VERITAS Observations of Blazars

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Abstract:

The VERITAS array of four 12-m diameter atmospheric-Cherenkov telescopes in southern Arizona is used to study very high energy (VHE; E>100 GeV) γ-ray emission from astrophysical objects. 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 ~25 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 14 AGN (12 blazars), including 7 for the first time at these energies. Here the blazar KSP is summarized and selected results are presented.

The Key Science Project:

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):** The trigger is either a VERITAS blazar discovery, or a flaring alert (optical, X-ray, Fermi-LAT, Whipple 10-m).
- **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.

The Blazar Discovery Program:

The blazars observed in the discovery program are largely high-frequency-peaked BL Lac objects (HBL). 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 ($-8° < \delta < 72°$), 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 & IBL recommended as potential VHE emitters in [1, 2, 3].
- The X-ray brightest HBL ($z<0.3$) in the recent Sedentary [4] and ROXA [5] surveys.
- Four distant ($z > 0.3$) BL Lac objects recommended by [1, 6].
- Several FSRQ recommended as potential VHE emitters in [2, 9].
- All nearby ($z < 0.3$) blazars detected by EGRET [7].
- All nearby ($z < 0.3$) blazars contained in the Fermi-LAT Bright AGN Sample [8].
- All sources ($|b| > 10°$) detected by Fermi-LAT where extrapolations of their MeV-GeV γ-ray spectrum (incl. EBL absorption; assuming z = 0.3 if z = ?) indicates a possible VERITAS detection in ≤ 20 h

Recent VHE Gamma-ray AGN Discoveries by VERITAS:

RBS 0413, a relatively distant HBL (z=0.19), was observed for 16 h good-quality live time in 2008-09. These data resulted in the discovery of VHE γ-rays (>270γ, ~6σ) at a flux (>200 GeV) of ~2% of the Crab Nebula flux. The discovery was announced simultaneously with the LAT MeV-GeV detection [ATel #2272] . VER J0521+211, likely associated with the radio-loud AGN RGB J0521.8+2112, was detected [ATel #2260] by VERTAS in ~4 h of observations in Oct. 2009 that 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.

Results from Blazars Not Detected by VERITAS:

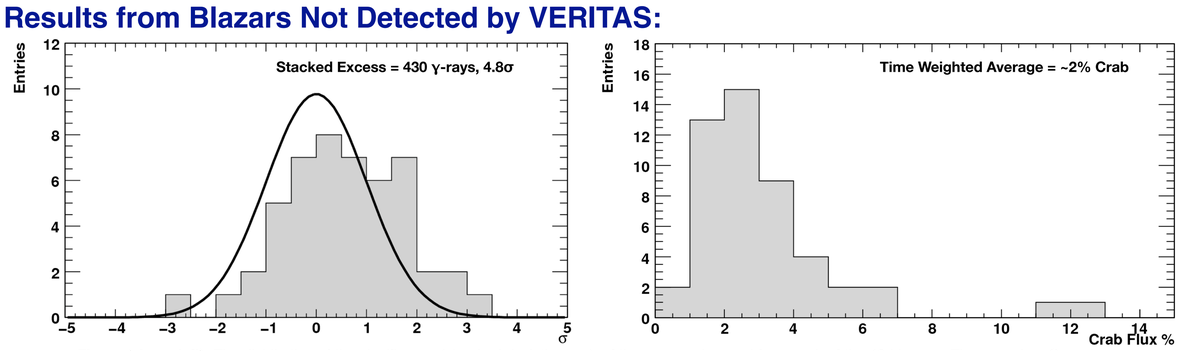


Figure (above-left): The distribution of the significance (standard deviations, σ), of the excess observed from each of the 49 blazars. The curve is a Gaussian distribution, with mean zero and standard deviation one, normalized to the number of observed blazars. **Figure (above-right):** The distribution of the integral flux upper limits, in Crab units, from each of the 49 observed blazars. These limits are often the most-constraining ever for each of the blazars.

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 (avg. 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. A stacking analysis performed on the entire data sample shows an overall excess of γ-rays observed from the directions of the candidate blazars. The IBL & HBL targets make up 96% of this excess, but also comprise ~80% of the total exposure. An identical stacked analysis of all the extragalactic non-blazar targets observed, but not clearly detected (>5σ), by VERITAS does not show a significant excess (~120 h exposure).

VERITAS Detections of Blazars & Other AGN:

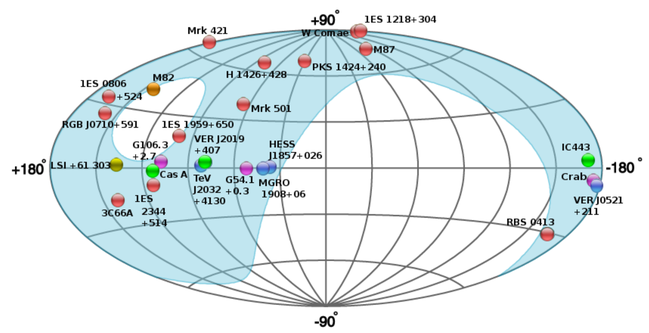


Figure (above): The VERITAS VHE gamma-ray source catalog. All AGN (incl. blazars) are marked with red dots. **Table (right):** All AGN (incl. blazars) detected by VERTAS, along with their source type and their redshift. All of these AGN are detected by the Fermi LAT instrument. M 87 is a radio galaxy (i.e. not a blazar) and the AGN association of the recently discovered VER J0521+211 is not certain. The AGN discovered by VERITAS at VHE are listed with purple text.

AGN	Type	z
M 87	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 1218+304	HBL	0.182
RBS 0413	HBL	0.190
3C 66A	IBL	0.444?
PKS 1424+240	IBL	?
VER J0521+211	?	?

Highlights from VERITAS Multi-wavelength Studies of VHE Blazars:

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, ToO MWL-observation campaigns were performed for every blazar/AGN discovered by VERITAS, and all include Swift (XRT & UVOT) data. All MWL campaigns on the VHE blazars discovered since the launch of Fermi (3C 66A, RGB J0710+591 - please see P. Fortin's poster & PKS 1424+240 - please see A. Furniss' poster) include LAT detections and are each the subject of a joint publication of both collaborations. Several MWL campaigns on the well-studied VHE blazars Mkn 421 and Mkn 501 (please see the posters of D. Gall and A. Konopelko) 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. The VHE & X-ray spectra harden during bright states, and a synchrotron self-Compton (SSC) model can explain the spectral energy distribution (SED) in both the high & low states.
- **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.
- **1ES 0806+524:** The observed SED of this new VHE HBL can be explained by an SSC model
- **W Comae:** This IBL, the first discovered at VHE, flared twice in 2008. 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. Similar to W Com & 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.

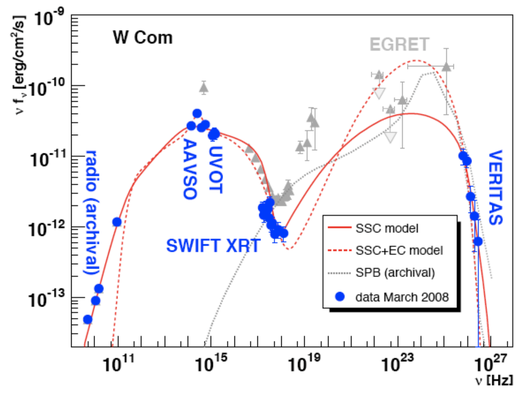
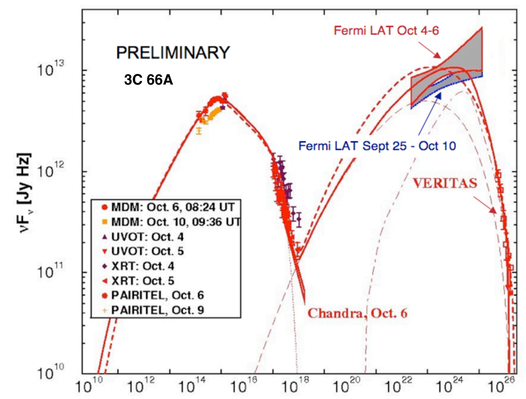


Figure (above): The SED of W Comae in during a flare in March 2008.
Figure (below): The SED of 3C 66A during a flare in Oct. 2008. The dashed line is a pure SSC fit & the solid line is an SSC fit with an EC component.



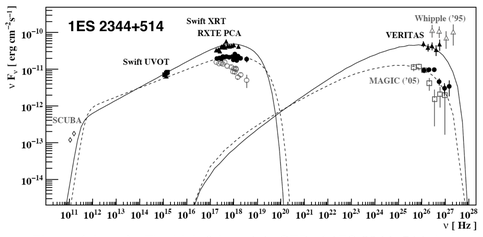


Figure (above): The high & low state SED of 1ES 2344+514 during high & low states in 2007. The curves are SSC fits to the data.

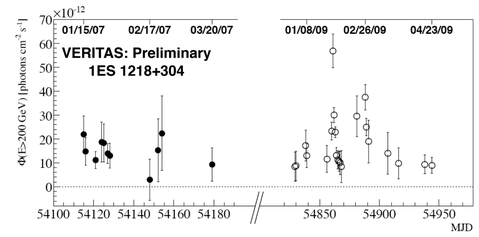
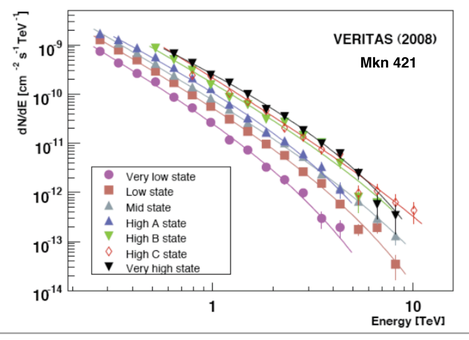


Figure (above): The long-term VHE light curve of 1ES 1218+304.
Figure (below): The VHE spectra of Mkn 421 during different states.



References & Acknowledgments

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