VERITAS highlights of observations and results

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Abstract

Located in southern Arizona, VERITAS is amongst the most sensitive detectors for astrophysical very high energy (VHE; E>100 GeV) gamma rays and has been operational since April 2007. We highlight some recent results from VERITAS observations. These include the long-term observations of the gamma-ray binaries HESS J0632+057 and LS I +61° 303, the observations of the Galactic Center region, and of the supernova remnant Cas A. We discuss the results from a decade of multi-wavelength observations of the blazar 1ES 1215+303, the EHT 2017 campaign on the M87 galaxy, the discovery of 3C 264 in VHE, and the observation of three flaring quasars. Brief highlights of the indirect dark matter searches and targets-of-opportunity (ToO) observations are also discussed. The ToO observations allow for rapid follow-up of multi-messenger alerts and astrophysical transients.

1 Introduction

VERITAS is one of the most sensitive ground-based γ-ray observatories. It is located at the Fred Lawrence Whipple Observatory in southern Arizona (31 40N, 110 57W, 1.3 km a.s.l.). The VERITAS array has four 12-m diameter, 12-m focal length imaging atmospheric Cherenkov telescopes. Each telescope has a Davies-Cotton-design segmented mirror dish of 345 facets and focuses the Cherenkov light from particle showers onto a pixelated camera having 499 PMTs and a total field of view of 3.5°. VERITAS began full operation in April 2007. Since then, it has undergone two major upgrades. In the first upgrade, during summer 2009, one of the four telescopes was relocated to a different position [1]. In the second upgrade, in summer 2012, PMTs (with the higher quantum efficiency and shorter time profile), and a new topological trigger system were installed [2]. The current configuration of the array can detect an object having 1% of the Crab Nebula flux in ∼25 hours with a gamma-ray-photon energy resolution
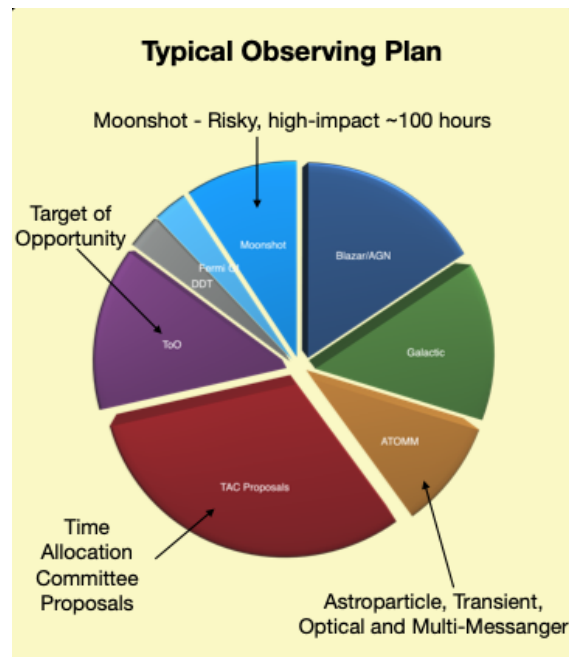
Figure 1: Typical observing plan of VERITAS.

of 15-25%. For a 1 TeV photon, the 68% containment radius is ≤0.1°, with a pointing accuracy of <50". The details of the evolution of the performance of the VERITAS instrument with time are discussed in [3]. In order to account for the changing optical throughput and detector performance over time, signal calibration methods have recently been implemented to produce a fine-tuned instrument response functions [4].

2 VERITAS observing program

The VERITAS observing season spans from September to July each year. Each year, the array collects ∼950 h of good-weather data during dark time and ∼250 h of data during bright moon (illumination of 30-65%). The typical annual VERITAS observation plan breakdown is shown in Figure 1.

3 Galactic science highlights

γ-ray binaries – HESS J0632+057 and LS I +61° 303: Based on the composition and energy output, gamma-ray binaries can be defined as systems consisting of a compact object orbiting a star (O or Be), with periodic release of large amounts of non-thermal emission at energies >1 MeV [5]. The VERITAS archive includes one of the largest data sets for the sources of this class, which includes ∼260 h and ∼174 h of good quality data (after applying weather-based time cuts) for HESS J0632+057 and LS I +61° 303, respectively.

Located at a distance of 1.1-1.7 kpc, HESS J0632+057 consists of an unknown compact object orbiting a Be star (MWC 148) with a period of 321 ± 5 days [6]. The data from three major atmospheric Cherenkov telescopes: H.E.S.S. [7], MAGIC [8], and VERITAS [3] were used to study the very high energy (VHE) γ-ray emission from this source, resulting in a total of 450 h over 15 years, between 2004 and 2019. The VHE γ-ray fluxes were found to be modulated with the orbital period of 316.7 ± 4.4(stat) ± 2.5(sys), consistent with the value
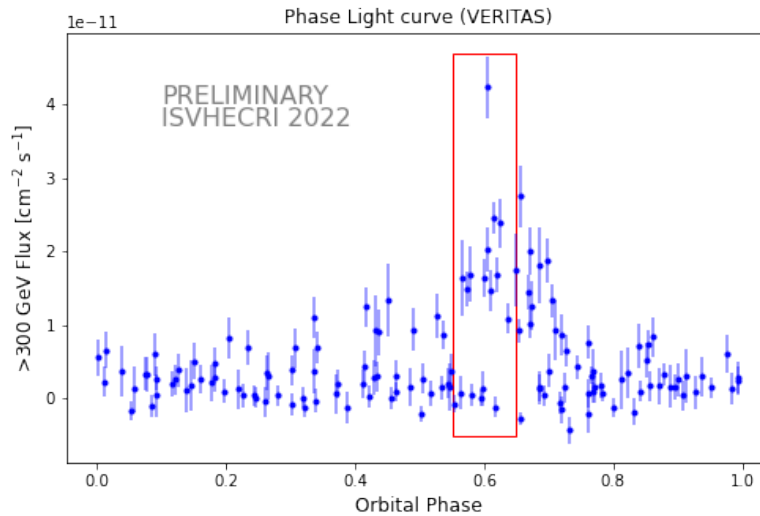
Figure 2: Orbital phase-binned light curve of LS I +61° 303. The starting MJD and the orbital period used are 43366.8 days and 26.5 days, respectively.

obtained at X-ray energies [9]. This large data set includes dense observational coverage for several orbits, which reveal short-timescale and orbit-to-orbit variability.

The γ-ray binary LS I +61° 303 consists of a rapidly rotating BeVe star located at 2.65 ± 0.09 kpc [10] and a compact object orbiting with a period of 26.5 days [11]. The recent detection of radio pulsations from the direction of this source by the the Five-hundred-meter Aperture Spherical radio Telescope suggests that the compact object is a rotating neutron star [12]. The orbital phase light curve of nightly-binned flux points from the analysis of ∼174 h of VERITAS data above 300 GeV is shown in Figure 2. The box shown in red includes the highest state (∼30% Crab Nebula flux above 300 GeV) of LS I +61° 303 occurred in October 2014, during which the flux variability on night-timescale was observed [13]. Other than this state, nearly a factor of two flux difference in the orbital phase bin of (0.55-0.65) suggests the orbit-to-orbit variability. LS I +61° 303 is detected above 5σ in most of the bins, except phase bins (0.1-0.2), (0.2-0.3), and (0.9-1.0), where the significance is about 4σ [14].

Galactic center region: The Galactic Center (GC) region hosts numerous powerful sources and potential sites of particle acceleration, including the supermassive black hole Sagittarius A* (Sgr A*), supernova remnants (SNRs), and pulsar wind nebulae. VERITAS observes the GC at large zenith angles (⩾ 60°), resulting in an increased effective area of about four times greater than the effective area at a zenith angle of 20° for energies above 10 TeV, and increased in the systematic. This also raises the energy threshold for the GC analysis to about 2 TeV. 125 h of VERITAS data resulted in a detection of Sgr A* at a significance of 38σ. The differential spectrum is best fitted with a power law with an exponential cutoff at $10.0^{+4.0}_{-2.0}$ TeV and a spectral index of $2.12^{+0.22}_{-0.17}$. The analysis of the diffuse GC ridge shows a power law spectrum extending to the highest observed energy of ∼40 TeV and a hard spectral index of 2.19 ± 0.20. This supports the evidence for a PeVatron in the GC region. A more detailed discussion of this analysis can be found in [15].

Supernova remnant – Cassiopeia A: SNRs are thought to be the most favorable sites for the acceleration of Galactic cosmic-rays up to PeV energies. Among the SNRs, the young SNR are considered the best candidates to be detected at VHE, since the highest energy cosmic rays,

which are believed to be produced early on, will not yet have escaped from the production site. The young (∼350 years old) core-collapse SNR Cassiopeia A is a potential PeVatron candidate. VERITAS has studied this source with a deep exposure of 65 h. The joint spectrum was produced with VERITAS data covering 200 GeV-10 TeV and 10.8 years of *Fermi*-Large Area Telescope data covering 0.1-500 GeV. The best fit was obtained with the power law spectral index of 2.17 ± 0.02(stat) and cutoff energy of 2.3 ± 0.5(stat) TeV [16]. Considering a one-zone model, proton acceleration up to at least 6 TeV is required to reproduce the observed γ-ray spectrum.

4 Extra-galactic science highlights

The VERITAS AGN observations are broadly conducted under four major programs, namely: discovery program, multi-wavelength (MWL) campaigns, ToO, and cosmology. The highlights of the first three programs are mentioned in this section.

Blazar – 1ES 1215+303: A high-synchrotron-peaked BL Lac (HBL) 1ES 1215+303 (z=0.13, [17]) was extensively studied in a MWL context using long-term data from radio to γ-ray energies. a VERITAS exposure of 175.8 h was used in this study, which includes regular monitoring observations since December 2008. The synchrotron peak frequency from a low state to the 2017 flaring state was observed to be shifted from infrared to soft X-ray [18].

Radio Galaxies – 3C 264 and M87: The misaligned geometry of radio galaxies provides a unique view of the AGN's jet and super massive back hole. Among TeV-detected radio galaxies, 3C 264 ($z = 0.0217$, [19]) is the most distant, and is only the fourth known radio galaxy at these energies. VERITAS has collected ∼57 h good quality data between February 2017 and May 2019, which yielded a detection with a statistical significance of 7.8σ. The VHE γ-ray spectrum was well described by a power law with an index of 2.20 ± 0.27 and a flux of ∼0.7% of the Crab Nebula flux above 315 GeV [20].

During the 2017 Event Horizon Telescope MWL campaign on M87, VERITAS captured the source in its historically low state, but still dominating over the nearest knot, HST-1 [21]. The most complete simultaneous MWL spectrum was reported in that study, which included 15 h of quality-selected VERITAS data. The analysis resulted in an overall statistical significance of 3.8σ. The legacy data set and analysis scripts were made available to the community through the Cyverse repository [22].

Quasars – 3C 279, PKS 1222+216, and Ton 599: Known flat-spectrum radio quasars (FS-RQs) are generally at larger distances compared to BL Lacs, hence with the current generation VHE γ-rays telescopes their detection is difficult, both because of the attenuation of VHE γ-rays from these distances due to absorption by the extra-galactic background light and because of possible intrinsic spectral cutoffs above GeV energies [23]. Three FSRQs; 3C 279, PKS 1222+216, and Ton 599, were studied to explore the γ-ray variability and spectral characteristics using almost 100 h of VERITAS data spanning over 10 years. The location of the γ-ray emission region and the jet Doppler factor were constrained during VHE-detected flares in 2014 and 2017, for PKS 1222+216 and Ton 599, respectively [24]. Also, theoretical constraints on the potential production of PeV-scale neutrinos were placed during these VHE flares.
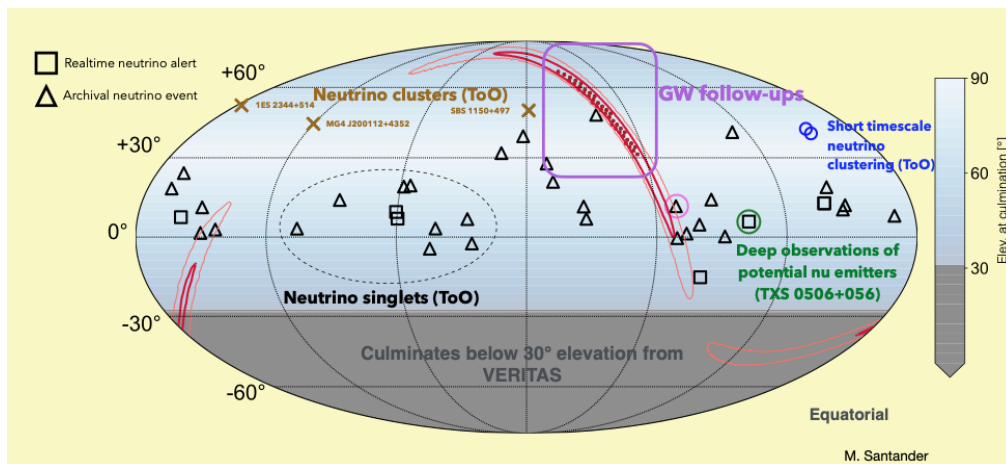
Figure 3: The sky map showing some MM triggers observed by VERITAS (Adopted from [27]).

5 Indirect dark matter search

Dwarf Spheroidal galaxies (dSphs) are a favorable target class for an indirect dark matter (DM) search. The analysis of four dSphs (Boötes I, Draco, Segue 1, and Ursa Minor) with the VERITAS data taken from 2007 to 2013 was reported in [25]. This included a total quality-selected observation time of 476 h to search for a DM signal and was sensitive to potential signals in the $\tau^+\tau^-$ and $b\bar{b}$ annihilation channels. No DM signal was detected.

6 Multi-messenger and astrophysical transient observations

VERITAS devotes a part of its observing time to multi-messenger (MM) and astrophysical transient observations to search for electromagnetic counterparts to high energy neutrinos and gravitational waves. These observations are proposal driven and result into significant fraction of total VERITAS observing time. Figure 3 shows some MM triggers observed by VERITAS. The IceCube observatory reported a well-reconstructed high energy neutrino event, IceCube-201114A (GCN 28887), on November 14, 2020, having an estimated energy of ∼214 TeV. It is spatially coincident with the high-energy-peaked object, NVSS J065844+063711 [26]. During November 15-19, 2020, VERITAS observed NVSS J065844+063711, and a differential upper limit was reported in [26] using 7 h quality-selected data.

7 Summary and Conclusions

VERITAS has a strong and multi-faceted science program in the γ-ray band. Selected science results are highlighted, covering results from Galactic, extra-galactic, fundamental physics, and multi-messenger observations. VERITAS is operating extremely well and continues to provide high quality VHE γ-ray data and scientific results to the community. VERITAS has been recommended for the next cycle of NSF operations funding through 2025.

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