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An unbiased search for TeV emission from high-frequency peaked BL Lacs

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High-frequency-peaked BL Lacs (HBLs) dominate the extragalactic TeV sky, with more than 50 objects detected with the current generation of ground-based TeV gamma-ray observatories. In the last three years, the VERITAS telescope array has observed a flux-limited sample of 36 X-ray selected HBLs with the goal of producing the first unbiased census of TeV emission from HBL blazars. The VERITAS HBL sample contains known TeV sources as well as 15 objects for which TeV emission has not been reported before. The results of this VERITAS campaign include the detection of new TeV blazars as well as unbiased estimates of the TeV flux of HBLs that have previously been reported only during flaring states. The implications of our results in understanding the intrinsic properties of HBLs as a source population will be discussed.

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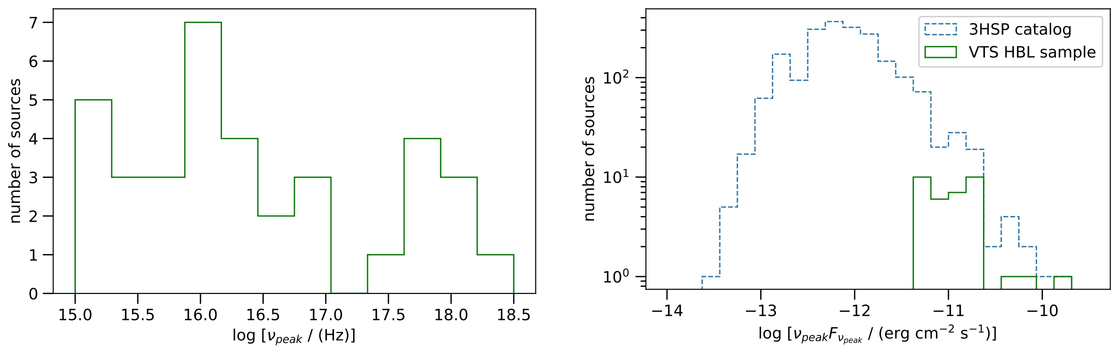

Figure 1: Distribution of the frequency where the synchrotron peak is located ($\nu_{\rm peak}$) and the flux at the synchrotron peak ($\nu_{\rm peak} F_{\nu_{\rm peak}}$) as estimated in the 3HSP catalog [22] for the VERITAS (VTS) HBL sample.

1. The population of TeV-emitting BL Lacs

High-frequency-peaked BL Lac-type blazars (HBLs) are the dominant population of extragalactic sources at $E > 1$ TeV. As of November 2022, they constitute at least 55 out of 94 extragalactic sources detected by ground-based gamma-ray telescopes [1]. HBLs are likely the main contributors to the total cosmic TeV radiation, with low-frequency-peaked BL Lacs and flat spectrum radio quasars being detected at TeV energies only during short-duration flares, with low duty cycles, and with very soft energy spectra that rarely extend beyond 1 TeV.

Even though more than 50 HBLs have been detected by current-generation Imaging Atmospheric Cherenkov Telescopes (IACTs), general properties of the population of TeV-emitting HBLs (spatial, spectral, luminosity, redshift distributions) are largely unconstrained due to the observational biases intrinsic to the operation of IACTs. A leading source of observational bias is the lack of sensitive blind surveys of the extragalactic TeV sky. These cannot be efficiently conducted with the current generation of IACTs due to their narrow field of view and limited sensitivity. Blazars with TeV fluxes of the order of 0.01 Crab still take $\gtrsim 25$ h of IACT exposure to detect. In addition, observations of TeV blazars are often triggered by flaring states, with the reported TeV fluxes not representing the average TeV emission from a source. Water Cherenkov observatories are not affected by the same sources of observational biases as IACTs thanks to their wide instantaneous field of view and large duty cycle, but with the current sensitivity level of the HAWC survey only four nearby blazars have been detected [2].

2. The VERITAS HBL sample

The most robust way to measure the luminosity function of TeV-emitting blazars would be to conduct a blind survey of the extragalactic sky [19, 20]. However, the population of blazars detected by the current generation of IACTs has a spatial density of $\sim 2 \times 10^{-3}$ deg^{-2}. This indicates that unless a large population of bright blazars has eluded detection, the odds of finding a new detectable blazar in a 25 h VERITAS exposure towards a random extragalactic direction are $\lesssim 1/100$.

A more efficient way to set constraints on the luminosity function of HBLs with IACTs is to measure the TeV flux of a complete sample of TeV-emitting HBLs. We started our selection with the 3HSP catalog [22], which cross-correlates sources with infrared spectra similar to known TeV blazars with radio and X-ray data to calculate the location and flux density of the synchrotron peak of the blazars. The VERITAS HBL sample comprises 36 blazars selected according to the following criteria:

- Object is listed in the 3HSP catalog, indicating $\log(\nu_{\rm peak}\,\text{Hz} > 15)$, i.e. a synchrotron peak in the ultraviolet to X-ray range (see Figure 1).
- Object is at declination $1.7^\circ \leq$ decl. $\leq 61.7^\circ$ to guarantee good observing conditions with VERITAS.
- Object is at galactic latitude $|b| > 10^\circ$ to avoid incompleteness in multiwavelength seed catalogs near the galactic plane.
- Object has an estimated flux at the synchrotron peak of $\log[\nu_{\rm peak} F_{\nu_{\rm peak}}/(\text{erg cm}^{-2}\text{s}^{-1})] > -11.2$ to focus observing efforts on sources with potential to be detected with VERITAS in $\lesssim 25$ h of exposure (see Figure 1).

The above selection criteria result in 36 northern HBL objects [23] out of which 21 are known TeV emitters [1]. The sources span a range of redshifts $0.03 < z \lesssim 0.36$.

3. VERITAS observations

The VERITAS observatory [24, 25] is an array of four imaging atmospheric Cherenkov telescopes located at the Fred Lawrence Whipple Observatory in southern Arizona (31° 40′ N, 110° 57′ W, 1.3 km altitude). Each telescope consists of a 12 m diameter reflector and a photomultiplier camera covering a field of view of 3.5°. VERITAS can detect a point source with 1% of the Crab Nebula flux[1] in ~ 25 h of exposure, covering the energy range between 0.1 TeV to > 30 TeV. The angular and energy resolution for reconstructed gamma-ray showers are $\sim 0.1^\circ$ and 15%, respectively, at 1 TeV.

Since the start of four-telescope operations in 2007, VERITAS has collected more than 2000 hours of exposure on the 36 sources that form the VERITAS HBL sample. This includes 155 h of dedicated observations between 2019 and 2021 that were obtained in order to achieve a sensitivity of $\sim$ 1% of the Crab Nebula flux for all objects. To avoid biasing the flux measurements towards flaring states, archival data were filtered by looking at observation logs and removing VERITAS observations that were triggered by high-flux states detected at other wavelengths (optical, X-ray, GeV), alerts and ATel notifications from other TeV observatories, or self-triggered by high flux states or signal excesses measured with VERITAS or the Whipple 10-m telescope. This typically results in the exclusion of $\sim$ 30% of the data in the VERITAS archive, although that figure varies significantly from source to source.

Analysis of the VERITAS data is underway. Figure 2 shows the significance distribution of the 15 sources in the VERITAS HBL sample that were not previously detected at TeV energies. The distribution is skewed towards positive values, indicating that sources in the VERITAS HBL

[1] 1 Crab = $2.1 \times 10^{-10}\text{cm}^{-2}\text{s}^{-1}$ at $E > 0.2$ TeV [26]

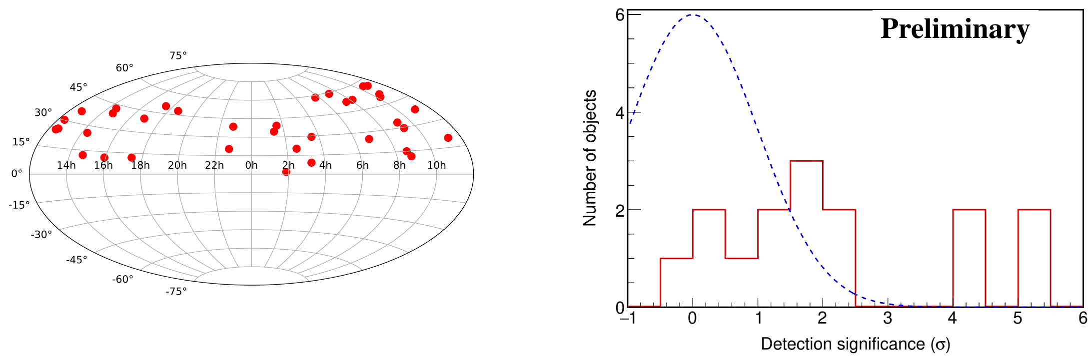

Figure 2: *Left:* Sky map in celestial coordinates of the location of the 36 blazars that are included in the VERITAS HBL sample. *Right:* Distribution of significances of the observations of the 15 sources in the VERITAS HBL sample that have not been previously detected at TeV energies. The dashed blue line shows the expected significance distribution from a population of non-TeV emitters. VERITAS observations instead show a population of weak TeV sources, including the detection of two new TeV sources with significance $> 5\sigma$.

sample as a population show a tendency towards positive gamma-ray excesses even though they are below the detection threshold for VERITAS. Once flux measurements or upper limits have been derived for all 36 sources in the VERITAS HBL sample, constraints on the luminosity function can be derived by estimating, with simulations, the completeness of the VERITAS survey and that of the seed 3HSP catalog, following established techniques [15]. Simulations indicate that VERITAS will be able to constrain the spectral index of a power-law luminosity function with an expected uncertainty of 30%, and will be sensitive to potential redshift evolution by detecting 10%-level deviations from 0.5 in $\langle V/V_{\rm max}\rangle$ [28].

Results from the distribution of TeV fluxes from the VERITAS HBL sample and the resulting measurement of the luminosity function will provide constraints to the total amount of TeV radiation produced by HBLs, informing future studies with the Cherenkov Telescope Array. Although HBLs are the dominant class of extragalactic TeV sources, VERITAS is also conducting studies to constrain the contribution of low- and intermediate-frequency peaked BL Lacs and flat spectrum radio quasars [29] to the cosmic TeV flux from blazars.

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