts to identify $\gamma$-ray sources and blazars of uncertain type. As an example, we apply the WBS as a new diagnostic tool to look for the counterpart of the recently unidentified BL Lac candidate discovered by VERITAS: VER J0648+152 (Ong & Paneque 2010). We note that the WISE 22 $\mu$m band also offers a similarly useful color diagnostic, but because of its larger beam, is less useful in this investigation.

2. BLAZAR WISE DETECTIONS
We considered all the blazars present in the ROMA-BZCAT\textsuperscript{3} (Massaro et al. 2009, Massaro et al. 2010), adopting the same nomenclature, namely, BL Lac objects (BZBs), flat spectrum radio quasars (BZQs), and blazars of uncertain type (BZUs). We note that the class BZU which contains sources showing occasional presence/absence of broad spectral lines or transition objects between a radio galaxy and a BL Lac, as well as sources with limited spectral data does not allow a precise classification.

The total number of blazars in the ROMA-BZCAT that fall in the area surveyed by WISE during the first year (corresponding to 57% of the whole sky) is 1487 (due to the inhomogeneity of the sky coverage of the ROMA-BZCAT). To search for the positional coincidences of blazars in the observed WISE sky we considered two different regions. The first of radius 2′4

\textsuperscript{3} \url{http://wise2.ipac.caltech.edu/docs/release/prelim/expsup/sec2_3g.html}

\textsuperscript{4} \url{http://www.asdc.asi.it/bzcat/}
corresponding to the combination of the error of 1″ assumed for the radio position reported in the ROMA-BZCAT (Massaro et al. 2009) and that of the fourth Wise band at 22 μm (i.e., 1′′4) (see Section 1 and reference therein); the second region has a radius of 6′5, equal to the angular resolution of the third Wise band. In our analysis, we excluded multiple cross-matches. We also note that the cross-match between the ROMA-BZCAT and the Wise catalog was performed considering only the sources present in the first year Wise catalog detected with a minimum signal-to-noise ratio (S/N) higher than 7 in at least one band.

The number of positional coincidences within the first region of 2′4 is 1365, corresponding to 92% of the blazars in the Wise first year survey, detected with a chance probability of 2.5%, evaluated applying the same method described in Maselli et al. (2011). We did not find any multiple matches adopting the area of 2′4. The number of blazars associated with Wise sources increases to 1446 with a chance probability of 11% considering the second region of 6′5, where we found eight multiple matches. Thus, 97% of the blazars appear to have a counterpart in the Wise catalog. To be more conservative in our analysis, for the rest of the discussion we consider only those blazars with Wise sources associated within the 2′4, unless stated otherwise.

3. THE WISE BLAZAR STRIP

In the Wise Preliminary Source Catalog (WPSC) the [3.4]–[4.6]–[12] μm color–color diagram, drawn from high and low galactic latitude regions, shows the location of different classes of objects (Cutri et al. 2011).5

Figure 1. The [3.4]–[4.6]–[12] μm color–color diagram of Wise thermal sources and blazars. We report the 1365 blazars associated with a Wise source within a region of radius 2′4. The two blazar classes of BZBs (blue filled circles) and BZQs (red filled circles) are shown together with the blazars of uncertain type (BZUs, green filled circles). The background gray dots correspond to the 453,420 Wise thermal sources detected in a region of 56 deg² at high Galactic latitude. The isodensity curves for the Wise thermal sources, corresponding to 50, 100, 500, 2000 sources in the 56 deg² area are reported (see Section 3). The location of different classes of objects is also shown, where QSRs, ULIRGs, and LIRGs indicate the quasars, the ultraluminous infrared galaxies, and the luminous infrared galaxies, respectively. The WBS is highlighted within the two black dashed lines.

In order to put blazar populations on the same plot, we selected 14 random regions of 4 deg² each, not overlapping, for a total in 56 deg² at high Galactic latitude, within the 116 deg² considered in the WSPC (Cutri et al. 2011). Then, we collected all the 453,420 sources detected by Wise in its first year catalog (hereinafter Wise thermal sources, because they are dominated by thermal emission in the infrared), within the selected 56 deg² region, having S/N > 7 in at least one band, a conservative level for the WPSC release to emphasize catalog reliability (Cutri et al. 2011).3 Being far from the Galactic plane, the majority of these sources have extragalactic origin and only a few stars lie in the selected region.

We built a [3.4]–[4.6]–[12] μm color–color diagram using the magnitudes reported in the Wise Catalog6 for all the sources present in the 56 deg² and for all the blazars detected by Wise. We note that the relative errors for both the infrared colors are less than 0.1 for 95% of the entire blazar sample but less than 0.05 for ~85%. In Figure 1, the two subclasses of blazars and those of uncertain type are shown, overlaid to the isodensity contours for all the sources in the 56 deg² of the Wise selected area. The four levels of the isodensity contours correspond to 50, 100, 500, 2000 sources, in the 56 deg² area, respectively. Finally, in Figure 1, we also annotated the location of different classes of objects.

The main striking result is that the blazars lie in a distinct region (i.e., the WBS) of the [3.4]–[4.6]–[12] μm color–color plot with respect to the Wise thermal sources, in particular where the density of the other extragalactic sources decreases and that of the blazar population increases (see below for more details). Moreover the two main classes of BZQs and BZBs are themselves separated in two distinct regions of the WBS, where BZQs are generally redder and lie closer to the normal quasars (QSRs) and Seyfert galaxies.

In Figure 2, we consider only the BZBs distinguishing between the subclasses of HBLs and LBLs. We calculated the

5 http://wise2.ipac.caltech.edu/docs/release/prelim/preview.html

6 All Wise magnitudes are in the Vega system.
ratio between the X-ray and the radio flux $\Phi_{\text{XR}}$ for those sources with these fluxes available in the ROMA-BZCAT to distinguish between HBLs and LBLs in the above sample. We adopted a very conservative classification considering as HBLs the BZBs with $\Phi_{\text{XR}} \geq 1$ (Maselli et al. 2010) and LBLs for all the others.

All the BZBs without X-ray data available are omitted from Figure 2 because it is not possible to classify them. The BZUs have been excluded from our investigation, because of the uncertainties in their nature (Massaro et al. 2009, Massaro et al. 2010).

As many authors have pointed out, the infrared spectrum of BL Lac objects, being dominated by non-thermal emission, can be described as a power-law spectrum with index $\alpha$, that is, $S_\nu \propto \nu^{-\alpha}$ (e.g., Impey et al. 1982, Bersanelli et al. 1992). Then, different values of $\alpha$ correspond to different colors in the $\mu$ color–color diagram (Wright et al. 2010). In Figure 2, we show the line corresponding to the power-law spectrum for different $\alpha$ values, ranging between 2 and −2. It is evident that the sources in the WBS are in agreement with the path described by the power-law model, confirming the non-thermal origin of their infrared emission. There is also marginal evidence that HBLs tend to lie below the power-law line model in Figure 2 while LBLs lie above the same. This deviation could be due to a contribution of the host galaxy or to a mild curvature of the infrared spectra in the WISE bands. Such interesting effects will be investigated in more detail in a forthcoming paper (Massaro et al. 2011a).

Finally, we considered the list of HBLs detected at TeV energies (TLBs) as reported in the TeVcat,\footnote{http://tevcat.uchicago.edu/} updated on 2011 August, with $\Phi_{\text{XR}} > 1$. Only 13 TLBs are present in the sky mapped by WISE during the first year, and all of them have a counterpart in the WISE archive within a region of radius 6′.5 while this number decreases to 11 if a smaller region of radius 2′.4 is considered. We marked the TLBs in Figure 3 in order to investigate if they have a different behavior from the TeV undetected HBLs (UBLs) as found in the X-ray analysis of a subsample of the ROMA-BZCAT (Massaro et al. 2011b). We found that the TLBs are more concentrated near the center of the WBS (see Figure 3).

To highlight the separation between the WBS occupied by the BZBs in the $\mu$ color–color diagram and the region spanned by the overall distribution of WISE extragalactic sources, we have evaluated the two-dimensional densities of both populations of source using the Kernel Density Estimation (KDE) technique (Figure 4) (see, e.g., D’Abrusco et al. 2009, Laurino & D’Abrusco 2011 and reference therein). The KDE method provides an effective way of estimating the probability function of a multivariate variable and does not require any assumption about the shape of the “parent” distributions. In Figure 4, the isodensity contours drawn from the KDE density probabilities and associated with different levels of density are plotted for the two classes of sources (i.e., BZBs and WISE thermal sources). The separation between the region of higher density of the BZB distribution and that of the general WISE source distribution is evident.

In particular, the line A shown in Figure 4 has been obtained by a linear regression of the BZB density population in the $\mu$ color–color diagram, using the 95% of BZBs detected by WISE in 2′.4. It represents the main WBS axis. The second WBS axis (i.e., line B in Figure 4) displays the direction of maximum gradient of the density ratio for the distributions of the two populations (i.e., BZBs and the WISE thermal sources). The strong density gradient, visible along the line B, suggests a fairly good separation between the two distributions of BZBs and WISE thermal sources. The ratio of the BZBs’ density to the WISE thermal sources’ density increases toward its maximum (i.e., point C in Figure 4) and along the curve A, while the density of the WISE thermal sources decreases.
The separation of the WBS from the distribution of WISE thermal sources is also evident in the normalized density histograms of the distances $|D_A|$ from the line A for both populations (see the inset of Figure 4). The peak of the BZB density histogram (inset of Figure 4) suggests a strong clustering of this source population, while that of the WISE thermal sources, with a completely different shape, peaks at a significantly large distance from the axis of the WBS.

4. VER J0648+152: AN UNIDENTIFIED TeV SOURCE

The blazar position over the WBS can be used as diagnostic tool to identify extragalactic $\gamma$-ray sources. We applied this to the case of the TeV unidentified source VER J0648+152 recently discovered by VERITAS (Ong & Paneque 2010) that has been likely associated with a blazar at low galactic latitudes (Stephen et al. 2010). The blazar identification has been suggested on the basis of both the X-ray counterpart (Stephen et al. 2010) and the Fermi detection of the $\gamma$-ray source 1FGLJ0648.8+1516 within the positional error circle of 0.03 deg (Abdo et al. 2010).

We considered the positional circle of radius 108$''$ = 0.03 deg, corresponding to the error on the position of the Fermi source and we report the infrared colors for all the WISE sources over the [3.4]–[4.6]–[12] $\mu$m color–color diagram. We found that the closest WISE object (20$''$) to the Fermi position lies out of the WBS in the area of the [3.4]–[4.6]–[12] $\mu$m color–color mostly dominated by stars and elliptical galaxies. However, the second closest WISE source (29$''$) lies in the region of the WBS where the TBLs are mostly concentrated (see Figure 3), corresponding to the position of the X-ray counterpart within the error box of XMM-Newton (i.e., 7$''$2) (Stephen et al. 2010). In Figure 3, the open squares indicate all the sources associated with the VER J0648+152 unidentified object within the error box of the Fermi position, while the filled square points to the corresponding WISE source. The association of this WISE source strongly supports its blazar classification; given its position on the WBS, we suggest it is a new TBL.

5. SUMMARY AND DISCUSSION

The most striking result of our investigation is that in the [3.4]–[4.6]–[12] $\mu$m color–color diagram blazars lie in a distinct region (WBS) with respect to the other extragalactic sources. This is due to the fact that blazars are dominated by non-thermal emission, while all the other extragalactic classes of galaxies are dominated by thermal radiation at infrared frequencies. This is strongly supported by the infrared colors of the WBS that are in agreement with the power-law model for the IR spectrum of the BZBs (see also Figure 2).

A similar attempt has been previously performed using the Two Micron All Sky Survey (2MASS) archival data (e.g., Chen et al. 2005) to investigate the behavior of blazars with respect to the normal galaxies in the $J$–$H$–$K$ color–color diagram. However, our new approach has two main advantages: first, because we are using mid-IR wavelengths where the stellar photospheric contributions do not dominate galaxy colors, the blazar population covers a distinct region in the [3.4]–[4.6]–[12] $\mu$m color–color plot that separates them from the other extragalactic sources and second, because the Galactic absorption at the WISE wavelengths is negligible.

The discovery of the WBS has several implications. When the WISE data over the whole sky are available, it will be possible to place all sources over the [3.4]–[4.6]–[12] $\mu$m color–color diagram and those unidentified that lie in the WBS could be considered to be good blazar candidates. Multifrequency observations can be used to rule out this hypothesis; the task will be simplified by the good astrometric precision of WISE data.

An additional use of the regions in the WBS is that they provide a diagnostic tool for the blazar associations. As previously discussed in Section 2, in our analysis we excluded the multiple associations between a WISE source and a blazar in the ROMA-BZCAT. However, our investigation shows that if at the position of the ROMA-BZCAT source within a few arcseconds there is a corresponding source in the WBS, this could be identified and associated with the blazar.

A similar procedure could be applied to solve the problem of the unidentified $\gamma$-ray sources (see Section 4). In the $\gamma$-ray sky most of the extragalactic $\gamma$-ray sources are blazars, in particular those that are emitting at GeV–TeV energies, where the HBLs dominate. We showed the use of the WBS as a diagnostic tool for the case of VER J0648+152 recently detected at TeV energies by VERITAS (Ong & Paneque 2010), and already present in the first year Fermi catalog (Abdo et al. 2010). Our analysis of the infrared colors for all the WISE sources in the Fermi positional error circle strongly support its blazar classification (Stephen et al. 2010). Its position on the WBS suggests that VER J0648+152 is a new TBL.

Finally, we note that the region of the WBS covered by the TBLs is well defined. Thus when WISE data are released this region could be used to identify new TeV candidates for future observations. A more accurate analysis on the possible use and developments of the WBS as a diagnostic tool for classifying blazars as well as the unidentified $\gamma$-ray sources will be presented in more detail in a forthcoming paper (D’Abrusco et al. 2011, Massaro et al. 2011a).

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