The 2WHSP catalog of VHE blazars

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Blzars are extremely important for GeV-TeV astronomy; however, the number of cataloged blazars are still small relative to other AGNs. Thus, we built a HSP blazar catalog based on multi-frequency selection criteria, listing the most complete HSP blazar catalog (2WHSP) up to date. We cross-match all available radio, IR, and X-ray data, selecting only sources with Synchrotron peak larger than 10^{15}Hz. In total the 2WHSP catalog includes 1695 objects, which are promising candidates for future high energy surveys.

Keywords: Galaxies: active; BL Lacertae objects: general; radiation mechanisms: non-thermal; gamma rays: galaxies.

1. Introduction

High Synchrotron peaked BL Lac objects (HSPs) are a group of blazars characterized by the largest energy peaks, both in the synchrotron and the inverse Compton component, this last extending to γ-ray and VHE. Most of the extragalactic VHE-detected objects are HSPs (TeVCat[a]); however, the number of known HSPs is still relatively small with only around 1000 cataloged HSPs till now (See Ref. 1, 3). In this work, we cross-matched the multi-wavelength data (Infrared, radio, and X-ray), and applied a selection criteria based on the flux density slope between different energy bands: Radio to IR and IR to X-rays. We examined the SED of each candidate to select genuine HSPs in order to build an HSP catalog (2WHSP) containing over 1500 blazars expected to emit at VHE energies. The 2WHSP catalog is an extension of the 1WHSP catalog (See Ref. 1) to the Galactic latitude $|b| > 10°$, and uses less stringent color-color requirements in the IR. This catalog includes previously known sources, newly discovery blazars, and candidate blazars.

2. Data Selection and Cross-matching

Since blazars are detected from radio to X-ray and even γ-ray, we began with collecting almost all available radio and X-ray and then cross-matched them with AllWISE Infrared catalog, with the help of TOPCAT[b]. According to the position

[a] http://tevcat.uchicago.edu
[b] http://www.star.bris.ac.uk/ mbt/topcat/

errors of each target, we used 0.3 arcmin for NVSS and SUMSS, and we used 0.1 arcmin for FIRST; the position from NVSS and SUMSS are not as precise as FIRST. We then cross-matched the available radio catalogs with the AllWISE and get the IR-radio matched data. The cross-match radius we used here is same as in the first step. The reason we start by cross-matching the radio with IR catalogs is that the observed position for these two wavelengths is generally better than X-ray.

We cross-matched the IR-radio subsample with each X-ray catalog individually according to its maximum position error. Some X-ray catalogs have very wide range of positional uncertainties, thus we separated the data by position errors and used different cross-matched radii for these X-ray catalogs. The radii of cross-matching IR-radio matched data with each X-ray catalog are shown in Table 1. After we cross-matched the X-ray catalogs, we combined all the IR-radio-X-ray matched data and applied an internal cross-match keeping only single sources within 0.1 arcmin radius.

Table 1. The cross-matched radii of X-ray catalogs

Catalog	Error position	Cross-matched radius
RASS	0-36 arcsec	0.6 arcmin
	>37 arcsec	0.8 arcmin
Swift 1SWXRT	0-5 arcsec	0.1arcmin
	>5 arcsec	0.2 arcmin
Swift deep XRT GRB	all data	0.2 arcmin
3XMM DR4	0-5 arcsec	0.1 arcmin
	>5 arcsec	0.2 arcmin
XMM Slew DR6	all data	10 arcsec
Einstein IPC	all data	40 arcsec
IPC Slew	all data	1.2 arcmin
WGACAT2	all data	50 arcsec
Chandra	all data	0.1 arcmin
BMW	all data	0.15 arcmin

3. Flux Density Slopes

Next, we used the slope criteria which are obtained from studying the characteristic shape of the SEDs of well-known bright HSPs to clean our sample (see Fig. 1). According to the shape of the SED of typical HSPs, we used two criteria in 1WHSP paper to select our sample. We also restricted the sample by Galactic latitude $|b| > 10°$ to avoid the influence from galactic plane. In the end, the final sample of HSP-candidates includes 5518 pre-selection targets, and 922 of them are also in 1WHSP catalog. The two criteria applied for 1WHSP paper and are listed in Eq. 1.

$$\begin{aligned} 0.05 < \alpha_{1.4GHz-3.4\mu m} < 0.45 \\ 0.4 < \alpha_{4.6\mu m-1keV} < 1.1 \end{aligned} \quad (1)$$

where $\alpha_{\nu 1-\nu 2} = -\frac{\log(f_{\nu 1}/f_{\nu 2})}{\log(\nu_1/\nu_2)}$.

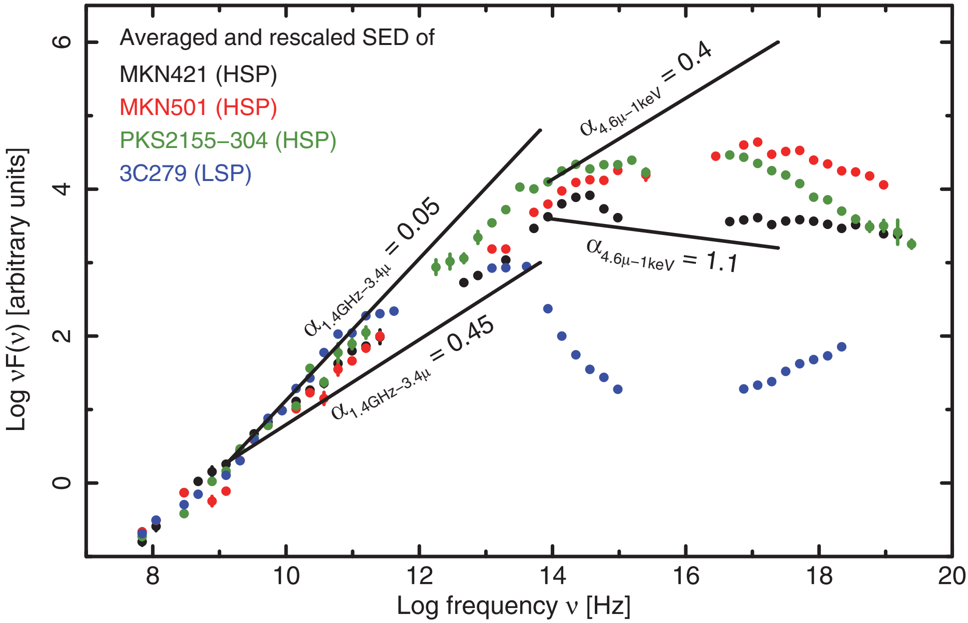

Fig. 1. Slope criteria (Arsioli et al. 2015). Average and rescaled to 10^{10} Hz SEDs of three well-known and representative HSP blazars: MKN 421, MKN 501, and PKS 2155−3304, and one LSP, 3C279. The solid lines represent the radio to infrared and infrared to X-ray slope limits used in our selection criteria, which are highly effective in differentiating HSP- from LSP-like SEDs.

4. Example Selected SEDs

We used ASDC SED builder tool[c] to examine 5518 targets one by one to select the HSP using multi-wavelength analysis. We fitted the synchrotron peak of each target and accepted the source if the peak located at the frequency $> 10^{15}$ Hz (See Ref. 4). Fig. 2 and Fig. 3 are the example SEDs of the HSPs we selected to 2WHSP catalog. With the optical spectra, these two targets are believed to be HSPs. Note that we lost some good HSPs/candidates (around 40) due to the slope criteria. To fix this problem, we add 45 2FGL sources and 4 TeVCat sources directly to the catalog.

There are some HSPs whose host galaxies are strong enough to be seen in the SEDs or the non-thermal components are not so strong to embed the host galaxies; such as the SED shown in Fig. 3. Thus another different between 1WHSP and 2WHSP is that we did not use the Infrared criterion $-1.0 < \alpha_{3.4\mu m-12.0\mu m} < 0.7$ to cut off our sample. By doing so, we obtain more targets and avoid the limitation of loosing good candidates due to the IR contamination with the host galaxy light.

[c]http://tools.asdc.asi.it/SED/

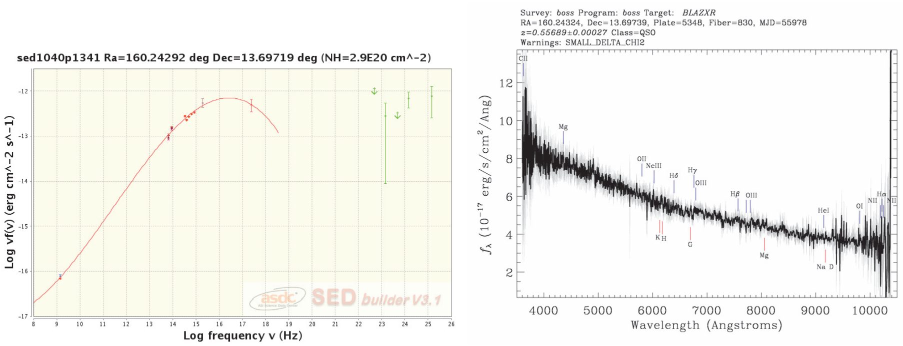

Fig. 2. The SED and optical spectrum of 2WHSP J104058.38+134150.6. From the SED, we know that the non-thermal is very clear and this target also has the Fermi counterpart. The host galaxy is swamped by the non-thermal emission.

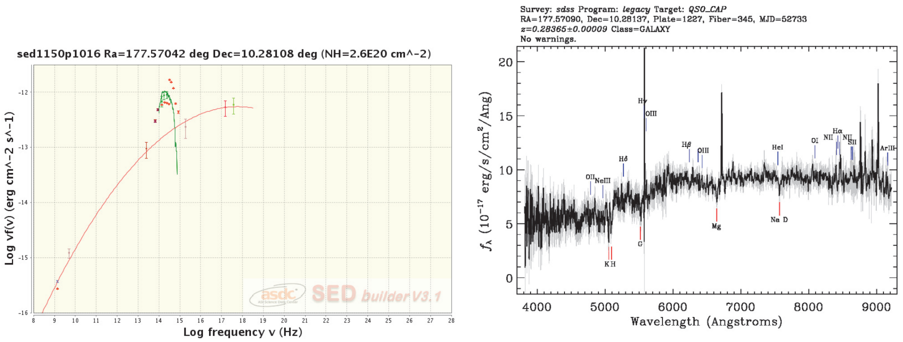

Fig. 3. The SED and optical spectrum of 2WHSP 115017.01+101652.9. We can easily see the host galaxy (the green line) in this SED, but the non-thermal contribution also is very strong. No γ-ray counterpart has been found yet.

Besides, 12.0 μm observation (W3 band) from AllWISE catalog sometimes has bad signal to noise ratio. However, the drawback is that some of the selected targets in 2WHSP are dominated by host galaxies and we found many sample targets are located in cluster of galaxies.

5. Results and Discussion

In the end, the 2WHSP catalog has 1695 sources in total and comprises 290 new identified HSPs, 540 previously known HSPs, 816 HSP candidates, 45 2FHL sources, and 4 TeV sources. Arsioli et al. (2016) (See Ref. 2) analyzed the *Fermi* 7-yrs Pass 8 data with the position of 2WHSP sources and they found around 170 new γ-ray identifications. Fig. 4 shows two of the new identifications, with their multi-frequency SED showing the γ-ray spectrum together with *Fermi* sensitivity. Both sources were selected as promising γ-ray candidates, and indeed they were identified in the 0.3-500GeV band with $> 5\sigma$ level when considering 7 yrs of Fermi-LAT exposure. From the SED, it is obviously that the green new γ-ray data are consistent with the other waveband data. Furthermore, the sources may be detected by CTA in future since it is above the CTA sensitivity for exposure time 50 hours (the blue lines). The positions of HSP blazars therefore is proof to be a good seed for exploring γ-ray and VHE sources.

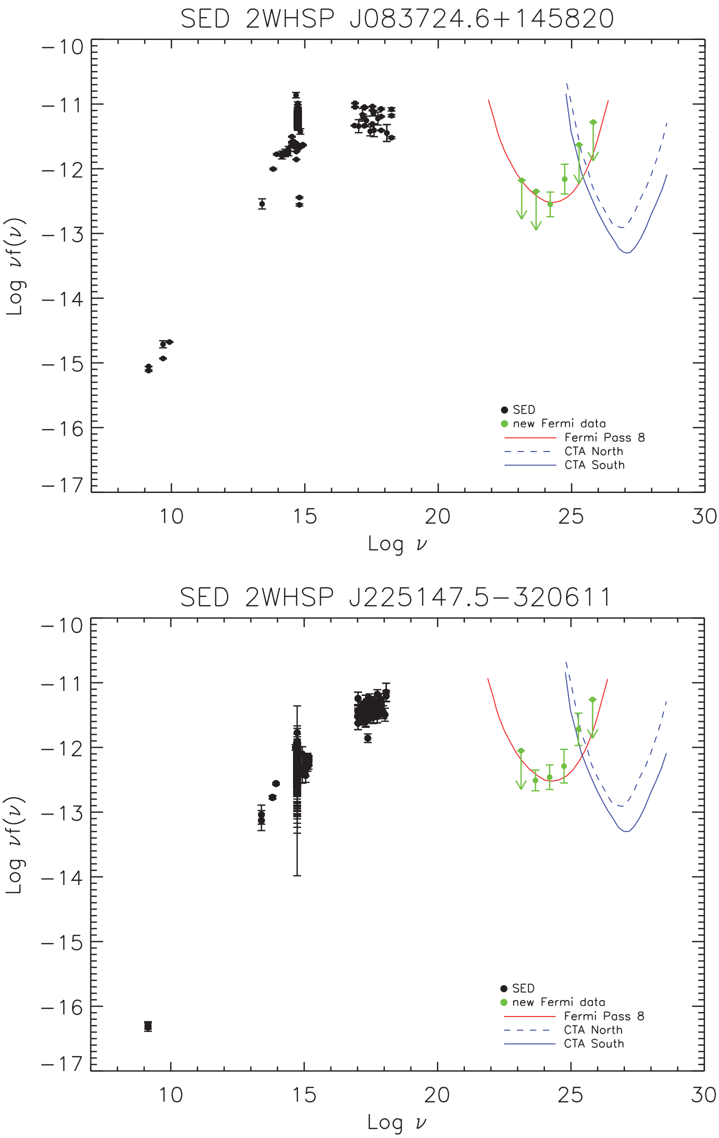

Fig. 4. The The VHE observations candidates. 2WHSP J083724.6+145820 and 2WHSP J225147.5-320611.

6. Conclusions

Since HSPs are the dominant extragalactic population in the VHE energy sky, the 2WHSP catalog provides promising targets for observations in the VHE band. We have selected a total of 1695 targets including previously known, newly discovered, and candidate blazars. There are many examples of HSPs with synchrotron component well characterised along radio to X-rays, but not yet detected in the GeV-TeV energy band: 2WHSP 115017.01+101652.9, 2WHSP J083724.6+145820, and 2WHSP J225147.5-320611. Those are good seeds for a direct search of γ-ray signatures within *Fermi*-LAT data. Indeed, Arsioli et al. (2016) (See Ref. 2) has already identified ≈150 new GeV γ-ray counterparts when integrating over 7 years of Fermi observations. Later with better instruments like CTA, we may find the VHE counterpart of these source as well.

Acknowledgments

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