The VERITAS Blazar Key Science Project

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***Abstract*. The VERITAS array of 12-m atmospheric-Cherenkov telescopes in southern Arizona is currently the world's most-sensitive detector of astrophysical very high energy (VHE; E>100 GeV) γ-rays. Approximately 25 blazars are known to emit VHE photons, and observations of blazars are one of the VERITAS collaboration's key science projects (KSP). More than 50 of these objects have been observed with the array, in most cases with the deepest-ever VHE exposure. This contribution summarizes the VERITAS blazar KSP, with a focus on the upper limits measured in the blazar discovery program. VERITAS blazar detections are presented in detail elsewhere in these proceedings.**

***Keywords*: VERITAS Gamma-ray Blazar**

I. Introduction

Active galactic nuclei (AGN) are the most numerous class of identified VHE γ-ray sources. These objects emit non-thermal radiation across $\sim$20 orders of magnitude in energy and rank among the most powerful particle accelerators in the universe. A small fraction of AGN possess strong collimated outflows (jets) powered by accretion onto a supermassive black hole (SMBH). VHE γ-ray emission can be generated in these jets, likely in a compact region very near the SMBH event horizon. Blazars, a class of AGN with jets pointed along the line-of-sight to the observer, are of particular interest in the VHE regime. Approximately 25 blazars, primarily high-frequency-peaked BL Lacs (HBL), are identified as sources of VHE γ-rays, and some are spectacularly variable on time scales comparable to the light crossing time of their SMBH ($\sim$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) observations of VHE blazars, can measure both SED peaks and are crucial for extracting science 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 emission. 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.

II. VERITAS Blazar KSP

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 5σ detection of a 1% Crab Nebula flux object in <50 hours. The sensitivity of VERITAS will increase by a factor of $\sim$1.2 in Fall 2009, after the relocation of one of the telescopes, and should not degrade over time due to an active maintenance program (e.g. frequent mirror re-coating). For more details about VERITAS, see [4]. VERITAS observes for $\sim$750 h and $\sim$250 h each year during periods of astronomical darkness and partial moonlight, respectively. The moonlight observations are almost exclusively used for blazar discovery observations, and a significant fraction of the dark time is used for the blazar key science project (KSP). The VERITAS blazar KSP consists of:

- A VHE blazar discovery program
- A Target-of-opportunity (ToO) observation program
- Multi-wavelength studies of VHE blazars
- Studies of distant VHE blazars to constrain the EBL

A major goal of the blazar KSP is to increase the number of identified VHE blazars such that scientific conclusions may be drawn from many members of the VHE population, rather than studies of a few remarkable objects. Each year $\sim$10 blazars considered as potential VHE γ-ray emitters are selected for VERITAS discovery observations in astronomical darkness. This fixedduration exposure (10 h goal for each target, of which 200 min is guaranteed) is supplemented by observations of other candidates during partial moonlight, resulting in more than 200 h per year devoted to the discovery of new VHE blazars. The discovery program is discussed in detail later, and the four VHE blazars discovered by VERITAS [5], [6], [7], [8] are presented elsewhere [9].

As part of the KSP an allocation of ∼40 h per year is set aside for ToO observations of blazars. Should this initial allocation be exhausted, additional time can be requested from a pool of ∼80 h set aside for VERITAS director's discretionary time. This ToO component is triggered by either a VERITAS blazar discovery, a VHE flaring alert (>2 Crab) from the Whipple 10-m monitoring of known VHE blazars, or a flaring alert at lower energies from other observatories (optical, X-ray or Fermi-LAT). All four VERITAS discoveries have triggered ToO observations (∼20 h each) to enable a better measurement of the spectrum and light curve. These ToO data are particularly important in the case of a VHE discovery (e.g. RGB J0710+591) during moonlight observations, such that potential systematic effects in the data can be ruled out. The Whipple 10-m blazar monitoring program has triggered one ToO observation. Here, bright flaring of Mkn 421 was discovered in early 2008 triggering deep (∼40 h) VERITAS observations. Six VERITAS snapshot exposures (<5 h) have also been triggered, primarily by Fermi-LAT, but also by an active optical flux monitoring program.

The MWL component of the blazar KSP consists of both pre-planned and ToO campaigns on VHE blazars. For the pre-planned aspect, one VHE blazar is selected each year (e.g. 1ES 2344+514 in 2007-08 & 1ES 1218+304 in 2008-09) to receive a ∼30 h exposure that is coordinated in advance with extensive X-ray, optical/UV and radio observations. For the ToO MWL program, proposals triggered by either a VERITAS discovery or a Whipple 10-m flaring alert are submitted each year to major X-ray, optical and radio observatories. Each blazar discovered by VERITAS, as well as the aforementioned Whipple 10-m alert for Mkn 421, has triggered successful MWL observations. Highlights of the VERITAS MWL observation program are given elsewhere in these proceedings [10].

The blazar KSP also has a program to measure the EBL via deep observations of distant, hard-spectrum VHE blazars. The relatively distant HBL 1ES 1218+304 was observed (see, e.g., [11], [12]) extensively to generate these EBL constraints. Unfortunately there are not many blazars similar to 1ES 1218+304 known in the Northern Hemisphere. Thus the EBL program is, in part, incorporated into the VERITAS blazar discovery program via the inclusion of distant targets.

III. Discovery Program

During the first years of VERITAS' full-scale observations, the discovery of new VHE blazars was a primary focus of the blazar KSP. The targets observed were largely HBL, but also included intermediate-frequency-peaked (IBL) and low-frequency-peaked BL Lac objects (LBL), as well as flat spectrum radio quasars (FSRQs), in an attempt to increase the types of blazars known to emit VHE γ-rays. The blazar discovery targets were drawn from a "target list" containing objects visible to the telescopes at reasonable zenith angles ($-8^\circ < \delta < 72^\circ$). No blazar with a previously published VHE limit below the sensitivity of a typical VERITAS exposure (∼10 h) was included in this target list. Since VHE γ-rays from distant extragalactic sources are strongly attenuated by interactions on EBL photons, only a few objects having a large ($z > 0.3$) were included in the target list. All other large z blazars, or those without a measured redshift, meeting the selection criteria described later were excluded. After considering visibility, redshift, and pre-existing VHE-exposure constraints, the VERITAS target list contains ∼50 suitable blazars. Many of these candidates were already observed by VHE instruments, but the pre-existing VHE flux limits are generally well above (factor of ∼10) the flux sensitivity of VERITAS.

The target list is compiled largely from nearby HBL and IBL recommended as potential VHE emitters in three separate publications [15], [14], [13]. The criteria of Costamante & Ghisellini ([15]; henceforth, CG02) select blazars ($z < 0.45$) that are bright at both X-ray and radio wavelengths, where the X-ray emission can be attributed to synchrotron emission from relativistic electrons in the blazar jet. The criteria of the other two publications [14], [13] are similar, effectively requiring a bright synchrotron X-ray flux and low redshift. However each uses different surveys, minimum X-ray fluxes, and maximum redshifts, resulting in overlapping, but distinct, candidate lists. All recommended candidates (i.e. those not yet detected) are included in the target list. As the most recent of the three aforementioned candidate lists is now ∼7 years old, many nearby HBL have since been identified in new surveys. The X-ray brightest HBL in the recent Sedentary [16] and ROXA [17] surveys meet the CG02 selection criteria and are also included in the VERITAS target list. To continue the VERITAS program of constraining the EBL via the detection of distant blazars, three distant BL Lac objects ($z > 0.3$) recommended by [18], [15], are included in the target list. More than half of the nearby ($z < 0.3$) EGRET blazars are already VHE-detected, and those not yet VHE-detected are also included in the VERITAS target list. It is important to note that the non-HBL AGN detected at VHE energies are all EGRET sources, and were seen exclusively during recent VHE flaring episodes. In February 2009, the Fermi-LAT released its first catalog of MeV-GeV-bright blazars. All nearby Fermi-LAT blazars not-yet-detected in the VHE band are also included in the VERITAS target list. In addition, several FSRQ recommended as potential VHE emitters by [19], [14] are also included in the target list.

IV. Results of Discovery Observations

More than 50 VHE blazar candidates were observed by VERITAS between September 2007 and May 2009. Results from the 2 HBL and 2 LBL discovered as VHE emitters by VERITAS [5], [6], [7], [8] are reported elsewhere [9]. Excluding these 4 discoveries, a total of 47 candidates have some exposure surviving data-quality selection. The total exposure on all these candidates is $\sim$310 h live time, yielding an average exposure of $\sim$6.5 h per candidate. The 47 candidates and their exposures are shown in Table I. Approximately 170 h (54%) of the total exposure is split amongst the 25 observed HBL. The remainder is divided amongst the 9 IBL ($\sim$80 h; 27%), 5 LBL ($\sim$20 h, 6%), and 8 FSRQ ($\sim$40 h, 13%).

The calibration and analysis of the VERITAS data is performed with the standard analysis package [20]. The distribution of the significance observed from each of the blazars is shown in Figure 1 for two different, but correlated, analysis. The first analysis is performed with the *standard-cuts* analysis optimized using VERITAS Crab Nebula data for a weak (3% Crab flux) source. The second *soft-cuts* analysis uses cuts that are modified to considerably increase the sensitivity for steep-spectrum sources ($\Gamma > 4$). The cuts differ in the minimum image size and the size of the on-source integration region. A small trials penalty must be accounted for due to the use of two sets of cuts.

The significance distribution for both analyses is skewed towards positive values compared to what is expected from a Gaussian distribution. Unfortunately there are no clear outliers at positive significance which might indicate evidence for VHE emission from a particular blazar. The lack of outliers is largely the result of a selection effect, since targets which show such "hints" for VHE emission receive follow-up observations until they are either detected or fall below a subjective significance threshold. Keeping this important observational bias in mind, a stacking analysis is performed on the entire data sample. Overall, there is an excess of $\sim$420 γ-rays, corresponding to a statistical significance of 4.8σ, observed from the directions of the candidate blazars in the *standard-cuts* analysis[1]. Ninety percent of the observed excess come from the HBL and IBL targets. This is perhaps not surprising since almost all of the known VHE blazars are HBL or IBL, and $\sim$80% of the total exposure is on HBL and IBL.

The upper limits on the VHE flux emitted by these 47 blazars will be presented at the conference. Preliminary analysis yields a typical limit of $\sim$1.5% of the Crab Nebula flux. The limits are almost always the most-constraining ever measured (see Table I). Given blazar variability considerations, these flux limits are somewhat difficult to interpret. However, these VHE limits do significantly constrain the low-state SED of the blazars.

[1]Stacking the *soft-cuts* results yields an excess of $\sim$770 γ-rays (4.9σ).

V. Conclusion

The first two years of the VERITAS blazar KSP have been highly successful. Highlights include the detection of more than a dozen VHE blazars, including 4 discoveries, with the observations almost always having contemporaneous MWL data. All but a handful of the blazars on the initial VERITAS target list have been observed. The excess seen in the stacked blazar analysis presented here suggests that the direction of the VERITAS discovery program is well justified. Although some of the targets on the current VERITAS list require initial or follow-up observations, a new list of candidates will be observed by VERITAS in future seasons. These targets will likely be drawn from very hard spectrum blazars detected by Fermi-LAT, perhaps only above 1 GeV, 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 campains will increase as data from the Fermi-LAT will be publically available. In particular, future MWL observations of 1ES 0229+200 ($z = 0.139$, $\Gamma = 2.5$) are tentatively planned given the potential EBL implications [3].

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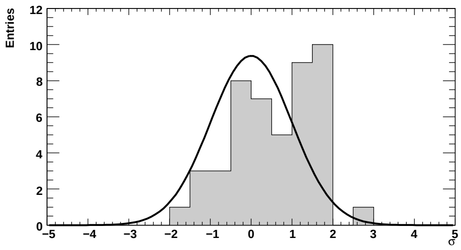
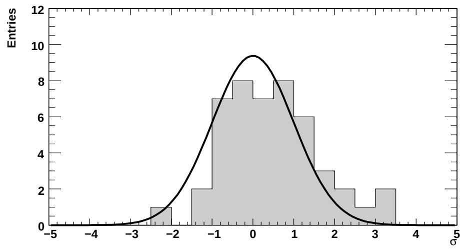


(a) Standard Cuts



(b) Soft Cuts

Fig. 1. The preliminary significance measured from each of the 47 blazars. The *standard-cuts* (a) and *soft-cuts* analysis (b) are most-sensitive to weak sources with Crab-like ($\Gamma \approx 2.6$) and very steep (($\Gamma > 4$) spectra, respectively. The significance observed with each set of cuts is correlated. The curve shows a Gaussian distribution, with mean zero and standard deviation one, normalized to the number of blazars.

TABLE I

THE VERITAS BLAZAR-DISCOVERY TARGETS. THE COORDINATES AND REDSHIFT ARE FROM THE NED DATABASE. THE BL LAC CLASSIFICATION (HBL, IBL, LBL) IS TAKEN FROM [21], UNLESS OTHERWISE NOTED († FROM [16], LM FROM [22], * FROM THE BZCAT SED [23]). THE VERITAS EXPOSURE IS HOURS OF GOOD-QUALITY LIVE TIME. THE 1ES 1215+303 EXPOSURE IS MOSTLY FROM OBSERVATIONS OF 1ES 1218+304 ($\sim$0.8° SEPARATION) AND THUS HAS A LARGER AVERAGE OFFSET THAN THE TYPICAL 0.5° WOBBLE-MODE OBSERVATION. THE NOTES INDICATE THE FOLLOWING: VHE RECOMMENDATION FROM CO [18], CG [15] , P [14], PA [19], SDS [13]; SS = SEDENTARY SURVEY OBJECT [16]; R = ROXA SURVEY OBJECT [17]; F = FERMI-LAT DETECTION [24]; E = EGRET DETECTION [25]; TOO = TOO TRIGGER. THE MOST-CONSTRAINING VHE LIMIT, (CRAB UNITS), CURRENTLY PUBLISHED IS ALSO SHOWN: HEG = HEGRA [26]; H = HESS [27]; M = MAGIC [28]; MIL = MILAGRO; W = WHIPPLE [29], [30], [31].

Source Name	RA (J2000)	Dec (J2000)	Type	Redshift	Exposure [h]	Notes	Prior VHE Limit
RBS 0042	00 18 27.7	29 47 30	HBL†	0.100	5.5	SS	–
1ES 0033+595	00 35 52.6	59 50 05	HBL	0.086	23.7	CG, P	W (11%)
RGB J0110+418	01 10 04.8	41 49 51	HBL	0.096	2.7	P	MIL (11%)
1ES 0120+340	01 23 08.6	34 20 49	HBL	0.272	2.1	CG, SS	M (3.2%)
QSO 0133+476	01 36 58.6	47 51 29	FSRQ	0.859	0.8	ToO	–
RGB J0214+517	02 14 17.9	51 44 52	HBL	0.049	3.0	CG, P	W (17%)
RBS 0298	02 16 32.1	23 14 47	HBL†	0.289	3.0	SS	–
RBS 0319	02 27 16.6	02 02 00	HBL†	0.457	0.3	SS	–
AO 0235+16	02 38 38.9	16 36 59	LBL	0.940	4.6	F, ToO	–
RGB J0314+247	03 14 02.7	24 44 33	LBL	0.054	3.0	P	MIL (18%)
RBS 0413	03 19 51.8	18 45 34	HBL	0.190	9.9	SS	M (3.3%)
1H 0323+342	03 24 41.1	34 10 46	FSRQ	0.061	8.3	P	W (10%)
1ES 0414+009	04 16 53.8	01 04 57	HBL	0.287	9.4	CG, SS	M (5.7%)
1RXS J044127.8+150455	04 41 27.4	15 04 55	HBL†	0.109	9.8	SS	–
1ES 0446+449	04 50 07.2	45 03 12	IBL^{LM}	0.203	5.3	SDS	–
RGB J0643+422	06 43 26.7	42 14 19	IBL*	0.080	1.2		–
1ES 0647+250	06 50 46.5	25 03 00	HBL	0.203	17.6	CG	HEG 13%
RGB J0656+426	06 56 10.6	42 37 03	HBL	0.059	9.4	P	MIL (15%)
PKS 0829+046	08 31 48.9	04 29 39	LBL	0.174	2.4	E	HEG (6%)
Mkn 1218	08 38 10.9	24 53 43	FSRQ	0.028	5.9		W (5%)
RGB J0847+115	08 47 12.9	11 33 50	HBL	0.199	7.1	SS	–
OJ 287	08 54 48.9	20 06 31	IBL*	0.306	6.2	CG, E	MIL (26%)
1ES 0927+500	09 30 37.6	49 50 26	HBL	0.187	11.2	R, SS	M (5.2%)
1ES 1028+511	10 31 18.5	50 53 36	HBL	0.360	11.2	CG, R, SS	MIL (20%)
RGB J1053+494	10 53 44.1	49 29 56	IBL	0.140	5.6	F	–
RBS 0921	10 56 06.6	02 52 14	HBL†	0.236	2.1	SS	–
RX J1117.1+2014	11 17 06.2	20 14 07	HBL†	0.139	1.8	CG, SS, ToO	H (3.0%)
RX J1136.5+6737	11 36 30.1	67 37 04	HBL	0.134	5.0	CG, R, SS	MIL (54%)
1ES 1215+303	12 17 52.1	30 07 01	IBL	0.130?	28.0	CG, F	W (22%)
PKS 1222+21	12 24 54.4	21 22 46	FSRQ	0.432	2.7	F, ToO	–
3C 273	12 29 06.7	02 03 09	FSRQ	0.158	9.2	E, F, R	–
1ES 1255+244	12 57 31.9	24 12 40	HBL	0.141	13.1	SDS, SS	H (1.4%)
RX J1326.2+2933	13 26 14.9	29 33 32	IBL*	0.431	2.4	Co, R	–
RGB J1341+399	13 41 04.9	39 59 35	HBL	0.163	0.9		–
RGB J1417+257	14 17 56.7	25 43 26	HBL	0.237	8.5	CG, R, SS	M (2.3%)
PKS 1424+240	14 27 00.4	23 48 00	IBL	0.160	7.2	F	–
1ES 1440+122	14 42 48.3	12 00 40	IBL	0.162	16.4	CG, R, SDS	H (3.3%)
PKS 1510-08	15 12 50.5	-09 06 00	FSRQ	0.360	2.8	F, ToO	–
RGB J1532+302	15 32 02.2	30 16 29	HBL	0.064	1.5	P	MIL (24%)
RGB J1610+671B	16 10 04.1	67 10 26	HBL	0.067	1.2	P	MIL (73%)
1ES 1627+402	16 29 01.3	40 08 00	FSRQ	0.272	9.2	Pa	W (9%)
GB6 J1700+6830	17 00 09.3	68 30 07	FSRQ	0.301	0.8	F, ToO	–
PKS 1717+177	17 19 13.0	17 45 06	LBL	0.137	5.1	F	–
RGB J1725+118	17 25 04.4	11 52 15	IBL	0.018	9.1	CG, P	M (4.6%)
1ES 1741+196	17 43 57.8	19 35 09	HBL	0.084	2.0	CG	W (5.3%)
RGB J2322+346	23 22 44.0	34 36 14	HBL	0.098	3.2	P	MIL (25%)
1ES 2321+419	23 23 52.1	42 10 59	LBL	0.059	4.2	SDS	HEG (3%)