VHE Blazar Discoveries with VERITAS

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Abstract: The VERITAS array of 12-m atmospheric-Cherenkov telescopes is used in an intensive observation program focused on the discovery of VHE ($E > 100$ GeV) γ-ray-emitting blazars. Since VERITAS began full-scale operation in 2007, more than 1000 hours of observation, on $\sim$90 targets, have been devoted to the VHE blazar discovery effort and to timely follow-up in multi-wavelength (MWL) observation campaigns. These data have resulted in the discovery of VHE emission from 10 blazars (6 HBLs and 4 IBLs). A summary of these VHE discoveries is presented.

Keywords: VERITAS, AGN, Blazar, Gamma-ray, TeV, VHE

1 Introduction

Blazars, a class of active galactic nucleus (AGN) with relativistic jets pointed along the line of sight to the observer, are the most numerous class of identified VHE γ-ray sources. Of the forty-one blazars observed to emit VHE γ-rays, 73% (30) are high-frequency-peaked BL Lac objects (HBL). The remaining 11 blazars were largely detected at VHE only during flaring episodes, and include 5 intermediate-frequency-peaked BL Lac objects (IBLs), 3 low-frequency-peaked BL Lac objects (LBLs), and 3 flat-spectrum radio quasars (FSRQs). Since VHE blazar studies probe the environment very near the central supermassive black hole of the AGN, such studies can address a wide range of physical phenomena, including the accretion and jet-formation processes, and can also be used to provide strong constraints on both the extragalactic background light (EBL) and the intergalactic magnetic field. VHE blazars have double-humped spectral energy distributions (SEDs). 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 leptonic processes, although hadronic scenarios are also plausible. Given that blazar emission spans $\sim$20 orders of magnitude in energy and is highly variable, MWL observations of these objects to measure both SED peaks contemporaneously are crucial for extracting the underlying science. Previous MWL studies have already yielded considerable understanding of VHE blazars and their related science. It is particularly important to now develop these implications further based on a large population of VHE blazars, from different blazar sub-classes, with contemporaneous SED modeling in all cases.

2 The VERITAS Blazar Discovery Program

VERITAS began routine scientific observations with the full array in September 2007. The performance metrics of VERITAS include an energy resolution of $\sim$15%, an angular resolution of $\sim$0.1°, and a sensitivity yielding a 5 standard deviation (σ) detection of an object with flux equal to 1% Crab Nebula flux (1% Crab) in $\sim$25 hours. For more details about VERITAS, see [1]. VERITAS observations are performed for $\sim$1100 h each year, and a major goal of the VERITAS collaboration is to increase the number of identified VHE blazars.

Since the start of full-scale VERITAS operations, observations of blazars have averaged $\sim$410 h per year. During the first three years (2007-2010), the discovery of new VHE blazars was a primary focus of the VERITAS blazar program. Indeed, $\sim$80% of the VERITAS blazar data came from discovery observations and follow-up observations of any new sources. In September 2010, VERITAS began to focus more on deep studies of known VHE sources, and only 40% of the blazar observations are now focused on VHE discovery. Between September 2007 and June 2011, a total of $\sim$1130 h of blazar-discovery data were taken.

The targets observed in the VERITAS blazar discovery program are largely HBLs, but also include IBLs, LBLs and FSRQs. The selection of the targets from 2007-09 is described in detail in [2]. The targets include EGRET-detected blazars, together with X-ray-bright HBLs, IBLs, and FSRQs recommended in the literature (or objects first reported in later catalogs meeting the earlier recommendation criteria), all subject to constraints based on redshift ($z < 0.5$), observability, and prior VHE exposure. In February 2009, the Fermi-LAT collaboration released its

Blazar	z	Type	$\log_{10}(\nu_{\rm synch})$	Flux [Crab %]	Γ	References
W Comae	0.102	IBL	14.8	Flares (9% & 23%)	3.8 ± 0.4	ATel #1422, #1565, [3, 4]
RGB J0710+591	0.125	HBL	21.1	3%	2.7 ± 0.3	ATel #1941, [5]
1ES 0806+524	0.138	HBL	16.6	2%	3.6 ± 1.0	ATel #1415, [7]
1ES 1440+122	0.162	IBL	16.5	1%	3.4 ± 0.7	ATel #2786
RX J0648.7+1516	0.179	HBL*	-	2%	4.4 ± 0.8	ATel #2486
RBS 0413	0.190	HBL	17.0	2%	3.2 ± 0.7	ATel #2272
3C 66A	?	IBL	15.6	Varies (6%)	4.1 ± 0.4	ATel #1753, [8, 9]
PKS 1424+240	?	IBL	15.7	5%	3.8 ± 0.5	ATel #2084, [10]
RGB J0521.8+2112	?	HBL*	-	Varies (5%)	3.5 ± 0.2	ATel #2260, #2309
1ES 0502+675	?	HBL	19.2	6%	3.9 ± 0.4	ATel #2301

Table 1: The blazars discovered at VHE by VERITAS. The blazar classification and synchrotron peak frequencies are taken from [12], except for two cases (marked with asterisks) where the classification is determined from VERITAS-led MWL studies. The time-averaged VERITAS flux and photon index are also shown.

first catalog of MeV-GeV-bright blazars. From this point onwards, the VERITAS blazar discovery program has focused on objects detected by Fermi-LAT, where either the power-law extrapolation of the LAT photon spectrum (including EBL absorption) indicates a likely VHE detection, or where clusters of $>$10 GeV photons are found nearby.

In total, 20 VHE blazars are detected with VERITAS, including 10 discoveries. The 10 blazars detected for the first time at VHE with VERITAS are shown in Table 1. Following the discovery of a new VHE blazar, target-of-opportunity (ToO) observations are initiated with VERITAS to enable a better measurement of the VHE spectrum and light curve, as well as with X-ray satellites (typically Swift) and optical/radio observatories. The goal of these MWL data is to provide a contemporaneous spectral energy distribution (SED) for modeling of the broadband emission. Indeed, such an SED has been generated for every VERITAS VHE blazar discovery.

3 Pre-ICRC-2009 Discoveries

As of the 2009 ICRC, 11 VHE blazar detections were reported by VERITAS. Of these, 5 were VHE discoveries, including the first 3 VHE IBLs.

1ES 0806+524 is an HBL at a redshift of $z = 0.138$. It was recommended as a likely VHE emitter by [6], and was observed by VERITAS for 65 h of quality-selected live time in 2006-08, largely during the commissioning of the instrument [7]. A point-like excess (VER J0809+523) of 245 VHE γ-rays is detected, corresponding to a statistical significance of 6.3σ. The VHE spectrum observed between $\sim$300 GeV and $\sim$700 GeV is soft, with photon index $\Gamma = 3.6 \pm 1.0$, and the measured flux above 300 GeV is 1.8% Crab. No VHE flux variability is observed within limited statistics. An SED was generated using contemporaneous MWL observations and is reasonably described by a one-zone synchrotron-self-Compton (SSC) model.

W Comae is a bright, nearby ($z = 0.102$), EGRET-detected IBL. It was observed with VERITAS for $\sim$40 h of good-quality live time between January and April 2008 [3]. A weak detection ($\sim$5σ) of VHE γ-ray emission (VER J1221+282) is found in the overall data set, with 70% of the excess (275 γ-rays, 8.6σ) occurring during a 4-night flare in March 2008. During the brightest two nights, the VHE flux is 9% Crab above 200 GeV, and the VHE spectrum is characterized by a soft power law ($\Gamma = 3.8 \pm 0.4$). While the contemporaneous MWL SED can be described by an SSC model, an SSC model with an additional external-Compton (EC) component yields a more natural set of fit parameters and is therefore preferred. W Comae is the first IBL detected at VHE energies, and the improvement in the fit from adding an EC component, not needed in typical HBL modeling, suggests there may be different underlying processes generating the VHE γ-ray emission in different parts of the blazar sequence. In June 2008, a second VHE flare, $\sim$3 times as bright as the first, was observed from W Comae [4]. Modeling of the SED observed during this episode yields similar conclusions to the first episode.

3C 66A is an EGRET-detected IBL with an uncertain redshift. VERITAS observed this iconic blazar for 33 h of quality-selected live time in 2007-08 [8], resulting in the discovery of an excess (VER J0222+430) of 1791 VHE γ-rays (21.2σ). The observed integral flux above 200 GeV is 6% Crab and shows evidence for variability on a timescale of days. The VHE spectrum is soft ($\Gamma = 4.1 \pm 0.4$), and does not change (within limited statistics) during the nights of the observed flare [9]. The nearby (separation $\sim$0.12°) radio galaxy 3C 66B, suggested as the possible origin of the MAGIC excess observed from the same region [13] in 2007, is excluded (at a level of 4.3σ) as the location of the VERITAS excess. During the flaring episode in October 2008, a simultaneous MWL SED was built with VERITAS, Fermi-LAT, F-GAMMA, GASP-WEBT, PAIRITEL, MDM, ATOM, Swift, and Chandra observations. While the observed SED can be successfully modeled using a standard SSC model, with or without an EC component, the observed MWL variability can only be explained with the addition of the EC component [9].

RGB J0710+591 is an HBL at $z = 0.125$ with its synchrotron peak at an unusually high-frequency ($10^{19.2}$ Hz).

It was observed with VERITAS for $\sim$22 h of good-quality live time between December 2008 and March 2009 [5]. VHE γ-ray emission was discovered from this blazar (5.5σ) during this exposure. The observed VHE flux from VER J0710+591 shows no variability (within statistics) and is 3% Crab above 300 GeV. The measured VHE spectrum between $\sim$310 GeV and $\sim$4.6 TeV is among the hardest ($\Gamma = 2.69 \pm 0.26$) observed by VERITAS from a blazar. Following the VERITAS detection, the Fermi-LAT collaboration performed a specific high-energy analysis of their data and found γ-ray emission with a very hard spectrum ($\Gamma_{LAT} \sim 1.5$) between 100 MeV and 300 GeV. The contemporaneous MWL SED, including both Fermi-LAT and Swift UVOT/XRT data, is well-described by an SSC model. An additional EC component does not improve the fit. Here it is interesting to note that the inverse-Compton peak of the SED may be located beyond the highest energy point of the VERITAS spectrum.

PKS 1424+240 is an IBL with an unknown redshift. It was observed by VERITAS for 28.5 h of quality-selected live time, between February and June 2009, because of its inclusion in the Fermi Bright Source List [14]. Soft-spectrum ($\Gamma = 3.8 \pm 0.5$) emission above 140 GeV is detected (370 γ, 8.5σ) with VERITAS [10], making this the first VHE discovery motivated by Fermi-LAT data. The VHE flux from VER J1427+238, $\sim$5% Crab, is steady within the observation period, as is the Fermi-LAT flux. A contemporaneous MWL SED is well-described by a one-zone SSC model regardless of the assumed redshift, provided that $z < 0.66$. This limit is determined using a recent EBL model and combining the Fermi-LAT ($\Gamma_{LAT} = 1.73$) and VERITAS spectra. Addition of an EC component does not improve the SED modeling, in contrast to the trend seen in other VERITAS IBL detections.

4 Post-ICRC-2009 Discoveries

Nine additional blazars have been detected by VERITAS since the 2009 ICRC. Five of these were discovered as VHE emitters, and for each of these, results from a contemporaneous MWL observation campaign, including VERITAS, Fermi-LAT, Swift XRT/UVOT, and optical data, are in preparation. It should also be noted that marginal signals ($\sim$4σ) existed in large amounts of VERITAS data (>25 h) for 1ES 0414+009 and B2 1215+30 at the time of their announced VHE discoveries by the HESS and MAGIC collaborations, respectively. These two blazars are now strongly detected by VERITAS [11].

RGB J0521.8+2112 was initially observed by VERITAS because of the identification of a nearby cluster of high-energy photons in a simple binned search (>30 GeV) of the initial public release of the Fermi-LAT photon data. VERITAS observed the likely blazar for $\sim$15 h of quality-selected live time between October 2009 and January 2010. An excess of VHE γ-rays (VER J0521+211), corresponding to a statistical significance of $\sim$16σ, is observed from the direction of RGB J0521.8+2112. The observed VHE flux is variable, with an average value of $\sim$5% Crab above 200 GeV, and the time-averaged VERITAS spectrum is soft ($\Gamma = 3.47 \pm 0.19$). Follow-up optical spectroscopy of the VERITAS source, with MDM and the MMT, reveal a continuum dominated spectrum typical for BL Lac objects. Unfortunately no absorption lines are identified and hence the redshift cannot determined.

RBS 0413 is an HBL with a redshift of $z = 0.190$. This blazar was initially selected for observation with VERITAS because it is one of the X-ray-brightest HBLs in the Sedentary Survey [15], and met the selection criteria used to identify likely VHE emitters in [6]. Deeper observations were later motivated by the identification of this blazar as a bright, very hard-spectrum ($\Gamma \sim 1.5$; [16]) MeV-GeV source by the Fermi-LAT collaboration. RBS 0413 was observed by VERITAS for $\sim$26 h of quality-selected live time between September 2008 and January 2010. An excess of 108 VHE γ-rays (VER J0319+187), corresponding to a statistical significance of 5.5σ, is observed from the direction of RBS 0413. The observed VHE flux has an average value of $\sim$2% Crab above 200 GeV and does not vary within the limited statistics. The time-averaged VERITAS photon index is $\Gamma = 3.2 \pm 0.7$.

1ES 0502+675 observations were motivated by the flux and spectrum reported in the Fermi-LAT Bright Source List for 0FGL J0507.9+6739 [14, 16]. This HBL was observed by VERITAS for $\sim$30 h of quality-selected live time between September 2009 and January 2010. An excess of VHE γ-rays (VER J0507+676), corresponding to a statistical significance of $\sim$11σ, is observed from the direction of the blazar. The VHE flux is constant within the observed statistics, with an average value of $\sim$6% Crab above 300 GeV, and the time-averaged VERITAS photon index is $\Gamma = 3.92 \pm 0.35$. Although the catalog redshift of this blazar is 0.341, possibly explaining the softness of the observed spectrum, the value is from a private communication and the original MMT spectrum could not be located. Following the VERITAS detection, a $\sim$10 times more sensitive observation was performed with the same spectrograph at the MMT. No significant absorption/emission lines were observed and hence the redshift is uncertain.

RX J0648.7+1516 observations were motivated by the identification of a nearby cluster of >10 GeV photons by the Fermi-LAT collaboration. This unidentified radio and X-ray emitter was observed by VERITAS for $\sim$19 h of quality-selected live time between March 4 and April 15, 2010. An excess of VHE γ-rays (VER J0648+152), corresponding to a statistical significance of 5.3σ, is observed from the direction of RX J0648.7+1516. No strong variations are observed in the VHE flux ($\sim$2% Crab above 300 GeV), and the time-averaged VERITAS spectrum is very soft ($\Gamma = 4.4 \pm 0.8$). Follow-up optical spectroscopy was performed with the Shane 3-m telescope at Lick Observatory. A continuum dominated spectrum typical of BL Lac objects is observed, along with weak absorption lines compatible with $z = 0.179$.

1ES 1440+122 is an IBL (borderline HBL), with a well-determined redshift of $z = 0.162$. This hard-spectrum

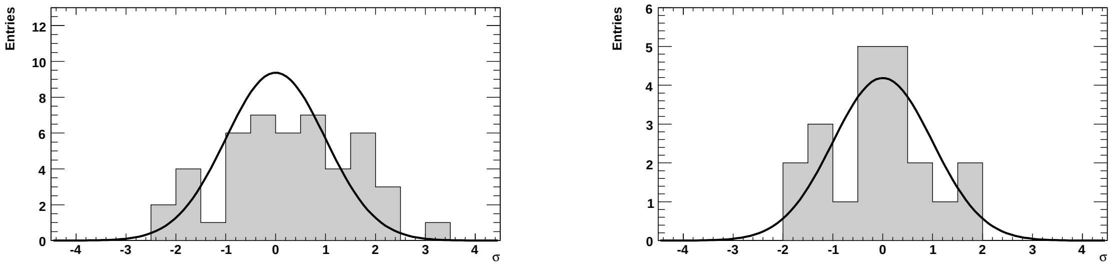

Figure 1: Left: The distribution of significance (soft cuts) observed from 47 candidate VHE blazars, selected for VERITAS discovery observations prior to the Fermi launch, during exposures taken between 2007 and 2011. Right: The distribution of significance (soft cuts) observed from 21 candidate VHE blazars, selected using information in the 1FGL catalog, during exposures taken in 2009-11.

Fermi source ($\Gamma \sim 1.8$; [16]) was selected for observation with VERITAS because it was recommended as a likely VHE emitter by [6]. The blazar was observed by VERITAS for ~47 h of quality-selected live time between May 2008 and June 2010. An excess of VHE γ-rays (VER J1442+120), corresponding to a statistical significance of 5.5σ, is observed from the direction of 1ES 1440+122. The observed VHE flux does not vary within limited statistics and has an average value of ~1% Crab above 200 GeV. The time-averaged VERITAS photon index is $\Gamma = 3.4 \pm 0.7$.

5 Non-detected Blazars

VERITAS has observed approximately 90 blazars in search of VHE emission. Unfortunately, most of these observations did not successfully identify a new VHE emitter. The distribution of significance observed from 47 targets, taken from the X-ray/EGRET-selected list used between September 2007 and June 2009, is shown in Figure 1. The distribution is skewed towards positive values of significance. Stacking the result from all these observed blazars (~280 h exposure) yields an excess of 656 events (4.1σ) using selection cuts optimized for soft-spectrum sources[1]. This excess is not seen when stacking results from an identical analysis of other non-detected extragalactic non-blazar observations. A similar VERITAS result was presented at the 2009 ICRC [2]. Interestingly, seven of the objects contributing to that excess have since been detected at VHE (five by VERITAS) and are removed from the stacking here. In addition, several targets now have larger exposures, and some objects from the initial target list were observed after June 2009 and are now included. Twenty-one Fermi-selected objects were observed, but not detected, in the 2009-10 season[2]. The distribution of significance observed is shown in Figure 1. There is no evidence for any stacked excess (~154 h exposure). This may be due to the lack of redshift measurements for many of these objects. Analysis of addtional Fermi-selected objects observed during the 2010-11 season is in preparation.

6 Conclusion

VERITAS has detected 20 blazars, including 10 for the first time at VHE. Every VERITAS discovery has initiated a deep MWL observation campaign and corresponding modeling of the resulting SEDs. In general, one-zone SSC models are reasonable descriptions of the data for the population of VHE HBL objects. Modeling of the objects in the VHE IBL population usually requires an additional EC emission component. Clearly, a deeper population of VHE blazars is desirable. In the future, VERITAS will continue to observe the targets in the initial X-ray/EGRET-selected list, particularly those with marginal excesses in previous VERITAS observations, as well as new targets identified using Fermi-LAT. The strategy for the Fermi-LAT targets may focus on deeper observations of objects, particularly non-HBLs, with large redshifts ($z > 0.3$), and on ToO observations of those that are flaring, as identified through automatic monitoring by the VERITAS collaboration of the public Fermi-LAT data.

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1. The excess is 294 events (3.4σ) using the standard event-selection criteria.

2. Further data were taken in the 2010-11 season.