

Highlights of recent results from the VERITAS gamma-ray observatory

Lucy Fortson¹ for the VERITAS Collaboration²

¹ University of Minnesota

² <http://veritas.sao.arizona.edu/>

E-mail: fortson@physics.umn.edu

Abstract. VERITAS is a major ground-based gamma-ray observatory comprising an array of four 12 meter air Cherenkov telescopes operating at the Fred Lawrence Whipple Observatory near Tucson, Arizona. Data taking has continued from 2007 with a major camera upgrade completed in 2012 resulting in the current sensitivity to very-high-energy (VHE) gamma rays between 85 GeV and 30 TeV. VERITAS has detected 54 sources (half of which have been discoveries) leading to many significant contributions to the field of VHE astronomy. These proceedings highlight some of the more recent VERITAS results from the blazar and galactic observing programs as well as measurements of the cosmic-ray electron spectrum, constraints on dark matter and a follow-up program for astrophysical neutrinos.

1. Introduction

This paper provides an overview of recent science results from the VERITAS very-high-energy (VHE) ground-based gamma-ray observatory located at the basecamp of the Fred Lawrence Whipple Observatory (FLWO) near Tucson, AZ. VERITAS comprises four 12 meter telescopes on an average baseline of 100 meters. Each telescope of Davies-Cotton design has a 3.5° FoV camera with 499 PMTs, currently 2.5 cm diameter Hamamatsu high quantum efficiency tubes with a 0.15° spacing. [1, 2, 3]. VERITAS saw first light with all four telescopes in 2007 and has been fully operational ever since. To improve our overall sensitivity and lower our energy threshold, we have undertaken several upgrades completed in 2012 as detailed in [3]. The impact of the combined upgrades has improved our overall sensitivity; the observation time for a 5σ detection of a 1% Crab source has been reduced from over 40 hours to about 20 hours.

VERITAS typically records ~ 1200 hours of dark and low illumination moonlight time per year with an additional ~ 200 hours of data taken under bright moonlight conditions operating with reduced high voltage (RHV) where the PMT voltages are reduced to 81% of their standard dark-sky observation values. The RHV observation mode enables VERITAS to operate when the moon is 35-65% illuminated. While this mode imposes a higher energy threshold (> 150 GeV), the sensitivity of the RHV observation mode is similar to the standard VERITAS sensitivity. RHV observations have enabled several detections an example of which is our recent detection of a flare in the nearby ($z=0.055$) blazar 1ES 0727+502 detected first under RHV observations in May 2013 and continued with dark time observations including MWL partners. The flare was 5x the detection flux by MAGIC and shows for the first time evidence of variability in the VHE band for this source [4].



Observations with VERITAS since 2007 have resulted in 54 detections spread over 8 source classes in both galactic and extragalactic categories. This review will necessarily be brief - for further details on recent results, see [5]. In §2 we discuss recent results from deep observations of supernovae by VERITAS while in §3 we describe the VERITAS blazar observing program with a focus on the recent detection of the distant flat-spectrum radio quasar (FSRQ) PKS 1441+25. We then present in §4 the most recent dark matter limits derived from deep observations of dwarf spheroidal galaxies as well as results from follow up observations of potential dark matter subhalos among the *Fermi*-LAT unassociated sources. The VERITAS cosmic-ray electron spectrum results are presented in §5 and we conclude in §6 with follow-up VERITAS observations on several IceCube astrophysical neutrino target locations.

2. Deep Observations of Three Supernovae

Supernova Remnants (SNRs) are broadly accepted as the main accelerators of galactic cosmic rays (CRs) with energies up to the knee region ($\sim 10^{15}$ eV). As part of our galactic observing program, VERITAS has taken deep exposures on three historical SNR – the two young remnants Cas A and Tycho and the older remnant IC 443. Through these observations, we hope to learn about the various cosmic ray acceleration mechanisms, the ensuing production of gamma rays, probe the distribution of energetic particles in the acceleration regions and understand the relationship of these to the SNR type, age and environment.

Figure 1 shows the spectral energy distributions (SED) of these three SNR including new VERITAS results as well as *Fermi*-LAT data in the high-energy gamma-ray regime (30 MeV to 300 GeV) [6]. The IC443 spectrum shows the pion bump result from *Fermi*-LAT indicating evidence of accelerated CR protons [7]. Interestingly, IC443 also shows a softer spectrum in VHE energies [8] compared to Cas A [9] which we might expect with the older remnant having lost its highest energy cosmic rays. However, the new VERITAS results from Tycho [10] also show a softer spectrum at the highest energies which is now in tension with both hadronic and leptonic emission models [11]. For Cas A, a hadronic model is preferred at lower energy [12] but at higher energy both leptonic and hadronic mechanisms may contribute [13].

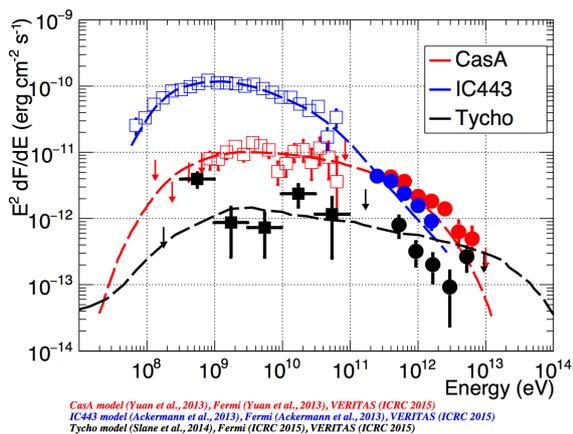


Figure 1. SED of three classic SNR with VERITAS points in filled circles and *Fermi*-LAT points in boxes; lines are from specific models given in the legend below plot and references: CasA [12], IC443 [7], Tycho [11].

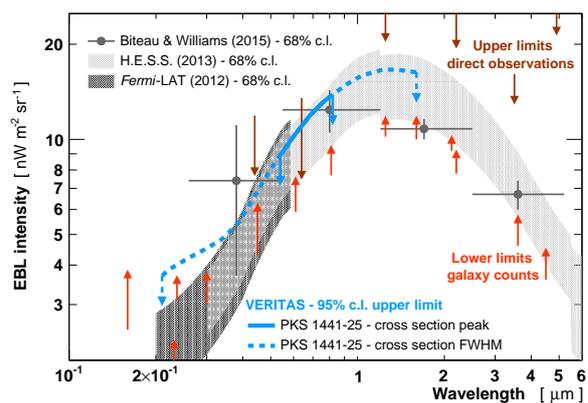


Figure 2. Near-ultraviolet to near-infrared spectrum of the EBL. The upper limit from VERITAS observations of the high-redshift FSRQ PKS 1441+25 is shown in regions corresponding to the peak (solid blue) and FWHM (dashed blue) of the cross section ($1 < \tau < 2$).

3. Blazar Program

The VERITAS blazar program [14] has detected 34 of the ~ 50 northern hemisphere known VHE emitting active galactic nuclei (AGN) including seven intermediate-synchrotron peaked BL Lac objects (IBLs), two Flat FSRQs and two Fanaroff-Riley type 1 (FR 1) galaxies. Twelve of these detections are VERITAS discoveries. All VERITAS AGN are also detected in *Fermi*-LAT and a vigorous multi-wavelength (MWL) program ensures that most detections have simultaneous MWL data. The scientific objectives of the program are to probe the origin of AGN jet emission; understand the dynamics and evolution of the environment surrounding the supermassive black hole at the centers of AGN; and utilize blazars for cosmological and fundamental physics studies. While 25% of VERITAS blazars have uncertain redshift, those with well-measured redshifts provide a large sample of blazars for studies of the extra-galactic background light (EBL) enabling VERITAS to probe a range of optical opacities across the gamma-ray horizon.

VERITAS recently detected PKS 1441+25, an FSRQ at $z=0.939$ making it the second most distant FSRQ detected in the VHE. After being detected by MAGIC following a *Fermi*-LAT trigger, VERITAS observed this object for ~ 15 hours from April 15-28, 2015, and found it to exhibit a steady flux above 80 GeV of $\sim 5\%$ Crab. Further observations a month later saw no detection.

VERITAS observed gamma rays emitted from PKS 1441+25 up to ~ 200 GeV which, when coupled with estimates of the black hole mass, suggests that the emission region for this outburst was located thousands of Schwarzschild radii away from the black hole. In addition, given the extraordinary distance of PKS 1441+25, its flux, particularly at higher energies, should be severely attenuated by the EBL. We make the assumption that the HE and VHE emission arise from the same component, then utilize the unattenuated HE spectrum to set an upper limit on the intrinsic hardness of the spectrum. After performing calculations following [15], we obtain stringent constraints on the EBL intensity below $1\mu\text{m}$ with the interpretation that galaxy surveys have resolved most, if not all, of the sources of the EBL in this region. See Figure 2 and [16] for details.

4. Dark Matter Limits

The VERITAS Dark Matter (DM) program searches for a gamma-ray flux of particle DM annihilation or decay from 100 GeV to the multi-TeV scale and comprises deep observations of four potential DM candidate classes: the Galactic Center, Galaxy Clusters, Dwarf Spheroidal Galaxies (dSphs) and *Fermi*-LAT Unassociated Sources. Recent results on the latter two classes are briefly described with further details in [17, 18], respectively.

DSph galaxies are relatively nearby (20-200 kpc), are thought to be DM dominated, and are unlikely sources of astrophysically produced gamma rays. For these reasons, they make excellent targets for the search for gamma-ray signatures of DM. For the past two years, VERITAS has spent $\sim 12\%$ of its annual observing time on dSph galaxies. A recent stacked analysis of four dSph fields (Segue 1, Draco, Ursa Minor, and Bootes) comprising a total of ~ 216 hours has yielded competitive preliminary exclusion limits for several annihilation channels including the $\chi\chi \rightarrow \tau\tau$ results shown in Figure 3.

Another promising target for gamma-ray signatures of DM is *Fermi*-LAT unassociated sources that could be clumps of DM within low mass substructure predicted in simulations of the distribution and evolution of DM in Milky-Way-like galaxies. With minimal accumulated baryonic matter (and thus unlikely emitters at longer wavelengths), these clumps would emit a steady flux of gamma rays due to DM annihilation, producing a characteristic cutoff in the HE-VHE range depending on the mass of the DM particle. VERITAS performed a search on two promising DM subhalo candidates identified using the 2FGL Catalog (2FGL J0545.6+6018 and 2FGL J1115-00701) with 8.5 and 13.6 hours respectively of observation time yielding no significant VERITAS detections. A dedicated *Fermi*-LAT analysis was also performed for

these sources. The results exclude 2FGL J1115-00701 as a subhalo candidate due to observed variability in the HE band. The SED of 2FGL J0545.6+6018 was interpreted in terms of several different DM annihilation channels with $b\bar{b}$ and W^+W^- providing reasonable fits, yielding respective WIMP masses of 78.3 GeV and 89.2 GeV.

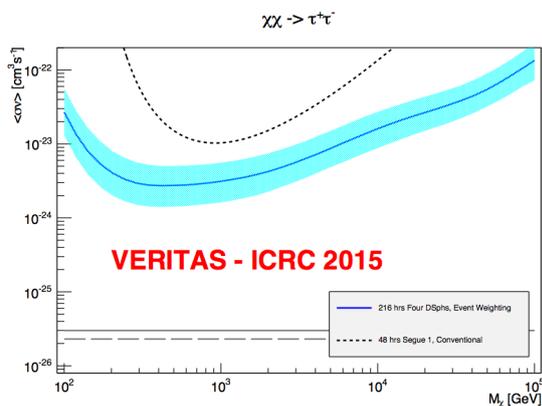


Figure 3. (From [17]). Expected annihilation cross section limits for the joint analysis of dSph data as a function of DM particle mass. Limits shown are for the 95% confidence level for the $\tau\tau$ channel. Also shown are VERITAS Segue 1 results [19]. The aqua band represents the 1σ systematic uncertainty on the DM density profile and the grey solid and dashed lines show generic values for the annihilation cross-section in the case of thermally produced dark matter.

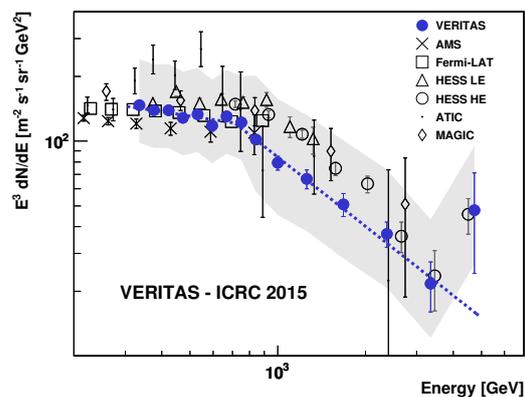


Figure 4. (From [20]). Preliminary cosmic-ray electron spectrum from ~ 290 hours of VERITAS data covering the $\sim 300\text{GeV} - 5\text{TeV}$ energy range. Also shown are other satellite-based and ground-based measurements with overlapping energy data points. The best fit to the VERITAS data comes from a broken power-law distribution and is shown as an overlaid dashed line. The gray band represents the systematic uncertainty.

5. Electron Spectrum

Ground-based gamma-ray observatories can measure the VHE component of the diffuse cosmic ray electron (CRE) spectrum providing information on the local galactic environment. CREs suffer energy-dependent losses in their propagation limiting their distance to be maximally within ~ 1 kpc for VHE electrons. When combined with HE data from space-based instruments such as *Fermi*-LAT and AMS, structure observed in the measured spectrum could be interpreted as, among other possibilities, a signature of dark-matter or arising from HE electron emission by a nearby pulsar. Figure 4 shows the preliminary cosmic ray electron (CRE) spectrum measured by VERITAS as described in [20]. The spectrum is best described as a broken power-law with a cutoff where the best fit for a cutoff energy is 710 ± 40 GeV and for spectral indices below (above) this energy is 3.2 ± 0.1 stat (4.1 ± 0.1 stat). These results are in reasonable agreement with the previous results from HESS that show a power-law with ~ 1 TeV cutoff [21] as well as results from prior ground-based and satellite-based measurements at lower energies.

6. Astrophysical Neutrino Follow-up

The IceCube neutrino observatory has recently published evidence for the detection of astrophysical neutrinos [22, 23]. VERITAS observed the sky positions of three contained and 15

uncontained muon events detected by IceCube that are candidate astrophysical neutrino events. The former positions are available publicly, the latter via a cooperative agreement between VERITAS and IceCube; only muon track positions are used as their angular uncertainty ($\sim 1^\circ$) is smaller than the VERITAS field of view. The analysis and results are discussed in detail in [24]. After accounting for the statistical trials involved in the analysis, there is no evidence for gamma-ray emission associated with any of the neutrino positions observed by VERITAS.

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