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Unbiased survey of high-frequency-peaked BL Lacs with VERITAS

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High-frequency-peaked BL Lacs (HBLs) are the dominant population of extragalactic sources at TeV energies, with more than 50 detected by ground-based TeV gamma-ray observatories. Between 2019 and 2022, the VERITAS observatory has conducted a campaign to observe a flux-limited sample of 36 X-ray selected HBLs in order to produce the first unbiased survey of TeV emission from HBL blazars. The VERITAS HBL sample includes 21 known TeV sources and 15 blazars which do not yet have reported TeV emission. The goal of these observations is to find unbiased estimates of the TeV flux of HBLs, which are generally only reported in their flaring states, and to detect new TeV blazars which have not previously been observed. Analysis of 25 out of 36 blazars in the sample has been completed, and two have been detected with significance above 5σ. This work presents detailed results of three sources and compares them to previously published work, as well as presenting overall results of the survey sample.

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1. Introduction

Blazars, which are active galactic nuclei with jets aligned with the observer's line of sight, emit radiation across the electromagnetic spectrum from low-frequency radio up to very-high-energy (VHE) gamma rays. The spectral energy distributions (SEDs) of blazars show two distinctive humps, and the location of the lower energy peak is used to classify BL Lacs into low, intermediate, and high-frequency-peaked subcategories [1]. High-frequency-peaked BL Lacs (HBLs) have their lower-energy peak in the UV to X-ray range, above 10^{15} Hz. Since this low-energy peak is well established to come from synchrotron emission, HBLs are sometimes referred to as high-synchrotron-peaked BL Lacs (HSPs). The high-energy peak, which is often theorized to come from inverse Compton scattering, is located at gamma-ray energies [2]. These blazars are variable sources, with flaring timescales that can be as short as a few minutes [3].

HBLs dominate the extragalactic TeV sky [4], but there are still many lingering questions about their attributes as a class, in part due to difficulties in performing a comprehensive survey at VHEs. Most VHE telescopes currently in operation are Imaging Atmospheric Cherenkov Telescopes (IACTs) with limited fields of view, which do not allow for an all-sky survey at these energies. This means that any attempt at an overall study must involve selecting a sample of HBLs that can be extrapolated to a complete sample and used to study the class as a whole. Details of constructing an appropriate HBL sample have been considered extensively in the development of this project [5]. HBLs are often observed when they are known to be flaring, since they are easier to detect when they are in an elevated flux state. This means that the results of blazar observations tend to be biased towards flaring states, which again inhibits attempts to study the sources as a whole unless that bias is accounted for. The goal of our project is to remove the observational bias towards flaring states within our sample of HBLs, in order to be able to make more generalized statements about this class of blazars.

2. VERITAS observations of HBL sample

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is a ground-based gamma-ray observatory located in southern Arizona. VERITAS is an Imaging Atmospheric Cherenkov instrument consisting of four 12-meter optical telescopes with a field of view of 3.5°. The instrument is sensitive between 100 GeV and 30 TeV and can detect 1% of the emission of the Crab Nebula at 5σ in 25 hours [6, 7].

The VERITAS HBL sample is based on the 3HSP catalog of radio and X-ray selected blazars [8], with sources selected from the catalog based on observability for VERITAS, taking into account position on the sky as well as expected brightness of the source [9]. Our sample consists of 36 sources, including 21 known TeV emitters that have been detected before and 15 candidates for new TeV detections. Many of these sources have been extensively observed by VERITAS throughout its over 15 years of operation through various AGN monitoring campaigns. 160 hours of additional dedicated observations for this project were taken within the last several years to supplement the >2100 hours of usable archival data on these sources. In order to avoid observational biases towards flaring states in the archival data, we excluded any observations that were triggered by reported high flux states at TeV or other energies.

Observation	Significance (σ)	Spectral index	Flux > 100 GeV (% C.U.)
VERITAS survey (2007-2021)	8.32	3.88 ± 0.42	4.61 ± 0.58
MAGIC 2009-2011	5.5	3.12 ± 0.37	2.0 ± 0.5
MAGIC 2014	5.3	3.25 ± 0.74	3.4 ± 1.6
MAGIC 2019	6.1	3.73 ± 0.58	8.0 ± 1.8
MAGIC 2020	22.9	3.7 ± 0.21	15.0 ± 1.0

Table 1: Detection significances, spectral indices, and flux values above 100 GeV for observations of 1ES 0647+250. The table includes results from four detections from MAGIC [13] as well as the results from this VERITAS unbiased survey. The 2009-2011 MAGIC observations took place during a low state of the blazar, and the remaining three MAGIC detections were during flares.

The data were processed and analyzed using standard VERITAS analysis methods and software [10] and cross-checked by independent analyses using a separate pipeline [11], using analysis cuts optimized for soft power-law spectra (index > 3). We fit a power-law spectrum for each source to find the best fit spectral index when possible, and calculated the flux using that index. For sources too weakly detected to fit the spectrum, flux upper limits were calculated using an assumed power-law index of 3.

3. Survey results and comparisons

Two thirds of the initial analysis work have been completed, with 25 of the 36 sources in our sample analyzed. We began our analysis with the 15 sources which have not been previously detected at TeV energies before starting to work our way through the known TeV sources. Most of the sources analyzed to date are not detectable in our dataset, and we saw only 2 sources above 5σ (1ES 0806+524 at 10.5σ and 1ES 0647+250 at 8.3σ).

Focusing in on a few of the sources from our survey, we can compare to previous published detections of these blazars in order to see how our results line up against observations taken at different times and during different states than our dataset. In particular, we compare our detection of 1ES 0647+250 from this survey with both low and high state detections by MAGIC (Major Atmospheric Gamma-ray Imaging Cherenkov)[12], our detection of 1ES 0806+524 with the original VERITAS discovery in 2008, and our non-detection of S3 1227+25 in the survey with a VERITAS detection during a 2015 flare. We can also compare the fluxes or flux upper limits for all the blazars in our survey with previously published gamma-ray fluxes for these sources.

3.1 1ES 0647+250

1ES 0647+250 is an HBL which was first discovered at TeV energies by MAGIC in 2011, and which has since been detected by both MAGIC and VERITAS. The redshift of the blazar is uncertain, with the most recent value given in a paper from the MAGIC collaboration as 0.45 ± 0.05 [13]. 1ES 0647+250 was detected with a significance of 8.3σ in our unbiased survey. The recent MAGIC paper [13] discusses four detections of this blazar: a low activity state between 2009-2011 and three flares in 2014, 2019, and 2020. All four of these observations fall within the timeframe of the VERITAS survey dataset, though any VERITAS data taken during the three flares would not

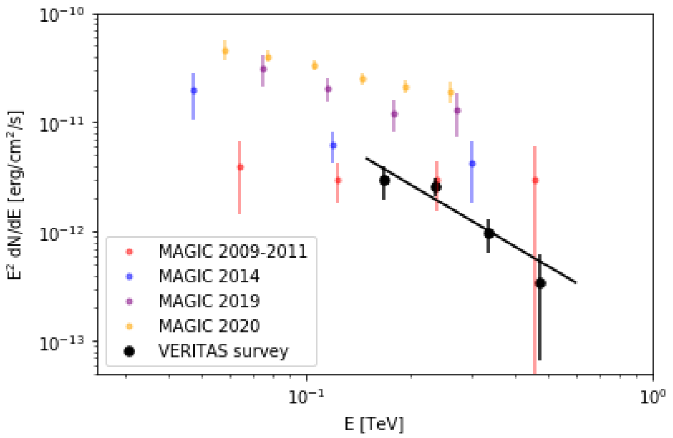

Figure 1: Plot of the spectrum for 1ES 0647+250, including published spectral points from four MAGIC detections [13] and from the VERITAS unbiased survey presented here. The MAGIC points are plotted in red (2009-2011 low flux state), blue (2014 flare), purple (2019 flare), and yellow (2020 flare), and the VERITAS points are in black. The black line represents the power law fit for the VERITAS data, which has a spectral index of 3.88 ± 0.42.

have been included in our survey. Comparing the results of the VERITAS unbiased survey with those found for these four published MAGIC detections of this source provide a frame of reference for the results of the survey. Table 1 lists the significances, power-law indices, and fluxes above 100 GeV for the VERITAS and MAGIC results.

It is immediately clear that the flux value found for 1ES 0647+250 in the survey falls between those of MAGIC's low state and high states. Since we have removed observations triggered by flares for the survey, we expect that the averaged flux value found in the survey would be closer to a low-state flux than to a flaring state. However, our survey is not necessarily removing all flares from the data set, but instead only taking out observations triggered by flares, so any higher states that happened occur during already scheduled observations are left in. Because of this, we would expect that the flux would be higher than if we were looking specifically at a time period where the blazar was in a quiescent state, like MAGIC's 2009-2011 observations. We can also see that while the spectral indices that MAGIC finds in their four time periods are consistent within their sometimes large error bars, there are hints that the spectrum of the HBL may change in different states. This reinforces the importance of removing observational bias towards flaring states when performing a survey, to avoid assuming that a high-state spectral index is representative of the average emission of the source. Figure 1 plots the published spectral points from the four MAGIC detections along with the power law spectrum found in our VERITAS survey.

3.2 1ES 0806+524

1ES 0806+524, an HBL at a redshift of 0.138, was first discovered at TeV energies by VERITAS in 2008, and has been subsequently detected by both VERITAS and MAGIC. In our unbiased survey, we detected the source with a significance of 10.5σ. The original VERITAS discovery dataset included observations taken between 2006-2008, and detected 1ES 0806+524 with a significance of 6.3σ [14]. Unlike in the case of 1ES 0647+250, where the survey results were very different

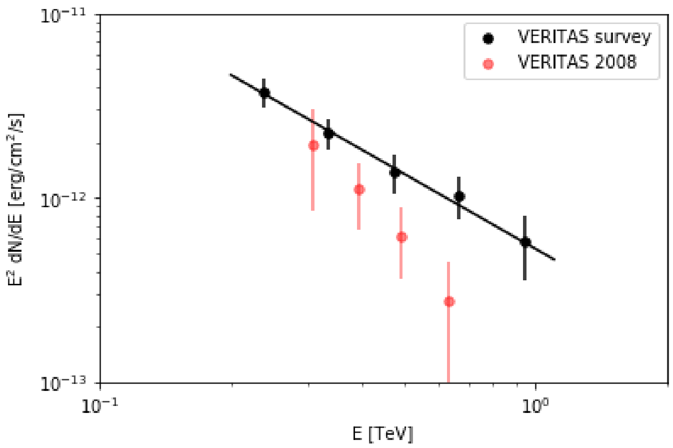

Figure 2: Plot of the spectrum for 1ES 0806+524, including published spectral points from the 2008 VERITAS discovery (red points) [14] and from the VERITAS unbiased survey presented here (black points). The black line represents the power law fit for the survey data, which has a spectral index of 3.35 ± 0.21.

from the earlier published detections, here the results of our survey are very similar to those of the older publication. The discovery paper lists a flux of (1.8 ± 0.5)% Crab flux above 300 GeV, while our survey found an almost identical flux of (1.75 ± 0.24)% Crab above the same energy threshold. The spectral indices of 3.35 ± 0.21 (survey) and 3.6 ± 1.3 (discovery) are also in agreement within error bars. Figure 2 shows the two spectra plotted together for comparison.

This agreement between the older VERITAS detection and the new detection with the VERITAS survey is also not surprising. The data used in the original 2009 paper did not come from only low-state observations or from only flaring observations (like the MAGIC observations discussed in the previous section). Instead it used an accumulation of data over several years, including a variety of flux levels. This created a data set similar in type to the larger one used in our survey, representing more of an average state of the blazar rather than its behavior during a particular time. This provides further validation of our methods in selecting our unbiased data, showing that the results we find are in agreement with the expectation for time averaged, random observations of an HBL.

3.3 S3 1227+25

S3 1227+25 is a blazar at redshift 0.325 which falls at the boundary between intermediate and high-frequency-peaked BL Lacs, and has been classified both ways in different situations. It was first detected by VERITAS during a flare in 2015 [15], but it was not detected in our unbiased survey, unlike the two previously discussed sources. The 2015 VERITAS observations were triggered by an elevated flux state seen by the Fermi Large Area Telescope (Fermi-LAT), and the source was detected at a significance of 13σ in 5 hours of data. In contrast to that, the unbiased survey dataset for S3 1227+25 consisted of 16 hours of data, yet only found a significance of 0.5σ. The data used in the discovery was not included in the survey, since the VERITAS observations had been triggered by Fermi-LAT and did not fit the "unbiased" requirement for the survey project. The S3 1227+25 flux during the flaring VERITAS detection was 9% of the Crab flux above 120 GeV, with

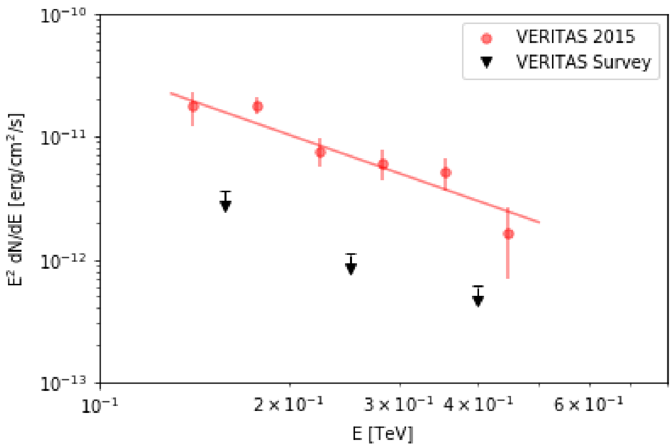

Figure 3: Plot of the spectrum for S3 1227+25, including published spectral points from the VERITAS discovery in 2015 (red points) [15] and the upper limits from the VERITAS survey presented here (black arrows). The red line represents the power law fit for the 2015 VERITAS data, which has a spectral index of 3.79 ± 0.4.

a power law index of 3.79 ± 0.4. In the unbiased survey we were only able to calculate an upper limit for the flux above the same energy limit, using an assumed spectral index of 3 since there was not enough data to fit the spectrum. We found a 99% confidence level upper limit of 2.6% Crab, which is significantly lower than the flux value found during the flare. This tells us that while S3 1227+25 is detectable by VERITAS during a bright enough flare, it is not generally visible at TeV energies, and we cannot extrapolate information about the non-flaring or averaged states from the flaring results. Figure 3 shows the spectral points from the 2015 VERITAS detection and from the VERITAS unbiased survey, with the spectral fit from the flaring detection for reference.

3.4 Flux comparisons

In addition to focusing on specific individual sources from our survey and comparing their fluxes and spectra with previously published detections, we can also look at the blazars in our survey sample as a whole. Figure 4 plots published gamma-ray fluxes against the fluxes or upper limits found in our survey. The published flux values are taken from TeVCat [16] for all of the analyzed survey blazars which also have published fluxes available in TeVCat. The survey fluxes and upper limits were calculated above the same energy threshold as the corresponding published flux for each blazar, which varied from source to source. The red y=x line on the plot marks where sources would fall if they had equal fluxes from the survey and the published detections. Most of the sources fall below this line, indicating higher published TeV fluxes than the values found by our survey. This is not surprising, since the flux values listed on TeVCat are generally reported during flaring states (when most blazars are first discovered), while our survey values come from an average over the entire dataset which includes both flaring and non-flaring states. The two exceptions in the figure, 1ES 0647+250 and 1ES 0806+524, have already been discussed in the previous sections. The published value for 1ES 0647+250 comes from a relatively low state and the published value for 1ES 0806+524 is from long-term observations, so it is reasonable that the survey fluxes would

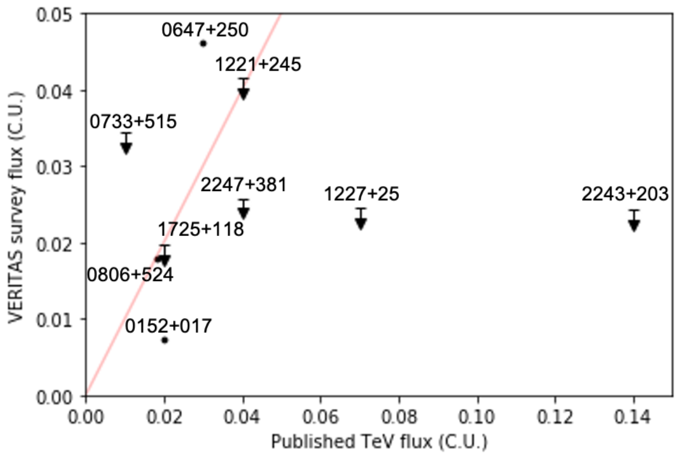

Figure 4: Plot comparing published gamma-ray fluxes to gamma-ray fluxes found in this unbiased survey for nine blazars (1ES 0647+250, NVSS J073326+515355, 1ES 0806+524, RGB J1725+118, RGB J0152+017, MS 1221.8+245, B3 2247+381, S3 1227+25, and RGB J2243+203). Published fluxes were taken from TeVCat [16] and survey fluxes or upper limits were calculated above the same energy thresholds as the corresponding TeVCat flux for each source. The red y=x line indicates the position of equal published and survey fluxes on the plot.

be higher (in the case of 1ES 0647+250) and approximately equal (for 1ES 0806+524).

4. Conclusions

High-frequency-peaked BL Lac objects are the most common extragalactic sources at TeV energies, yet most observations of these sources at very high energies are biased towards flaring states. This skews our understanding of their properties, and makes it more difficult to study the class as a whole. Our VERITAS survey selects a sample of 36 blazars and removes the observational bias towards flares in order to perform the first unbiased survey of HBLs at TeV energies. We have completed analysis of 25 of our sources, finding new measurements of unbiased average flux which are consistent with expected values when compared to earlier results from flaring and non-flaring states. When the remaining eleven HBLs in the sample are analyzed, the results of the complete survey can be used to derive a TeV luminosity function for HBLs, which will further our understanding of the blazar population.

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