Blazar Discoveries with VERITAS

J. S. Perkins* **for the VERITAS Collaboration**†

*Fred Lawrence Whipple Observatory, Harvard-Smithsonian Center for Astrophysics, Amado, AZ 85645, USA (jperkins@cfa.harvard.edu)

†see R. A. Ong et al. [1] or http://veritas.sao.arizona.edu/conferences/authors?icrc2009

***Abstract*. Blazars are among the most energetic and violent objects in the universe. By observing blazars at very high energies (VHE, E $>$ 100 GeV) we can better understand blazar emission mechanisms, jet structure, black hole accretion and the extragalactic background light (EBL). VERITAS, an array of four 12-meter diameter imaging atmospheric-Cherenkov telescopes, performs VHE studies of blazars through intense monitoring and discovery campaigns. Most blazars known to emit VHE gamma rays are high-frequency-peaked BL Lacertae (HBL) objects, and VERITAS has discovered VHE emission from two of these: 1ES 0806+524 and RGB J0710+591. VERITAS has also discovered VHE gamma rays from two intermediate-frequency-peaked BL Lacertae (IBL) objects: W Com and 3C 66A. The expansion of the VHE catalog to include IBL objects enables a better understanding of the AGN population as a whole. This contribution presents recent results from the VERITAS blazar discovery program.**

***Keywords*: Gamma-ray astronomy, Active Galactic Nuclei, VERITAS**

I. INTRODUCTION

VERITAS is an array of four 12m diameter imaging atmospheric Cherenkov telescopes (IACT) located at the Fred Lawrence Whipple Observatory in southern Arizona at an elevation of 1268m [2]. In less than 50 hours of observations, VERITAS can detect a source at the 1% Crab flux level in the energy range from 100 GeV to greater than 30 TeV. The array can reconstruct events with an energy resolution of ∼15% and an angular resolution (68% containment) of ∼0.1°. For more details on the VERITAS instrument and techniques, see [1]. The VERITAS capabilities are well suited to the study and search for blazars in the Northern Hemisphere and will become further enhanced once a planned move of one of the telescopes is completed later this year which will yield a ∼15% improvement in sensitivity.

A large fraction of the ∼750 hours of dark time (plus an additional ∼250 hours of moon time) during the VERITAS observing season is dedicated to observing active galactic nuclei (AGN). The focus of these observations is two fold: one, to study known VHE AGN such as Mrk421 or 1ES 1218+304 to learn about blazar emission mechanisms, black hole accretion and the extragalactic background light (EBL) and, two, to discover new types of VHE blazars which will expand the current VHE blazar catalog and perhaps reveal unknown VHE phenomenon. For more details about the VERITAS blazar key science program, see W. Benbow's contribution in this conference[3].

Blazars are characterized by their double-humped spectral energy distribution (SED) and are further classified according to the location of the lower energy hump, usually interpreted as synchrotron emission from

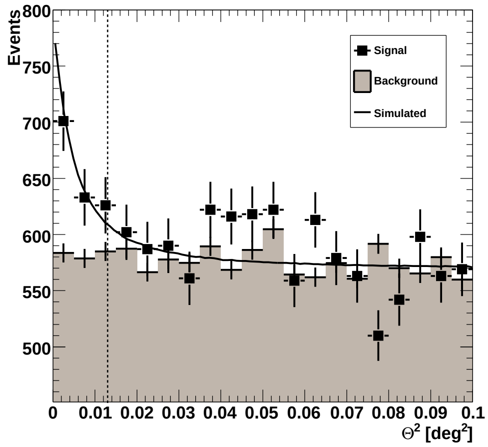


Fig. 1. Distribution of the squared angular distance between the shower direction and the location of 1ES 0806+524. The vertical dashed line indicates the size of the integration region. The solid line indicates the expected shape of the distribution for a point source.

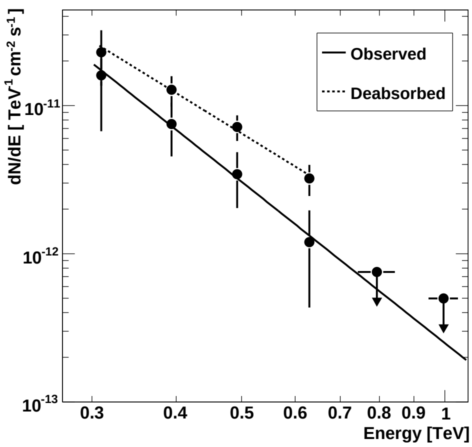
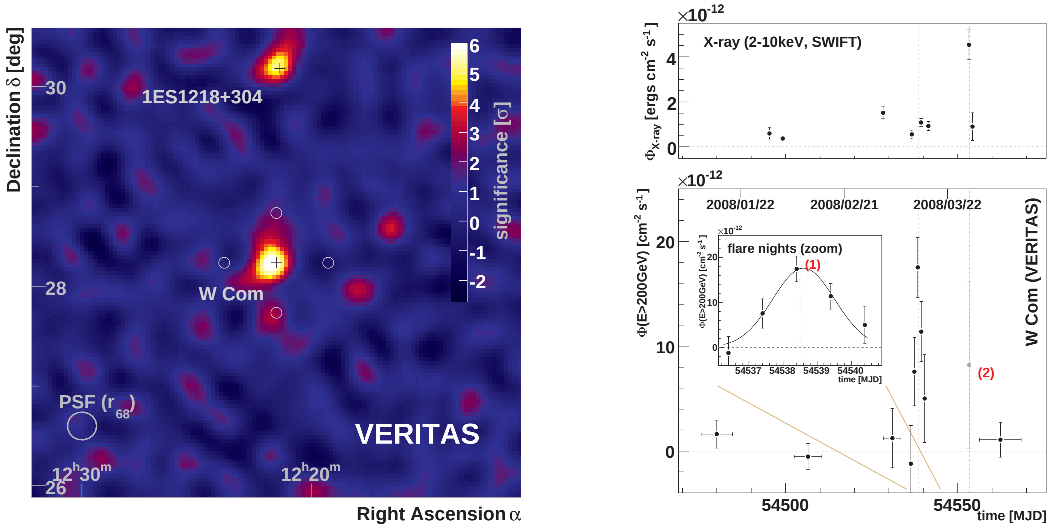


Fig. 2. Differential photon spectrum of 1ES 0806+524. The spectrum is well fit by a power law with index $3.6 \pm 1.0_{stat} \pm 0.3_{sys}$. The de-absorbed spectrum is calculated by applying the extragalactic absorption model according to Franceschini *et al.* , 2008[11].



(a) W Com Skymap (b) W Com Lightcurve

Fig. 3. *Left Panel (3a):* Sky map of significances from W Com. The excess $\sim 2°$ North of W Com corresponds to 1ES 1218+304 and demonstrates the capability of VERITAS to detect sources at the edge of the FoV of the camera. *Right Panel (3b):* The light curve of W Com is shown in the bottom section binned by observation period. The inset is a night-by-night light curve of the four day flaring period. The upper panel is the X-ray flux as measured by the *Swift* telescope.

relativistic electrons. Most of the ~25 VHE blazars detected by ground-based IACT are high-frequency peaked BL Lac (HBL) objects. VERITAS has discovered two HBL objects, 1ES 0806+524 and, more recently RGB J0710+591. In addition to these two HBL, VERITAS has discovered two intermediate-frequency peaked BL Lac (IBL) objects, 3C 66A and W Com. This contribution describes the discovery of VHE γ-rays from these four blazars. There are several other contributions in this conference which will detail the VERITAS observations of known blazars, including multiwavelength (MW) observations and EBL studies ([4], [5], [6], [7], [8], [9]).

II. 1ES 0806+524

The discovery [10] of the HBL 1ES 0806+524 was made with a combination of observations from the commissioning phase of VERITAS (30 hours) and full array time (35 hours). These observations resulted in 245 excess events corresponding to a detection at the 6.3σ level. Figure 1 shows the distribution of the squared angular distance between the shower direction and the location of 1ES 0806+524 indicating that this source is point-like. The photon spectrum shown in Figure 2 is characterized by a power law with photon index $3.6 \pm 1.0_{stat} \pm 0.3_{sys}$ between 300 and 700 GeV. The integral flux above 300 GeV is $2.2 \pm 0.5 \pm 0.4 \times 10^{-12} cm^{-2} s^{-1}$ corresponding to 1.8% of the Crab Nebula's flux. Assuming absorption on the infrared component of the EBL according to Franceschini *et al.* , 2008 [11], the de-absorbed spectrum is calculated to be 2.8 ± 0.5. The VERITAS data together with simultaneous *Swift* observations in the UV to optical to X-ray energies was used to construct a spectral energy distribution (SED) of the object. The SED is well fit by a pure synchrotron-

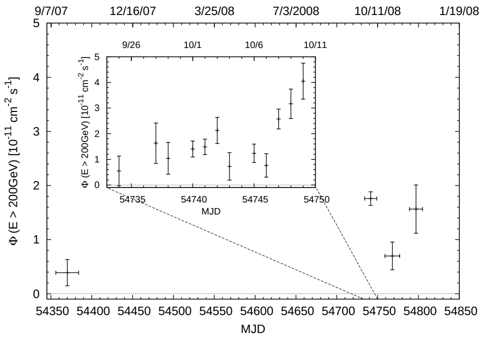
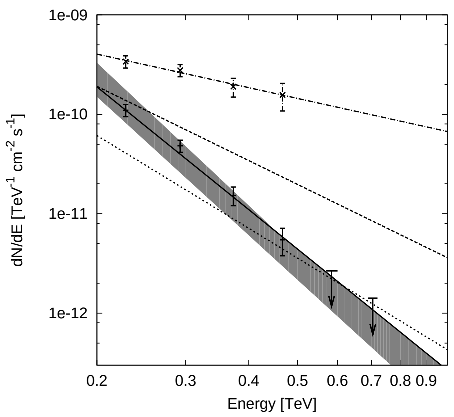


Fig. 4. Light curve binned by observation period for 3C 66A. These data indicate night-by-night variability for the second dark period but not within any of the other dark periods. The inset shows the night-by-night lightcurve for the October observation period.

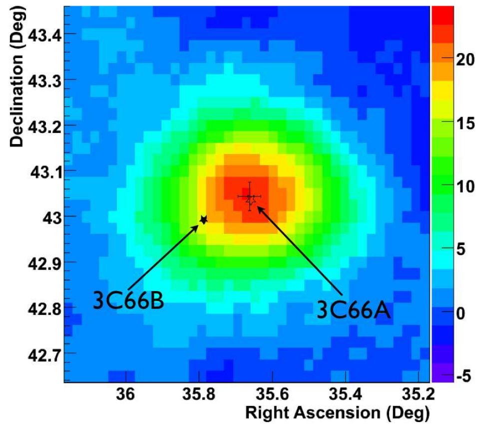
self-Compton (SSC) model [12]. For more details on the multiwavelength observations of this object see J. Grube's talk in this conference [6].

III. W Com

VERITAS discovered the first IBL in VHE γ-rays, W Com, in a flaring state in March 2008 [13] (see Figure 3a). W Com is a known γ-ray source detected previously by EGRET in the 100 MeV - 10 GeV band [14]. The flare, which lasted only four days (see Figure 3b) resulted in a detection at the 8σ level. The significance of the full data set is 4.9σ. 70% of the total excess was from the four-day flaring period and during the two brightest nights, W Comae was observed at the 9% Crab flux level. Using quasi-simultaneous multiwavelength data, the SED can be reasonably modeled with a simple one-zone SSC but this yields an extraordinarily low magnetic field value (B = 0.007 G). A more natural set of fit



(a) Case I



(b) Case II

Fig. 5. *Left Panel (5a):* The photon spectrum of 3C 66A shown as solid points. The spectrum is well fitted by a power law with index $\Gamma = 4.1 \pm 0.4_{stat} \pm 0.6_{sys}$ (solid line). The shaded area outlines the systematic error in the photon spectral index. Using the model of Franceschini *et al.* [11] and assuming a redshift of $z = 0.444$, the de-absorbed spectral index is calculated to be 1.1 ± 0.4 showing that the very steep measured spectrum could be due to the distance of 3C 66A. The de-absorbed spectrum is shown as a dashed-dotted line and points. The MAGIC spectrum[19] with index $\Gamma = 3.1$ is shown as a dotted line. The Crab Nebula's spectrum divided by 10 is also shown for comparison (dashed line). *Right Panel (5b):*Smoothed significance map of 3C 66A. The location of 3C 66A is shown as an open star and 3C 66B as the closed star. The cross is the fit to the excess VHE emission resulting in a localization of 2h 22m 41.6s ± 1.7s ± 6.0s, 43^o 02' 35.5" ± 21" ± 1'30". Note that the bins are highly correlated due to an integration over angular space.

parameters is obtained with an external-Compton model indicating that the higher optical luminosity is likely providing a seed population of photons for inverse-Compton scattering. A second VHE flare was observed from W Comae in June 2008 wherein the flux was ∼3 times brighter than the previous flare [15]. For more details on this second flare, see G. Maier's contribution [9] in this conference. A multiwavelength campaign was triggered during this time and will be the subject of a future paper. Interestingly, the VHE HBL 1ES 1218+304 can also be seen in the field-of-view (FoV) of the W Comae observations which highlights the capabilities of off-axis observations with VERITAS (see Figure 3a).

IV. 3C 66A

The IBL 3C 66A was discovered by VERITAS in 33 hours of observations resulting in a 21.2σ detection (1791 excess events) [16]. Variability is seen on day time scales (see Figure 4) during a strong flare observed in October, 2008. The observed spectrum is well-fit by a soft power law with an index of $4.1 \pm 0.4_{stat} \pm 0.6_{sys}$. The redshift of 3C 66A is uncertain. It was measured to be 0.444 based on a single line [17] and there is a lower limit of 0.096 [18]. If the measured value of 0.444 is correct, the softness of the measured spectrum could be completely due to EBL attenuation of VHE photons (see Figure 5a). Using the model of Franceschini *et al.* [11] and assuming a redshift of $z = 0.444$, the de-absorbed spectral index is calculated to be a very hard 1.1 ± 0.4.

3C 66A lies only $0.12°$ from the radio galaxy 3C 66B and care must be taken in identifying the source of γ-rays from this region. Recently, the MAGIC collaboration reported the detection of VHE gamma-rays from the region in observations carried out in 2007 and claimed marginal evidence (at the 85% confidence level) for association with 3C 66B [19]. However, the VERITAS data exclude the position of 3C 66B at the 4.3σ level (see Figure 5b). In addition to this, the measured VERITAS spectrum does not agree with that measured by MAGIC. One explanation of the discrepancy in source localization is that 3C 66B must have been considerably brighter in 2007 than 2008, and similarly 3C 66A must have been considerably brighter in 2008 than 2007.

Recently the LAT instrument on the Fermi satellite also observed bright emission in the MeV-GeV range at a level higher than that reported by EGRET. In addition, observations of the blazar were made by the *Swift* and *Chandra* satellites. Details of these multiwavelength observations will be the subject of a future paper and are highlighted in L. Reyes' contribution [4].

V. RGB J0710+591

RGB J0710+591 was only recently discovered to emit VHE emission and is the fourth VERITAS blazar discovery [1]. Located at a redshift of 0.125, VERITAS observed RGB J0710 for ~ 20 hours resulting in a $> 6\sigma$ detection from 140 γ-rays corresponding to $\sim 2\%$ of the Crab Nebula's flux. A future publication will describe the VERITAS observations as well as multiwavelength observations from the *Swift*, *Chandra* and Fermi satellites. A preliminary skymap is shown in Figure 6. The preliminary observed spectrum can be described as a power law with photon index $\Gamma = 2.8 \pm 0.3_{stat} \pm 0.3_{sys}$. While not as hard as 1ES 0229+200 which placed the strongest constraints to date on the density of the EBL in the mind-infrared band, the moderately high distance and relatively hard spectrum of RGB J0710+591 confirms the constraints presented in [20].

TABLE I
VERITAS BLAZAR DISCOVERIES.

Source	Type	Redshift	Exposure [hours]	Excess	Significance [σ]	Integral Flux [$10^{-11}cm^{-2}s^{-1}$]	[% crab]	[GeV]	Spectral Index [Γ]
W Com	IBL	0.102	39.5	111	4.9[1]	1.99	9.0	> 200	$3.8 \pm 0.4_{stat} \pm 0.3_{sys}$
RGB J0710+591	HBL	0.125	22.4	141	6.3				$2.8 \pm 0.3_{stat} \pm 0.3_{sys}$
1ES 0806+524	HBL	0.138	65.0	245	6.3	0.22	1.8	> 300	$3.6 \pm 1.0_{stat} \pm 0.3_{sys}$
3C 66A	IBL	0.444	32.8	1791	21.2	1.30	6.0	> 200	$4.1 \pm 0.4_{stat} \pm 0.6sys$

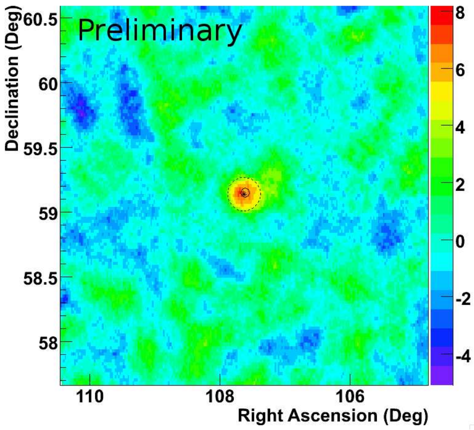


Fig. 6. Preliminary significance skymap of the region centered on RGB J0710+591. The star is the location of the HBL RGB J0710+591. The solid circle is the fit to the position of the γ-ray excess including the statistical and systematic error. The dashed circle is the integration region.

VI. CONCLUSIONS

To date, VERITAS has detected more than a dozen blazars and has discovered VHE emission from four blazars: 1ES 0806+524, RGB J0710+591 W Com and 3C 66A (see Table I). The first two of these are HBL objects while the latter two are IBL objects. The discovery of 1ES 0806+524 highlights the capabilities of VERITAS to detect low-flux objects while the detection of the two IBL objects opens a new window into the study of blazar populations in the VHE regime. Additionally, the detection of 1ES 1218+304 in the FoV of W Com provides an example of the ability to detect objects at the edge of VERITAS' FoV. Future studies of the moderately distant RGB J0710+591 might provide interesting constrains on the EBL.

VII. ACKNOWLEDGMENTS

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