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IDENTIFYING TEV BLAZAR SOURCES USING WISE COLOR-COLOR DATA

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ABSTRACT

We present a method using *Wide-field Infrared Survey Explorer* (WISE) data to perform an all-sky survey which efficiently identifies high-frequency-peaked BL Lacertae (HBL) objects. Due to their entirely non-thermal beamed emission, blazars are found to lie in a strip (the WISE blazar strip, or WBS) when plotted in a WISE color-color diagram. This method is also used to identify infrared companions to gamma-ray emitting objects found in *Fermi*-LAT surveys, which can be used to reduce positional uncertainty by up to two orders of magnitude and can further aid in the identification of the source. The scientific applications of a HBL survey are discussed using the specific examples of extragalactic background light (EBL) and extragalactic magnetic fields (EGMF).

Key words: BL Lacertae objects: general – galaxies: active – gamma rays: galaxies

1. INTRODUCTION

Blazars are some of the most energetic and rapidly variable objects in the universe. The prototype object, BL Lacertae (BL Lac hereafter), was originally identified via optical observations in the 1920's as a variable star in the constellation of Lacerta. Its true nature wasn't revealed until it was identified as the optical counterpart to the radio source VRO 42.22.01 (Schmitt 1968). At that time, BL Lac was already known to be highly variable in the visual band, with an apparent magnitude varying from 13 to 16 within a period of a few days. The combination of rapid optical variability with polarized radio emission and an unusual radio spectrum garnered BL Lac considerable attention as a highly unusual object. Further optical observations the following year (DuPuy et al. 1969) revealed a continuous optical spectrum devoid of emission or absorption lines, which was in contrast to the behavior observed in other types of quasi-stellar objects known at that time (Oke 1967). These results were extended by Visvanathan (1969), who showed that the optical continuum was also strongly polarized and very likely a continuation of the polarized radio continuum. This was strong evidence that non-thermal synchrotron emission was responsible for both the radio and optical emission. Many similar objects were soon discovered (Strittmatter et al. 1972), and BL Lac became the archetype of an entirely new class of astronomical objects.

A revolution in our understanding of BL Lac objects occurred with the introduction of the concept of relativistic jets. Jet-like structures had been known to exist in association with M87 for quite some time (Curtis 1918; Rees 1978), but it wasn't until the seminal paper by Blandford and Königl (1979) that relativistic jets were fully associated with active galactic nuclei (AGN). A major motivation for the introduction of relativistic jets was that the synchrotron brightness temperatures of some luminous objects were found to be on the order of 10^{15} K. It had been previously predicted that when the synchrotron brightness temperature exceeded 10^{12} K, rapid cooling would occur via inverse-Compton scattering – the so-called "inverse-Compton catastrophe" (Kellermann & Pauliny-Toth 1969). This embarrassing state of affairs was avoided by means of special relativistic Doppler beaming, which can make a source appear several orders of magnitude brighter when the relativistic jet is aligned with the observer's line of sight. The Doppler beaming also provides a convenient explanation for why no counter-jet is typically observed. In addition to adding the now canonical concept of jets to our understanding of AGN, Blandford and Königl's paper also revolutionized our understanding of BL Lac objects by making the following predictions: the flux and polarization angle should both exhibit rapid variability; the lack of observed emission and absorption lines in the spectra of BL Lac objects is likely due to the beamed non-thermal continuum completely outshining the thermal contribution; that BL Lac objects be identified as AGN embedded in elliptical galaxies; and that BL Lacs and other types of quasars, particularly optically-violent variables (OVVs), are all essentially the same thing (collectively called blazars), differing only in the angle between the emission axis of the jet and the observer's line of sight. These predictions have all borne out and form the basis of our current understanding of BL Lac objects.

As with the rest of astronomy, our understanding of blazars has evolved dramatically as new electromagnetic windows have been opened for exploration by the creation of new technologies and observatories. BL Lac objects are not easily identifiable using optical measurements alone, which is why, for instance, BL Lacertae was originally mistaken for a variable star. As with BL Lacertae itself, radio observations are key to identifying BL Lac objects. Later on, X-ray astronomy would prove to be another powerful tool for finding and identifying BL Lac objects. BL Lacs appear as bright and highly-variable sources in X-rays (Mushotzky et al. 1978) so that BL Lacs could be selected using X-ray measurements only, independent of radio measurements. This would lead to a distinction between radio-selected and X-ray selected BL Lacs. Surprisingly, it was later found that the spectral energy distributions (SEDs) of X-ray selected BL Lacs were intrinsically different than those of radio-selected BL Lacs. Later multi-wavelength campaigns would measure the SEDs of BL Lacs (see,

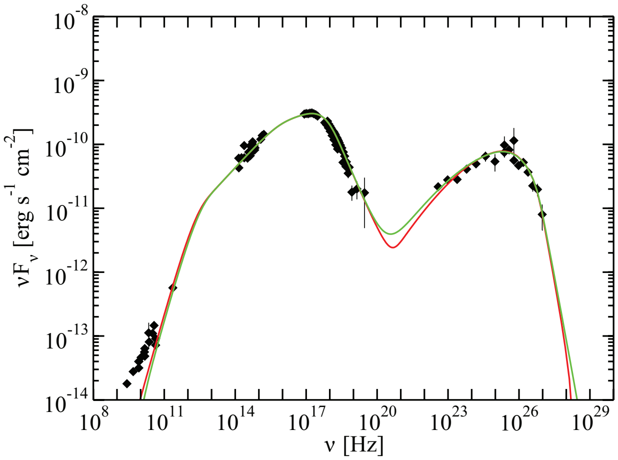

Figure 1. Multi-wavelength spectral energy distribution (SED) of Markarian 421, extending from radio up to VHE, exhibiting the characteristic double-bump spectrum of blazars. The two continuous lines are synchrotron self-compton (SSC) fits for time variability scales of 1 day (red curve) and 1 hour (green curve). Figure from Abdo et al. (2011).

e.g., Abdo et al. (2011)) and would reveal a characteristic double-peaked spectrum (Figure 1) with a lower-frequency synchrotron peak and a higher-frequency peak that is thought to be the result of either inverse-Compton up-scattering or hadronic emission, or some combination of the two. The apparent difference between radio-selected and X-ray selected BL Lacs is now known to result from the location of the lower-energy synchrotron peak in frequency space: radio-selected BL Lacs typically exhibit a synchrotron peak in the IR-Optical bands, whereas X-ray selected BL Lacs typically peak in the UV or X-ray bands. This would lead to the reclassification of radio-selected BL Lacs as low-freqency-peaked BL Lacs (LBLs) and X-ray selected BL Lacs as high-frequency-peaked BL Lacs (HBLs). An additional class of blazars which are considered distinct from BL Lacs, flat-spectrum radio quasars (FSRQs), typically have their synchrotron peaks at even lower frequencies than LBLs and are more likely to exhibit emission lines (Massaro et al. 2011).

In this paper, we will focus on gamma-ray emission from blazars, and specifically emphasize the very high energy (VHE) window which includes TeV gamma-rays. Although gamma-ray astronomy has been in development since the 1960's—see Weekes (1988) for a good review—it wasnt until the launch of the European gamma-ray satellite COS-B that a blazar (FSRQ) was detected in gamma-rays (Swanenburg et al. 1978). The Challenger disaster in 1986 and the subsequent moratorium on US space missions and the failure of the Gamma-1 telescope on the Soviet Gamma satellite resulted in little progress during the 1980's (Weekes 1992). The 1990's saw the launch of the *Compton Gamma Ray Observatory* (CGRO), which operated in the 20 keV − 30 GeV band, and the maturation of ground-based imaging atmospheric Cherenkov telescopes (IACTs), which are typically sensitive in the ∼100 GeV − 10 TeV regime. The blazar Markarian 421 was first observed by the Whipple and HEGRA collaborations (Punch et al. 1992; Petry et al. 1996), being only the second TeV source detected (after the Crab) at $> 5\,\sigma$. The detection of Markarian 421 by CGRO was published shortly thereafter (Lin et al. 1992). An all sky survey taken with CGRO's EGRET instrument later found that most of the extragalactic gamma-ray emitting sources in the sky are blazars. Moreover, it was discovered that most of the power output of blazars is emitted in the form of gamma-rays (Fichtel 1994). As noted in a survey of the development of blazar gamma-ray astronomy by Weekes (2003), had gamma-ray observatories existed earlier, it is likely that blazars would be considered primarily as gamma-ray emitters.

An interesting use of TeV-emitting blazars is as probes of the extragalactic background light (EBL), as done by Orr et al. (2011). The EBL is not a truly diffuse radiation field like the cosmic microwave background (CMB), but is instead the accumulation of infrared light from numerous unresolved point sources. The spectral energy distribution of the EBL is thought to be bimodal (see Figure 2), with a peak at $\sim 1\,\mu$m which is thought to be due to star formation and active galactic nuclei (AGN) accretion, and a peak at $\sim 100\,\mu$m which is thought to be re-radiated emission from dust. Unfortunately, measuring the EBL directly is difficult since practically everything emits IR radiation as heat and it is difficult to subtract out foreground contributions from the detector and telescope, as well dust contributions from the solar system and Milky Way. Although several novel methods for measuring the EBL indirectly exist, one of the most promising is to use photon-photon collisions of TeV gamma-rays from distant, hard-spectrum blazars with the EBL. The maximum cross section for the interaction of a gamma-ray with an infrared EBL photon is

$$\epsilon_{IR} \sim \frac{2(m_e c^2)^2}{E_\gamma} = 0.5 \left(\frac{1\ TeV}{E_\gamma} \right) eV$$

Therefore, attenuation of gamma-rays by the EBL does not become important until gamma-ray energies exceed $\gtrsim$ 0.5 TeV. If the spectrum of a blazar source can be measured from the GeV up to several TeV, the effects of attenuation by the EBL will be seen as either a deviation from an assumed power-law spectrum which is measured in the GeV range and extrapolated to the TeV, or as a spectral break in a broken power-law model which occurs at $\sim$1 TeV. This procedure was used in Orr et al. (2011)

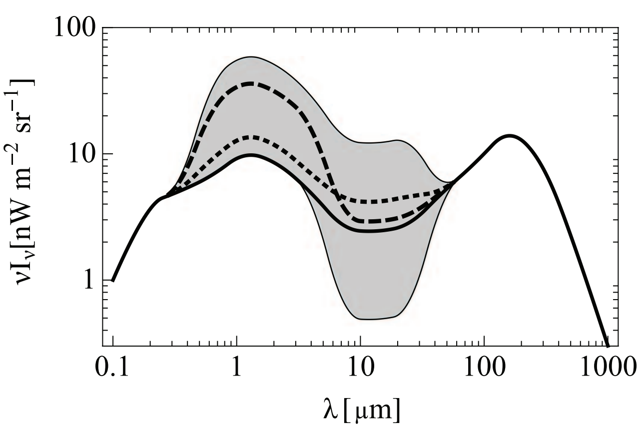

Figure 2. Plot of EBL intensity vs. wavelength. Shaded region indicates parameter space of Orr, Krennrich, and Dwek's model. The EBL is thought to be double peaked at $\sim 1\,\mu$m and $\sim 100\,\mu$m. Figure taken from Orr et al. (2011).

to provide some of the tightest constraints on the EBL to date.

In a closely related vein, TeV-emitting blazars are useful for investigating extragalactic magnetic fields (EGMF). As noted above, gamma-rays with energies $\gtrsim 1$ TeV can interact with the EBL, creating electron-positron pairs. These charged particles can then be deflected by the EGMF while traveling some distance before perhaps being annihilated into a new high-energy photon. This process may happen more than once on the way from the source to the observer, as shown schematically in Figure 3. An interesting consequence of this behavior is that if the EGMF has a magnetic field strength between $10^{-16} - 10^{-10}$ G, it is predicted that observations of point-like blazars will also be accompanied by a halo of high-energy gamma-rays around the point source. As is discussed in Dolag et al. (2009), the opening angle of this halo can be used to infer the average strength of the EGMF. Should the EGMF be weaker than 10^{-16} G, the EGMF will not deflect the electron-positron pairs sufficiently to form a halo. Should the EGMF be stronger that 10^{-10} G, the electron-positron pairs will be deflected too much, and the halo will be blurred to the point where it is undetectable. It should be noted that this scheme strongly depends on acquiring sufficient photon counts to resolve the halo, which is difficult given the relative low count-rates of gamma-ray astronomy (1 count/minute is not an uncommon count rate). Likewise, this strategy also requires nearby blazars that are very luminous at high-energies. However, it is hypothesized that the current generation of IACTs, or perhaps the next generation, should have sufficient sensitivity to detect these blazar halos if sufficient observing time is allotted, making the prospect of investigating the EGMF in this way particularly intriguing.

In this paper we present a strategy for identifying new HBLs using data from the *Wide-field Infrared Survey Explorer* (WISE) mission. Using the preliminary data release of WISE, it has been shown (Massaro et al. 2011) that blazars tend to lie along a strip when plotted in a color-color diagram. We follow a similar process using the full WISE data release and verify that this is indeed the case. We then show that the infrared data from WISE can be used to efficiently select HBLs from all other types of WISE sources. Noting that EBL measurements require distant blazars with hard VHE spectra, and EGMF measurements require nearby blazars that are very luminous at higher energies, it is clear that a variety of HBLs at varying redshifts and with hard spectra are needed. Since the infrared data from WISE are only loosely correlated with the TeV behavior of these HBLs, surveying HBLs in this manner should provide a good sample of HBLs to be used in a myriad of interesting scientific studies, including those presented here. We also show that WISE data can be used to help identify blazars in all-sky gamma-ray surveys done by *Fermi* and can be used to fix the position of these sources to an accuracy of $\sim$1", two orders of magnitude better than the angular resolution of *Fermi*.

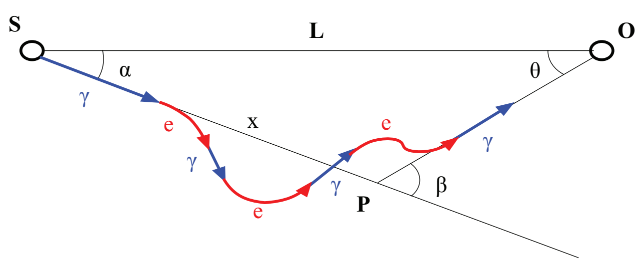

Figure 3. Schematic of blazar-halo creation due to scattering off of the EGMF. Source blazar emits a gamma-ray at an angle α to the line of sight between the source and observer. This gamma-ray can interact with the EBL, creating a photon positron-pair, which can then be deflected by the EGMF. The charged particles can then annihilate to create a new gamma-ray. This process may happen several times before the final gamma-ray reaches the observer, creating a halo around the blazar point source with an opening angle θ. Figure taken from Dolag et al. (2009).

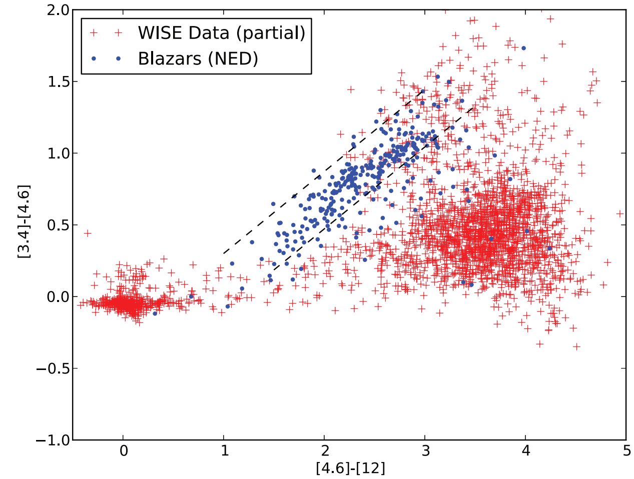

Figure 4. The [3.4]-[4.6]-[12] μm color-color diagram of WISE sources and blazars. The WISE data (red crosses) are taken from a 4 deg^2 area of the sky and used as reference for the blazars (blue filled circles). It is seen that the blazars tend to fall along a strip known as the WISE Blazar Strip (WBS).

2. METHODOLOGY

Using the positions of all known blazars in the NASA/IPAC Extragalactic Database (NED), ROMA-BZCAT, HEASARC-ROXA, and TeVCat, we searched for positional coincidences in the WISE data within a positional error of 2.4". This choice of positional error comes from a combination of the 1" error in ROMA-BZCAT, which is our largest set of data, and an error in position of 1.4" for the 22 μm band from WISE. We also only considered sources in WISE with a minimum signal-to-noise ratio (S/N) of 7 in at least one band. All cross-matches between catalogs are excluded as well as any sources for which there are multiple objects within the given positional error. From a total of 1965 sources, it is found that 1596 sources are found in the WISE catalog within the positional error. We consider only these sources in the analysis and discussion for the rest of this paper.

The [3.4]-[4.6]-[12] μm color-color diagram can be used to differentiate between classes of objects by their position on the diagram (Wright et al. 2010). We have constructed a color-color diagram from the magnitudes in the WISE data for all sources within a random 4 deg^2 region of the sky as well as all known blazar sources (Figure 4). In Figure 4, the known blazars in WISE (from NED) are overlaid on the thermal sources from this random patch of sky in WISE for comparison. It is imme-

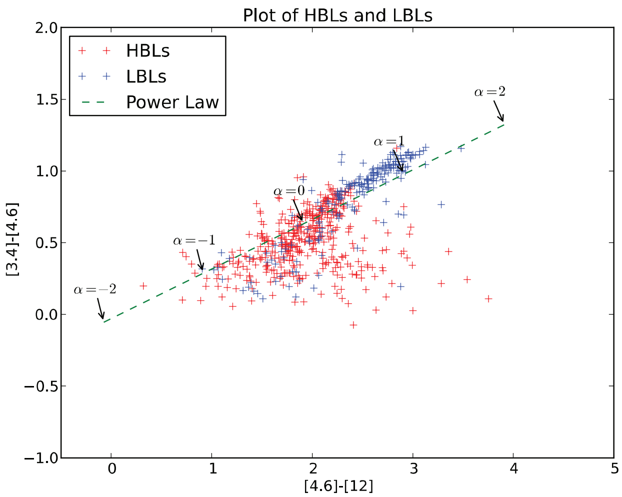

Figure 5. Results when plotting a power law in the color-color diagram. The dashed line corresponds to an IR non-thermal power law spectrum with index ranging from -2 to 2. The HBLs (red crosses) and LBLs (blue crosses) are also plotted and seem to fall mostly along the line.

diately evident that blazars tend to populate a distinct region of the diagram that we call the WISE blazar strip (WBS).

It is thought that this separation of blazars from other WISE sources is due to the blazars' non-thermal emission versus the other WISE sources' thermal emission (Massaro et al. 2011). In the WISE bands, the non-thermal emission from blazars comes from synchrotron radiation and will follow a power law, $S_\nu \sim \nu^{-\alpha}$, where different values of the index α correspond to different colors on the diagram. A derivation of this relation can be found in the following section. Figure 5 shows the line corresponding to different values of α, and it is evident that the blazar sources in the WBS lie near this line. This seems to confirm the non-thermal versus thermal emission distinction as the cause of blazars lying in this separated region of the color-color diagrams.

3. DERIVATION OF POWER LAW FOR COLOR-COLOR DIAGRAM

The infrared spectrum of BL Lac objects is dominated by non-thermal emission and thus can be described by a power law spectrum, $S_\nu \propto \nu^{-\alpha}$, with index α. Different values of α correspond to different colors in the WISE color-color diagram. A brief derivation to show this relation is given below.

Start with the relation for flux and apparent magnitude,

$$m_\nu - m_{\nu,0} = -2.5\log_{10}\left(\frac{S_\nu}{S_{\nu,0}}\right), \quad (1)$$

where $m_{\nu,0}$ and $S_{\nu,0}$ are the reference magnitude and flux for the ν frequency band, respectively. From this one finds that the color for two bands, ν and ν', is given by,

$$m_\nu - m_{\nu'} = \alpha 2.5\log_{10}\left(\frac{\lambda'}{\lambda}\right) + 2.5\log_{10}\left(\frac{S_{\nu,0}}{S_{\nu',0}}\right), \quad (2)$$

where λ is the wavelength for the corresponding frequency band, ν. The reference fluxes given by Wright et al. (2010) correspond to magnitude zero points and have values of $306.681, 170.663$, and 29.0448Jy for the [3.4],[4.6], and [12]μm bands, respectively. Thus α, being the only free variable, parameterizes a line on the WISE color-color diagram, as shown in Fig. 5.

4. RESULTS AND DISCUSSION

In taking a closer look at the color-color diagram, it is seen that the different classes of blazars tend to lie along different parts of the WBS. In Figure 6 we see that FSRQs overlap with the region occupied by the quasars and Seyferts.

The BL Lacs, however, seem to occupy a region that is well separated from other sources. Looking closer still, one can see that in Figure 5 the HBLs and LBLs tend toward different areas of the diagram with HBLs remaining well separated from thermal sources. Further investigation shows that in Figure 7, BL Lac objects identified as TeV sources (TBLs) lie very near the center of the WBS. It is this feature that could prove useful in identifying new TeV blazars.

It is now important to note that in Figure 5, the HBLs and LBLs are classified in a somewhat dubious manner. We calculate Φ_{XR} the ratio between the X-ray flux and the radio flux using the given values for sources in the ROMA-BZCAT. Using the criterion given by Maselli et al. (2010), HBLs are classified as having a $\Phi_{XR} \geq 1$ and the rest are classified as LBLs. This is a very conservative approach since Φ_{XR} is expected to be much less than unity for LBLs (Massaro et al. 2011), but it may still incorrectly classify some HBLs as LBLs. The criterion hinges on the supposition that all HBLs emit much more strongly in X-rays than radio and that the opposite is true for LBLs. For most sources, this seems to be true (Maselli et al. 2010).

By plotting all of the WISE data on the color-color diagram, one could identify good TeV blazar candidates by determining if the source lies in the WBS. In doing this, the number of known blazars increases and further observations in other frequency bands can be done to

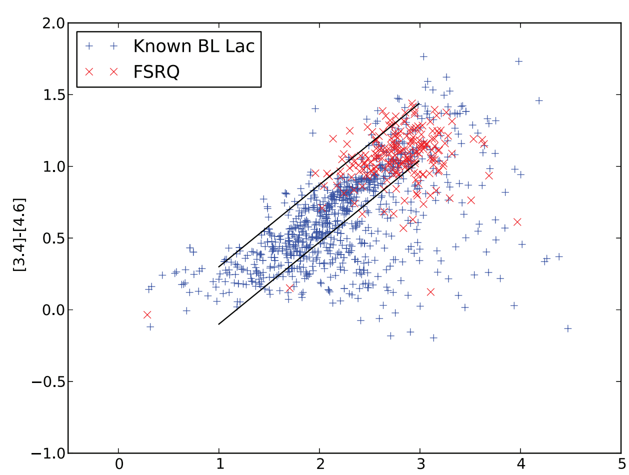

Figure 6. Blazar population is plotted and shown to separate according to type. Blue crosses are BL Lac objects and tend toward the center of the WBS. Red crosses are the Flat-Spectrum Radio Quasars (FSRQs) and tend to occupy the same regions as QSOs and Seyferts.

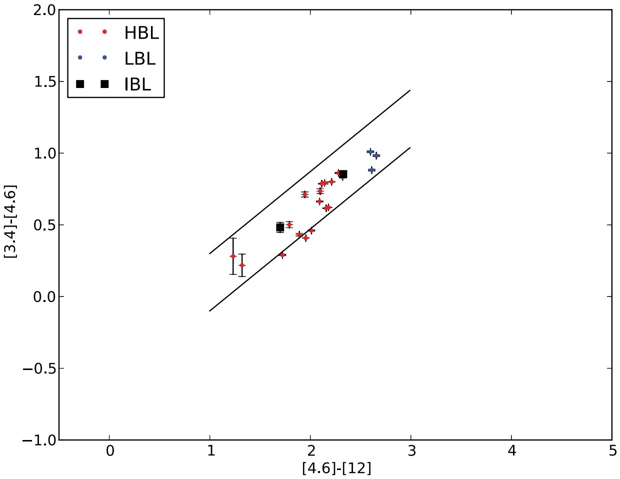

Figure 7. Sources found within TeVCat. HBLs (red crosses), LBLs (blue crosses) and the intermediate BL Lacs (IBLs, black boxes), all lie within the WBS.

confirm the blazar designation. By increasing the number of known observable blazars, one can hope to further constrain models of the relativistic jets as well as providing more sources with which to study blazar-related cosmological theories (quantum gravity, Lorentz invariance, etc.).

5. AN EXAMPLE: UNIDENTIFIED TEV SOURCE

Positions of blazars in the WBS may be used as a means to identify extragalactic γ-ray sources. We show a proof of concept in the case of VER J0648+12, a TeV unidentified source discovered by VERITAS that is likely associated with a blazar (Stephen et al. 2010). This possible identification is suggested by both the X-ray counterpart (Stephen et al. 2010) and the *Fermi* detection of a γ-ray source 1FGL J0648.8+1516 within the positional error of 108” (Abdo et al. 2010).

Using the positional circle of 108” corresponding to the positional error of the *Fermi* source, we plot all WISE sources within this circle using the [3.4]-[4.6]-[12] μm color-color diagram. It is found that the closest object, which lies ∼20” from the *Fermi* position, falls well outside the WBS (Figure 8). From Figure 8, one can see that the fifth closest source lies firmly within the WBS and is the only source within the WBS. It is found that this source has an X-ray counterpart detected with *XMM-Newton* with an error box of 7.2”. It is the only WISE source found within the *XMM-Newton* positional error box. This source also falls within the 50” error circle given by VERITAS. This association strongly supports its blazar classification and based on it being a TeV source, this suggests it may be a new TBL.

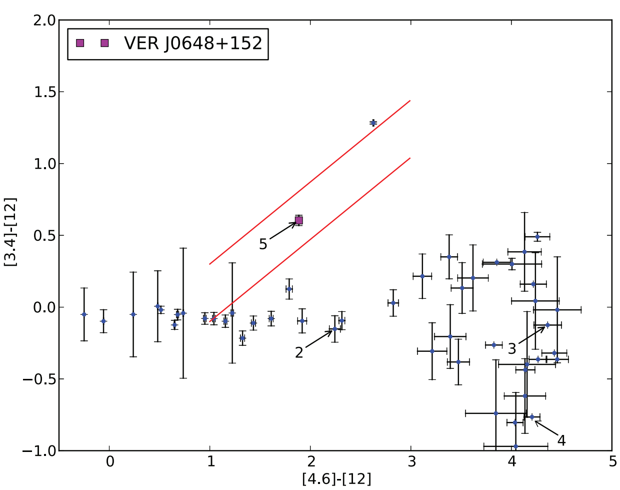

Figure 8. WISE sources found within 108” of the *Fermi* source 1FGL J0648.8+1516. Numbering indicates proximity to reported position of *Fermi* source. The purple box corresponds to the X-ray counterpart of the source as reported by *XMM-Newton* (7.2”).

6. CONCLUSIONS

In this paper, we have discussed how to leverage our understanding of the non-thermal emission from blazars at infrared frequencies to identify blazars with hard spectra with emission extending to TeV energies. The surprising result, originally discovered by Massaro et al. (2011), is that blazars lie in a strip on a WISE color-color diagram, the WISE blazar strip (WBS), which is well isolated from other types of sources. Moreover, the WBS can be further partitioned in such a way that efficiently selects high-frequency-peaked BL Lacs (HBLs) from all other types of sources. Given that the WISE dataset has deep all-sky coverage, this technique can efficiently generate a large set of potential HBLs which can be further investigated with instruments at other wavelengths. In particular, given that the infrared synchrotron emission component is related to the harder inverse-Compton component in a non-trivial way, the method discussed in this paper may allow the discovery of a host of hard-spectrum HBLs at a variety of redshifts. These hard-spectrum HBLs are extremely useful for investigating a variety of interesting scientific questions, such as measuring the strength of the extragalactic background light (EBL) and probing extragalactic magnetic fields (EGMFs), which were discussed earlier.

In order to fully utilize the WBS identification technique, it would be highly desirable to develop an automated method that would accept the coordinates of an arbitrary object as an input and return the most likely classification of that object with some confidence value. In principle, this should be a relatively straightforward application of the WBS technique, but in practice generating a rigorous, unbiased multi-variate statistical test is likely to prove extremely challenging. A promising idea, which is also hinted at in Massaro et al. (2011), is to use kernel density estimation (KDE) to model the non-trivial probability distribution function of blazars in WISE color-color space. This type of technique may prove to be very useful for assisting in the classification of unknown gamma-ray emitting objects found in surveys as discussed above.

Finally, a preliminary analysis of the potential of the WBS as a tool for locating new HBLs has been performed. This analysis used the WISE all-sky catalog to look at all sources in a RA band of 0–5 degrees, which contains ∼7.8 million sources. This analysis indicated that the WBS finds HBLs in a 1:11,000 ratio to all other types of WISE sources, which when extrapolated over the entire sky yields a total of ∼52,000 potential HBLs. This is more than an order of magnitude increase over the 1,596 HBLs currently listed in the ROMA-BZCAT.

Therefore, it seems likely that the WBS could be used to find a significant number of new HBLs, although it would be prudent to investigate additional cuts—particularly using multi-wavelength data—to reduce the potential number of false positives.

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