

# Highlights of Recent Multiwavelength Observations of VHE Blazars with VERITAS

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**Abstract.** We present long-term observations of several VHE ( $E > 100$  GeV) blazars with VERITAS, together with contemporaneous *Swift* and *RXTE* X-ray data. The observed targets include Mrk 421, Mrk 501, 1ES 2344+514. Strong flux and spectral variability is seen in Mrk 421 on nightly time-scales between January and June 2008, revealing a highly correlated X-ray to GeV/TeV connection. Modest X-ray variability is evident in Mrk 501. Observations of 1ES 2344+514 in December 2007 show VHE  $\gamma$ -ray and X-ray flux doubling on nightly time-scales.

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

## I. INTRODUCTION

Blazars (BL Lac objects and Flat Spectrum Radio Quasars) are active galactic nuclei (AGN) with a relativistic plasma jet oriented close to the line of sight [1]. These objects exhibit rapid variability and have broadband spectral energy distributions (SEDs) characterized, in a  $\nu F_\nu$  representation, by a synchrotron component extending from radio to X-ray frequencies, and a second component peaking at  $\gamma$ -ray frequencies due to either inverse-Compton radiation or from hadronic processes. BL Lac type blazars are further sub-divided based on the peak frequency of the synchrotron emission as low-, intermediate-, or high-frequency-peaked BL Lacs (LBLs, IBLs, and HBLs). Currently, 20 HBLs from a total of  $\sim 25$  VHE blazars are detected at very high energy (VHE,  $E > 100$  GeV)  $\gamma$ -rays.<sup>1</sup> Elsewhere in these proceedings, the VERITAS blazar observing program is described [2], and the discovery of VHE emission with VERITAS from two HBLs (RGB J0710+591 and 1ES 0806+524), and from two IBLs (3C 66A and W Comae) is highlighted [3].

Multiwavelength campaigns on BL Lacs are important to sample the broadband flux and spectral variability on time-scales ranging from minutes to months. Recent joint observing campaigns with VERITAS on two IBLs are presented elsewhere in these proceedings. Light curves and the broadband SED of 3C 66A are presented from contemporaneous VERITAS, *Fermi*, X-ray, and optical data between September and November 2008 [4]. Observations of W Comae in June 2008 reveal X-ray and VHE  $\gamma$ -ray flaring, with a marginal detection above 100 MeV from AGILE observations [5]. In this paper

<sup>1</sup>TeVcat catalog of VHE  $\gamma$ -ray sources: <http://tevcat.uchicago.edu>

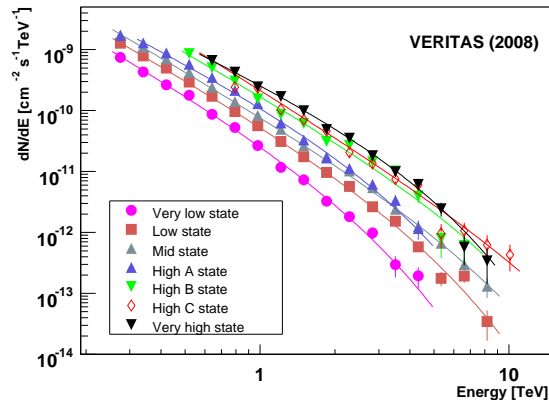


Fig. 1. Time-averaged VERITAS photon spectra of Mrk 421 for discrete flux levels. A power law with exponential cutoff model  $dN/dE = I_0 \cdot (E/1\text{TeV})^{-\Gamma} \cdot \exp(-E/E_{\text{cut}})$  is fit to each spectrum.

detailed multiwavelength results on the bright and well-studied HBLs: Mrk 421, Mrk 501, and 1ES 2344+514 are presented. Multiwavelength results on the recently observed HBL RGB J0710+591 will also be presented at the conference.

## II. VERITAS AND X-RAY DATA ANALYSIS

VERITAS is an array of four imaging atmospheric-Cherenkov telescopes located in southern Arizona. The array is sensitive over the energy range of 100 GeV to  $>30$  TeV, and can detect ( $5\sigma$  level) a source flux of 5% of the Crab Nebula flux in  $\sim 2.5$  hours. All observations presented here pass run quality selection criteria, which removes data taken during poor weather conditions or non-standard hardware configurations. The *wobble* mode, where the source is positioned at a fixed offset of  $0.5^\circ$  from the camera center, was used for all observations presented here. Standard data reduction and  $\gamma$ -ray selection cuts are applied [6]. The results presented here agree well with those performed using an independent VERITAS analysis package.

Long-term X-ray observations with *RXTE* PCA [7] and *Swift* XRT [8] were taken contemporaneously with the VERITAS data. All *RXTE* PCA data were taken with only PCU2 operational. For all *Swift* XRT data on Mrk 421 the observations were taken in window timing (WT) mode, while for 1ES 2344+514 the XRT data were all taken in photon counting (PC) mode. Data reduction is performed with the *HEASoft* 6.5 package, following the standard methods [9], [10]. In particular, annular

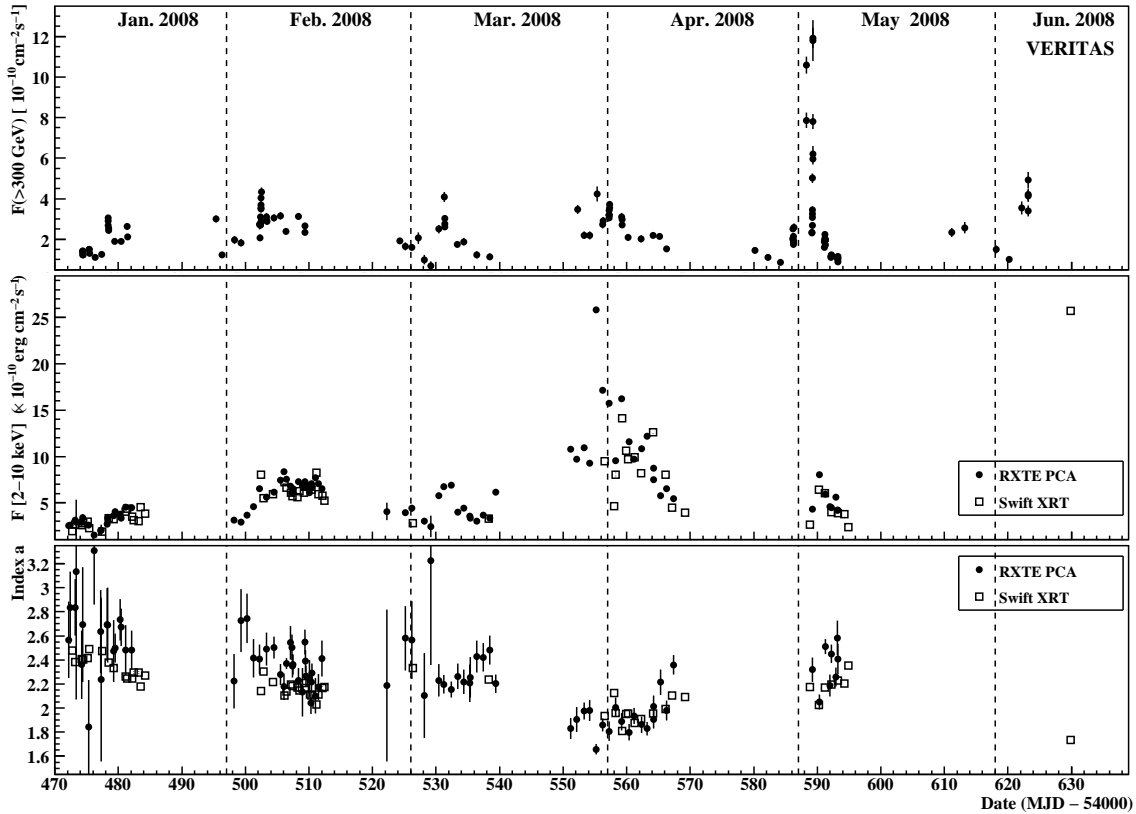


Fig. 2. VHE  $\gamma$ -ray and X-ray light curve of Mrk 421. Shown in the top panel are VERITAS  $F(>300 \text{ GeV})$  fluxes from observations of 20 minutes each. The middle panel shows the 2–10 keV fluxes from observations with *RXTE* PCA (circles) and *Swift* XRT (open squares). The bottom panel shows the X-ray spectral indices ( $\alpha$  parameter, see text) from log-parabolic fits to the 0.4–10 keV *Swift* XRT spectra and 3–20 keV *RXTE* PCA spectra.

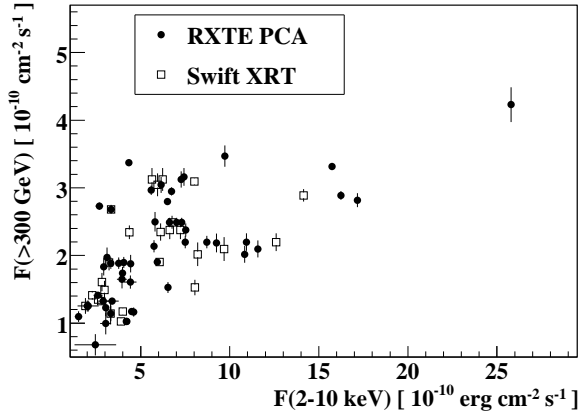


Fig. 3. VERITAS flux  $F(>300 \text{ GeV})$  from 20 min exposures versus the X-ray flux for observations of Mrk 421 taken within  $\pm 5$  hours.

source regions are used to extract the *Swift* XRT data in PC mode when photon pileup is evident [9].

### III. MRK 421

Mrk 421 is a nearby ( $z = 0.031$ ) HBL and is highly variable at UV to VHE  $\gamma$ -ray energies. VERITAS observed Mrk 421 between January and June 2008 for a total live-time of 43.6 hours. An average analysis energy threshold of 260 GeV is determined for the observations that span a range of zenith angles from

$6^\circ$ – $56^\circ$ . In the whole data set an excess of  $\sim 30000$   $\gamma$ -ray events is detected, corresponding to a significance of  $>270 \sigma$ . Previously observed VHE  $\gamma$ -ray spectral variability correlated with flux level [11] is investigated by dividing the VERITAS data into subsets according to flux level. Figure 1 shows the VERITAS spectra in six subsets with best-fit curves for a power law with exponential cutoff model of the form  $dN/dE = I_0 \cdot (E/1\text{TeV})^{-\Gamma} \cdot \exp(-E/E_{\text{cut}})$ . The nightly X-ray spectra from *RXTE* PCA and *Swift* XRT data are best fit with an absorbed log-parabolic model, which uses a fixed column density [10] and an energy dependent photon index  $\Gamma = a + b \cdot \text{Log}(E/E_0)$ . The mean reduced  $\chi^2$  values from log-parabolic fits to the *RXTE* PCA and *Swift* XRT spectra are 0.87 and 1.20 compared to reduced  $\chi^2$  values of 1.35 and 1.80 for an absorbed power law model.

Figure 2 shows on the top panel the nightly VHE  $\gamma$ -ray fluxes  $F(>300 \text{ GeV})$  from nightly VERITAS observations. Shown on the middle and bottom panels are X-ray fluxes  $F(2-10 \text{ keV})$  and spectral indices from *RXTE* PCA and *Swift* XRT observations. Strong flux variability on nightly time-scales is seen over the entire six month period in 2008, with exceptionally bright X-ray flaring in March to April, and VHE  $\gamma$ -ray flaring in early May. A measure of the integrated level of flux variability is the fractional root-mean-square (rms)

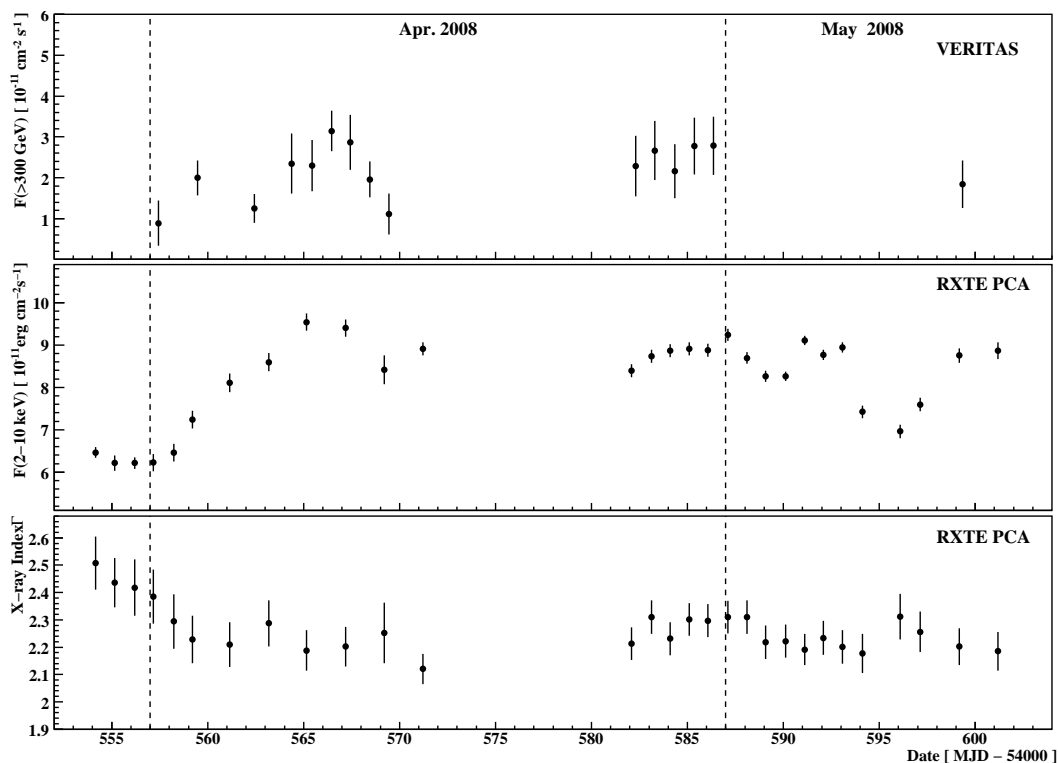


Fig. 4. VHE  $\gamma$ -ray and X-ray light curve of Mrk501. Shown in the top panel are the nightly VERITAS  $F(>300 \text{ GeV})$  fluxes. The middle and bottom panels shows the *RXTE* PCA 2–10 keV fluxes and power law indices, respectively.

variability amplitude  $F_{\text{var}}$  [12]. Significant VHE  $\gamma$ -ray flux variability of  $F_{\text{var}} = (66.5 \pm 0.6)\%$  and X-ray flux variability  $F_{\text{var}} = (57.4 \pm 0.3)\%$  was observed. Figure 3 shows the VHE  $\gamma$ -ray flux versus X-ray flux for observations taken within  $\pm 5$  hours of each other. The highest near-simultaneous X-ray fluxes are from the March to April period. Unfortunately, when VERITAS measured the highest VHE  $\gamma$ -ray fluxes on May 2 and May 3 there were no simultaneous *RXTE* PCA or *Swift* data. Combining all VHE  $\gamma$ -ray flux versus X-ray flux points, the correlation coefficient is  $r = 0.62 \pm 0.07$ . Clear X-ray spectral hardening with increasing 2–10 keV flux is shown in figure 2, with the log-parabolic index parameter  $a$  ranging from  $\sim 1.8$ –2.8.

#### IV. MRK 501

The nearby HBL Mrk501 ( $z = 0.034$ ) was discovered at VHE  $\gamma$ -ray energies by the Whipple 10 m telescope in 1996 [13]. VERITAS observed Mrk501 between April and June 2008 for a total live-time of 6.2 hours. An excess with the statistical significance of  $22 \sigma$  is measured for the total data set. Figure 4 shows the nightly VERITAS VHE fluxes  $F(>300 \text{ GeV})$  and *RXTE* PCA 2–10 keV fluxes and power law indices. Marginal variability is seen in the VERITAS  $F(>300 \text{ GeV})$  fluxes with  $F_{\text{var}} = (14 \pm 12)\%$ , while moderate 2–10 keV flux variability is evident with  $F_{\text{var}} = (12.7 \pm 0.4)\%$ . More detailed results from this campaign are presented elsewhere in these proceedings [14].

#### V. 1ES 2344+514

1ES 2344+514 is another close HBL ( $z = 0.044$ ), and was first detected at VHE  $\gamma$ -ray energies by the Whipple 10 m telescope in 1995 [15]. Figure 5 shows the nightly VHE  $\gamma$ -ray and X-ray light curve of 1ES 2344+514 from VERITAS, *RXTE* PCA, and *Swift* XRT observations. A strong VHE  $\gamma$ -ray flare is seen on December 7, 2007 (54441.12 MJD) at a flux  $F(>300 \text{ GeV})$  corresponding to 48% of the Crab Nebula flux. The measured increase in flux of a factor of  $1.92 \pm 0.53$  between the previous night and the flare night shows the first clear evidence of  $\sim$ day time-scale VHE  $\gamma$ -ray variability from 1ES 2344+514 since the initial Whipple 10 m detection in 1995. Excluding the December 7 flaring event, the average  $F(>300 \text{ GeV})$  is 7.6% of the Crab Nebula flux. For the full VERITAS data set a high level of variability  $F_{\text{var}} = (75 \pm 10)\%$  is implied. Excluding the flare night, a  $F_{\text{var}} = (34 \pm 16)\%$  is determined.

Figure 5 (lower panels) shows the 2–10 keV flux and photon index  $\Gamma$  measured over 3–20 keV from *RXTE* PCA and 0.4–10 keV from *Swift* XRT data. The X-ray flux is shown to be highly variable throughout the campaign, with  $F_{\text{var}} = (51 \pm 1)\%$ . In December 2007, large amplitude flaring is evident with flux doubling time-scales of  $\sim 1$  day. A 2–10 keV flux of  $(6.58 \pm 0.37) \times 10^{-11} \text{ erg cm}^{-2} \text{ s}^{-1}$  is seen from the *Swift* XRT data on December 8, 2007, representing the highest X-ray flux ever measured for 1ES 2344+514. Figure 6 shows the VERITAS flux  $F(>300 \text{ GeV})$  versus *RXTE* PCA and *Swift* XRT 2–10 keV fluxes for nights with

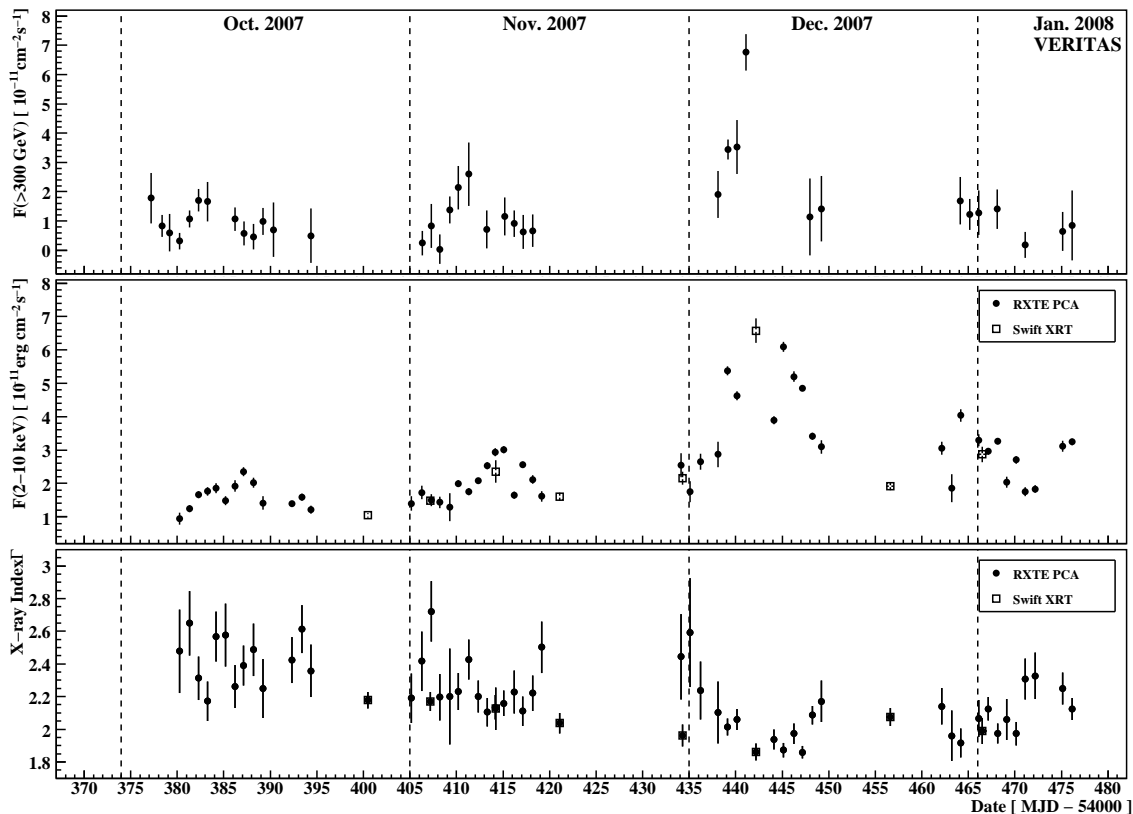


Fig. 5. VHE  $\gamma$ -ray and X-ray light curve of 1ES 2344+514. Shown in the top panel are the nightly VERITAS  $F(>300 \text{ GeV})$  fluxes. The middle panel shows the 2–10 keV fluxes from observations with *RXTE* PCA (circles) and *Swift* XRT (open squares). The bottom panel shows the power law indices  $\Gamma$  from the 0.4–10 keV *Swift* XRT spectra and 3–20 keV *RXTE* PCA spectra.

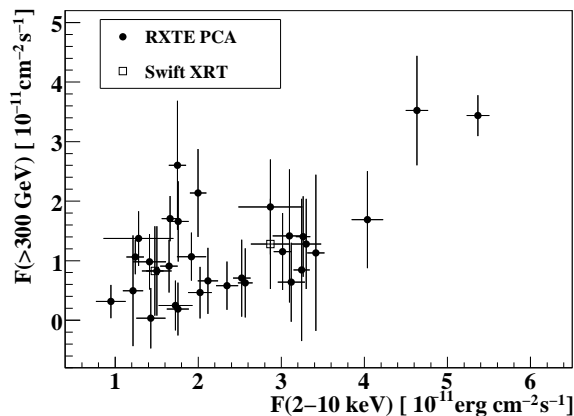


Fig. 6. VERITAS  $\gamma$ -ray flux  $F(>300 \text{ GeV})$  versus X-ray 2–10 keV flux for 1ES 2344+514 observations from nights with *RXTE* PCA (circles) and *Swift* XRT (open squares) data.

observations in both energy bands. A Pearson coefficient of  $r = 0.60 \pm 0.11$  is calculated for the VHE  $\gamma$ -ray to X-ray flux points, suggestive of correlated variability. Further results and discussion on this campaign are in press [16].

## VI. CONCLUSIONS

Joint VHE  $\gamma$ -ray and X-ray observing campaigns on the bright HBLs Mrk 421, Mrk 501, and 1ES 2344+514 with VERITAS reveal significant flux variability on

nightly time-scales. X-ray spectral hardening is shown at increasing flux levels. Results from synchrotron self-Compton (SSC) modeling of the broadband SED will be presented at the conference.

## ACKNOWLEDGMENTS

This research is supported by grants from the US Department of Energy, the US National Science Foundation, and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. We acknowledge the excellent work of the technical support staff at the FLWO and the collaborating institutions in the construction and operation of the instrument.

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