

VERITAS Observations of Blazars

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The VERITAS array of four 12-m diameter imaging atmospheric-Cherenkov telescopes in southern Arizona is used to study very high energy (VHE; $E > 100$ GeV) γ -ray emission from astrophysical objects. VERITAS is currently the most sensitive VHE γ -ray observatory in the world and one of the VERITAS collaboration's Key Science Projects (KSP) is the study of blazars. These active galactic nuclei (AGN) are the most numerous class of identified VHE sources, with ~ 30 known to emit VHE photons. More than 70 AGN, almost all of which are blazars, have been observed with the VERITAS array since 2007, in most cases with the deepest-ever VHE exposure. These observations have resulted in the detection of VHE γ -rays from 16 AGN (15 blazars), including 8 for the first time at these energies. The VERITAS blazar KSP is summarized in this proceeding and selected results are presented.

1. Introduction

Active galactic nuclei are the most numerous class of identified VHE γ -ray sources. These objects emit non-thermal radiation across ~ 20 orders of magnitude in energy and rank among the most powerful particle accelerators in the universe. A small fraction of AGN possess strong collimated outflows (jets) powered by accretion onto a supermassive black hole (SMBH). VHE γ -ray emission can be generated in these jets, likely in a compact region very near the SMBH event horizon. Blazars, a class of AGN with jets pointed along the line-of-sight to the observer, are of particular interest in the VHE regime. Approximately 30 blazars, primarily high-frequency-peaked BL Lacs (HBL), are identified as sources of VHE γ -rays, and some are spectacularly variable on time scales comparable to the light crossing time of their SMBH (~ 2 min; [1]). VHE blazar studies probe the environment very near the central SMBH and address a wide range of physical phenomena, including the accretion and jet-formation processes. These studies also have cosmological implications, as VHE blazar data can be used to strongly constrain primordial radiation fields (see the extragalactic background light (EBL) constraints from, e.g., [2, 3]).

VHE blazars have double-humped spectral energy distributions (SEDs), with one peak at UV/X-ray energies and another at GeV/TeV energies. The origin of the lower-energy peak is commonly explained as synchrotron emission from the relativistic electrons in the blazar jets. The origin of the higher-energy peak is controversial, but is widely believed to be the result of inverse-Compton scattering of seed photons off the same relativistic electrons. The origin of the seed photons in these leptonic scenarios could be the synchrotron photons themselves, or photons from an external source. Hadronic scenarios are also plausible explanations for the VHE emission, but generally are not favored.

Contemporaneous multi-wavelength (MWL) obser-

vations of VHE blazars, can measure both SED peaks and are crucial for extracting information from the observations of VHE blazars. They are used to constrain the size, magnetic field and Doppler factor of the emission region, as well as to determine the origin (leptonic or hadronic) of the VHE γ -rays. In leptonic scenarios, such MWL observations are used to measure the spectrum of high-energy electrons producing the emission, as well as to elucidate the nature of the seed photons. Additionally, an accurate measure of the cosmological EBL density requires accurate modeling of the blazar's intrinsic VHE emission that can only be performed with contemporaneous MWL observations.

2. VERITAS

VERITAS, a stereoscopic array of four 12-m atmospheric-Cherenkov telescopes located in Arizona, is used to study VHE γ -rays from a variety of astrophysical sources [4]. VERITAS began scientific observations with a partial array in September 2006 and has routinely observed with the full array since September 2007. The performance metrics of VERITAS include an energy threshold of ~ 100 GeV, an energy resolution of $\sim 15\%$, an angular resolution of $\sim 0.1^\circ$, and a sensitivity yielding a 5σ detection of a 1% Crab Nebula flux object in < 30 hours¹. VERITAS has an active maintenance program (e.g. frequent mirror re-coating and alignment) to ensure its continued high performance over time, and an upgrade improving both the camera (higher quantum-efficiency PMTs) and the trigger system has been proposed to the funding agencies.

¹A VERITAS telescope was relocated during Summer 2009, increasing the array's sensitivity by a factor ~ 1.3 .

3. VERITAS Blazar KSP

VERITAS observes for ~ 750 h and ~ 250 h each year during periods of astronomical darkness and partial moonlight, respectively. The moonlight observations are almost exclusively used for a blazar discovery program, and a large fraction of the dark time is used for the blazar KSP, which consists of:

- A VHE blazar discovery program (~ 200 h / yr): Each year ~ 10 targets are selected to receive ~ 10 h of observations each during astronomical darkness. These data are supplemented by discovery observations during periods of partial moonlight.
- A target-of-opportunity (ToO) observation program (~ 50 h / yr): VERITAS blazar observations can be triggered by either a VERITAS blazar discovery, a VHE flaring alert (> 2 Crab) from the blazar monitoring program of the Whipple 10-m telescope or from another VHE instrument, or a lower-energy flaring alert (optical, X-ray or Fermi-LAT). Should the guaranteed allocation be exhausted, further time can be requested from a pool of director's discretionary time.
- Multi-wavelength (MWL) studies of VHE blazars (~ 50 h / yr + ToO): Each year one blazar receives a deep exposure in a pre-planned campaign of extensive, simultaneous MWL (X-ray, optical, radio) measurements. ToO observation proposals for MWL measurements are also submitted to lower-energy observatories (e.g. Swift) and are triggered by a VERITAS discovery or flaring alert.
- Distant VHE blazar studies to constrain the extragalactic background light (EBL): Here distant targets are given a higher priority in the blazar discovery program, as well as for the MWL observations of known VHE blazars, particularly those with hard VHE spectra.

4. Blazar Discovery Program

The blazars observed in the discovery program are largely high-frequency-peaked BL Lac objects. However, the program also includes IBLs (intermediate-peaked) and LBLs (low-peaked), as well as flat spectrum radio quasars (FSRQs), in an attempt to increase the types of blazars known to emit VHE γ -rays. The observed targets are drawn from a *target list* containing objects visible to the telescopes at reasonable zenith angles ($-8^\circ < \delta < 72^\circ$), without a previously published VHE limit below 1.5% Crab, and with a measured redshift $z < 0.3$. To further the study of the

EBL a few objects having a large ($z > 0.3$) are also included in the target list. The target list includes:

- All nearby ($z < 0.3$) HBL and IBL recommended as potential VHE emitters in [5, 6, 7].
- The X-ray brightest HBL ($z < 0.3$) in the recent Sedentary [8] and ROXA [9] surveys.
- Four distant ($z > 0.3$) BL Lac objects recommended by [5, 10].
- Several FSRQ recommended as potential VHE emitters in [6, 11].
- All nearby ($z < 0.3$) blazars detected by EGRET [12].
- All nearby ($z < 0.3$) blazars contained in the Fermi-LAT Bright AGN Sample [13].
- All sources ($|b| > 10^\circ$) detected by Fermi-LAT where extrapolations of their MeV-GeV γ -ray spectrum (including EBL absorption; assuming $z = 0.3$ if the redshift is unknown) indicates a possible VERITAS detection in less than 20 h. This criteria is the focus of the 2009-10 VERITAS blazar discovery program.

5. VERITAS AGN Detections

VERITAS has detected VHE γ -ray emission from 16 AGN (15 blazars), including 8 VHE discoveries. These AGN are shown in Table I, and each has been detected by the Large Area Telescope (LAT) instrument aboard the Fermi Gamma-ray Space Telescope. Every blazar discovered by VERITAS was the subject of ToO MWL observations to enable modeling of its simultaneously-measured SED. The known VHE blazars detected by VERITAS were similarly the targets of MWL observations.

5.1. Recent VERITAS Blazar Discoveries

Prior to the launch of Fermi VERITAS had discovered VHE emission from 2 blazars. These included the first VHE-detected IBL, W Comae [14, 15], and the HBL 1ES0806+524 [16]. VERITAS has discovered 6 VHE blazars since the launch of Fermi. Three of these were initially observed by VERITAS prior to the release of Fermi-LAT results, due to the X-ray brightness of the synchrotron peaks of their SEDs.

VHE emission from 3C 66A was discovered by VERITAS in September 2008 [17] during a flaring episode that was also observed by the Fermi-LAT [18]. The observed flux above 200 GeV was 6% of the Crab Nebula flux and the measured VHE spectrum was very soft ($\Gamma_{\text{VHE}} \sim 4.1$). RGB J0710+591 was detected

Table I VERITAS AGN Detections. The only non-blazar object is the radio galaxy M87. The blazars discovered at VHE by VERITAS are marked with a dagger.

Object	Class	Redshift
M87	FR I	0.004
Mkn 421	HBL	0.030
Mkn 501	HBL	0.034
1ES 2344+514	HBL	0.044
1ES 1959+650	HBL	0.047
W Comae [†]	IBL	0.102
RGB J0710+591 [†]	HBL	0.125
H 1426+428	HBL	0.129
1ES 0806+524 [†]	HBL	0.138
1ES 0229+200	HBL	0.139
1ES 1218+304	HBL	0.182
RBS 0413 [†]	HBL	0.190
1ES 0502+675 [†]	HBL	0.341
3C 66A [†]	IBL	0.444?
PKS 1424+240 [†]	IBL	?
VER J0521+211 [†]	?	?

($\sim 5.5\sigma$; 3% Crab flux above 300 GeV; $\Gamma_{\text{VHE}} \sim 2.7$) during VERITAS observations from December 2008 to March 2009. The initial announcement of the VHE discovery [19] led to its discovery above 1 GeV in the Fermi-LAT data using a special analysis. RBS 0413, a relatively distant HBL ($z=0.19$), was observed for 16 h good-quality live time in 2008-09². These data resulted in the discovery of VHE gamma-rays ($>270\gamma$, $\sim 6\sigma$) at a flux (>200 GeV) of $\sim 2\%$ of the Crab Nebula flux. The discovery [20] was announced simultaneously with the LAT MeV-GeV detection. The VHE and other MWL observations, including Fermi-LAT data, for each of these three sources will be the subject of a joint publication involving both the VERITAS and LAT collaborations.

5.2. Discoveries Motivated by Fermi-LAT

The successful VHE discovery observations by VERITAS of three blazars was motivated primarily by results from the first year of LAT data taking. In particular, the VHE detections of PKS 1424+240 [21] and 1ES 0502+675 [22] were the result of VERITAS observations triggered by the inclusion of these objects in the Fermi-LAT Bright AGN List [13]. The former is only the third IBL known to emit VHE gamma-rays, and the latter is the most distant BL Lac object

($z = 0.341$) detected in the VHE band. In addition, VER J0521+211, likely associated with the radio-loud AGN RGB J0521.8+2112, was detected by VERITAS in ~ 4 h of observations in October 2009 [23]. These observations were motivated by its identification as a >30 GeV γ -ray source in the public Fermi-LAT data. Its VHE flux is 5% of the Crab Nebula flux, placing it among the brightest VHE blazars detected in recent years. VERITAS later observed even brighter VHE flaring from VER J0521+211 in November 2009 [24], leading to deeper VHE observations.

6. Blazars Upper Limits

More than 50 VHE blazar candidates were observed by VERITAS between September 2007 and June 2009. The total exposure on the 49 non-detected candidates is ~ 305 h live time (average of 6.2 h per candidate). Approximately 55% of the total exposure is split amongst the 27 observed HBL. The remainder is divided amongst the 8 IBL (26%), 5 LBL (6%), and 9 FSRQ (13%). There are no clear indications of significant VHE γ -ray emission from any of these 49 blazars [25]. However, the observed significance distribution is clearly skewed towards positive values (see Figure 1). A stacking analysis performed on the entire data sample shows an overall excess of 430 γ -rays, corresponding to a statistical significance of 4.8σ , observed from the directions of the candidate blazars. The IBL and HBL targets make up 96% of the observed excess. Observations of these objects also comprise $\sim 80\%$ of the total exposure. An identical stacked analysis of all the extragalactic non-blazar targets observed, but not clearly detected ($>5\sigma$), by VERITAS does not show a significant excess (~ 120 h exposure). The stacked excess persists using alternate methods for estimating the background at each blazar location, and with different event selection criteria (e.g. *soft cuts* optimized for sources with $\Gamma_{\text{VHE}} > 4$). The distribution of VHE flux upper limits is shown in Figure 1. These 49 VHE flux upper limits are generally the most-constraining ever reported for these objects.

7. Multi-wavelength Studies of VHE Blazars

During the first three seasons of VERITAS observations, pre-planned extensive MWL campaigns were organized for three blazars 1ES 2344+514 (2007-08), 1ES 1218+304 (2008-09) and 1ES 0229+200 (2009-10 - ongoing). In addition, numerous ToO MWL-observation campaigns were performed. These include campaigns for every blazar/AGN discovered by VERITAS, and all include Swift (XRT and UVOT) data. All MWL campaigns on the VHE blazars discovered

²RBS 0413 was observed further by VERITAS in Fall 2009.

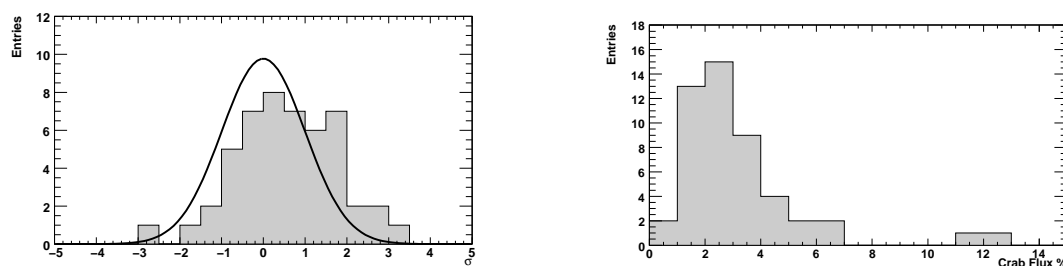


Figure 1: (Left) The preliminary significance measured from each of the 49 non-detected candidates using standard analysis cuts. The curve shows a Gaussian distribution, with mean zero and standard deviation one, normalized to the number of blazars. A similar result is obtained using analysis cuts optimized for soft-spectrum sources. (Right) The distribution of flux upper limits for the non-detected blazars in percentage of Crab Nebula flux above the observation threshold. The time-weighted average limit is less than $\sim 2\%$ Crab flux.

since the launch of Fermi include LAT detections. In addition, several MWL campaigns on the well-studied VHE blazars Mkn 421 and Mkn 501 (please see the contributions of D. Gall and A. Konopelko in these proceedings) were also performed. Highlights of these campaigns include:

- 1ES 2344+514: A major (50% Crab) VHE flare, along with correlations of the VHE and X-ray flux were observed from this HBL. The VHE and X-ray spectra harden during bright states, and a synchrotron self-Compton (SSC) model can explain the observed SED in both the high and low states [26].
- 1ES 1218+304: This HBL flared during VERITAS MWL observations. Its unusually hard VHE spectrum strongly constrains the EBL. The observed flaring rules out kpc-scale jet emission as the explanation of the spectral hardness and places the EBL constraints on more solid footing [27, 28].
- 1ES 0806+524: The observed SED of this new VHE HBL can be explained by an SSC model [16].
- W Comae: This IBL, the first discovered at VHE, flared twice in 2008 [14, 15]. Modeling of the SED is improved by including an external-Compton (EC) component in an SSC interpretation.
- 3C 66A: This IBL flared at VHE and MeV-GeV energies in 2008 [17, 18]. Similar to W Comae and PKS 1424+240, modeling of observed SED suggests a strong EC component in addition to an SSC component.
- Mkn 421: This HBL exhibited major flaring behavior for several months in 2008. Correlations of the VHE and X-ray flux were observed, along with spectral hardening with increased flux in both bands [29].

- RGB J0710+591: Modeling the SED of this HBL with an SSC model yields a good fit to the data. The inclusion of an external Compton component does not improve the fit.
- PKS 1424+240: The broadband SED of this IBL (at unknown redshift) is well described by an SSC model favoring a redshift of less than 0.1 [21]. Using the photon index measured with Fermi-LAT in combination with recent EBL absorption models, the VERITAS data indicate that the redshift of PKS 1424+240 is less than 0.66.

8. Conclusions

The first two years of the VERITAS blazar KSP were highly successful. Highlights include the detection of more than a 16 VHE blazars with the observations almost always having contemporaneous MWL data. Among these detections are 8 VHE blazar discoveries, including the first three IBLs known to emit VHE γ -rays. All but a handful of the blazars on the initial VERITAS discovery *target list* were observed, and the flux limits generated for those not VHE detected are generally the most-constraining ever. The excess seen in the stacked blazar analysis suggests that the initial direction of the VERITAS discovery program was well justified, and that follow-up observations of many of these initial targets will result in VHE discoveries. In addition, the Fermi-LAT is identifying many new compelling targets for the VERITAS blazar discovery program. These new candidates have already resulted in 3 VHE blazar discoveries. The future of the VERITAS blazar discovery program is clearly very bright.

The MWL aspect of the VERITAS blazar KSP has also been highly successful. Every VERITAS observation of a known, or newly discovered, VHE blazar has been accompanied by contemporaneous MWL observations. These data have resulted in the identifica-

tion of correlated VHE and X-ray flux variability, as well as correlated spectral hardening in both the VHE and X-ray bands. The VHE MWL observations were performed in both "quiescent" and flaring states for some of the observed blazars. For the observed HBL objects, the SEDs can be well described by a simple SSC model in both high and low states. However, an additional external Compton component is necessary to adequately fit the SEDs of the IBL objects.

The Fermi-LAT is already having a significant impact on the blazar KSP. In future seasons, the VERITAS blazar discovery program will focus its discovery program on hard-spectrum blazars detected by Fermi-LAT, and will likely have a greater focus on high-risk/high-reward objects at larger redshifts ($0.3 < z < 0.7$). In addition, the number of VHE blazars studied in pre-planned MWL campaigns will increase as data from the Fermi-LAT will be publicly available. In particular, the extensive pre-planned MWL campaigns will focus on objects that are noteworthy for the impact their data may have on understanding the EBL. The simultaneous observations of blazars by VERITAS and Fermi-LAT will completely resolve the higher-energy SED peak, often for the first time, enabling unprecedented constraints on the underlying blazar phenomena to be derived.

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