

VERITAS: Status and Recent Results

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Abstract. VERITAS has just completed its 11th year of full four-telescope scientific operations and continues to function with excellent efficiency. Its science program, encompassing galactic, extragalactic, and fundamental physics, entails dedicated observations of specific targets as well as multi-messenger target-of-opportunity observations. The current operational status of VERITAS is presented, as well as recent science highlights, and the future plans for the observatory are discussed.

1 Introduction

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) [1] is an array of four imaging atmospheric Cherenkov telescopes, located at the Fred Lawrence Whipple Observatory in southern Arizona, U.S.A., which has been in full scientific operation since 2007. The VERITAS Collaboration has 25 member institutions from Canada, Germany, Ireland and the U.S.A., in addition to approximately 20 active associate members who contribute through multi-wavelength observations and theoretical work. VERITAS conducts a broad observation program focussed on galactic, extragalactic and fundamental science, which incorporates significant flexibility through dedicated target-of-opportunity (ToO) and director's discretionary time (DDT) to respond to multi-messenger alerts. Self-triggering from real-time analysis of VERITAS's own observations has also proved invaluable. In this proceeding the status and future prospects of the VERITAS observatory will be presented along with select recent science highlights from its scientific program.

2 VERITAS Technical and Operational Status

VERITAS consists of four 12 m diameter optical reflectors, each equipped with 499 pixel photomultiplier-tube (PMT) cameras, that stereoscopically image the Cherenkov light generated by extensive air showers that develop when gamma and cosmic rays interact with the atmosphere. VERITAS entered full four-telescope scientific operation in 2007 and has undergone several significant upgrades, including the move of Telescope 1 to improve the geometric layout of the array in 2009 [2] and the upgrade of the cameras with higher quantum-efficiency PMTs in 2012 [3], to significantly improve its performance compared to the original configuration. A prototype Schwarzschild-Couder telescope (pSCT) for the Cherenkov Telescope Array (CTA) has been constructed on the original site

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of VERITAS Telescope 1, which will allow simultaneous operation with VERITAS to evaluate its performance and to conduct joint science studies. VERITAS operates in the energy range 85 GeV to 30 TeV, has an angular resolution of 0.08° at 1 TeV, a peak effective area $\sim 10^5 \text{ m}^2$, and can detect a 1% Crab source in less than 25 hrs. A detailed overview of VERITAS performance can be found in [4]. New analyses methods with improved sensitivity are currently under development and undergoing validation.

VERITAS typically obtains 950 hours of dark-sky observations per year and observations have been extended into moderate moonlight conditions to obtain approximately 200 additional hours per year. The excellent on-site technical support results in typically >95% four-telescope operation with 97% achieved in the most recent observing season. VERITAS is fully funded for operations through 2019 and in late 2018 will apply for funds for continued operations until at least 2022.

3 Recent Science Highlights

At the time of writing, the VERITAS catalogue consists of 63 objects, with 23 galactic and 40 extragalactic sources. The extragalactic sources are dominated by Active Galactic Nuclei (AGN), which constitute 39 of the detected sources, with starburst galaxy M82 being the one non-AGN extragalactic source detected. In addition to source detections, VERITAS observations have been used to derive dark matter limits, constrain the extragalactic background light intensity and intergalactic magnetic field strength, and to study the cosmic ray iron and electron spectra. A selection of recent science highlights are presented below.

3.1 Galactic Science Highlights

3.1.1 PSR J2032+4127 / MT91 213

TeV J2032+4130 was the first unidentified TeV gamma-ray source, discovered by the HEGRA observatory [5] and was later found by VERITAS to be extended [6]. A Fermi-LAT pulsar, PSR J2032+4127, is located in the southeast corner of TeV J2032+4130, which in 2015 was identified as being in a binary system with the $15 M_\odot$ star MT91 213, with an orbit of eccentricity ~ 0.95 and period ~ 50 years, and periastron due to occur on 13 November 2017. Extensive multiwavelength observations were conducted during the passage through periastron resulting in clear detections ($> 20\sigma$) of a variable point-source by both VERITAS (181 hrs of observations) and MAGIC (88 hrs), and variable X-ray flux by Swift XRT (135 hrs) [7]. The VHE spectrum changes shape during the periastron passage and the flux and spectral variability as a function of orbital phase is more complicated than predicted.

3.1.2 Supernova Remnants: Tycho's SNR, Cassiopeia A and IC 443

Supernova remnants (SNR) are among the leading candidates to be the sources of galactic cosmic rays with energies up to the 'knee' ($\sim 1 \text{ PeV} - 10^{15} \text{ eV}$, "PeVatron"), and young SNR are the best candidates to provide observational evidence as the highest energy cosmic rays, which are believed to be produced early on, will not yet have escaped from the site of production. The sites of cosmic ray acceleration should produce corresponding gamma-ray emission through the interaction of the accelerated cosmic rays with interstellar material.

VERITAS conducted a deep multi-year exposure on Tycho's SNR, a well studied young (~ 450 yr) Type Ia in a clean environment, yielding 147 hours of data, which were combined with 84 months

of *Fermi*-LAT observations. The centroids of both the VERITAS and *Fermi*-LAT observations are consistent with each other and with the centre of the remnant while the measured power-law spectral index at energies > 400 GeV of $2.92 \pm 0.42_{stat} \pm 0.20_{sys}$ compares to a power-law of index $2.14 \pm 0.09_{stat} \pm 0.02_{sys}$ measured in the *Fermi*-LAT band [8]. The VERITAS results point to a likely lower maximum particle energy than anticipated if such SNR are the PeVatrons.

VERITAS also conducted a deep, 65 hr, exposure on Cassiopeia A, a young (~ 350 year old) SNR of Type IIb. In the energy range from 300 GeV to 7 TeV the spectrum is best fit with a power-law of index $2.75 \pm 0.10_{stat} \pm 0.20_{sys}$ [9]. When compared to *Fermi*-LAT observations, the spectrum softens at energies > 300 GeV, again indicting a cut-off in the maximum particle energy in the remnant. The VERITAS results on both Tycho's SNR and Cassiopeia A indicate that more sources in addition to young SNR may be required to explain the origins of galactic Cosmic Rays.

IC 443 is a resolved middle-aged ($\sim 3,000$ - $30,000$ yrs) mixed-morphology SNR that VERITAS has observed for over 150 hrs of data since 2007. The overall nebula, and the nebula sub-divided into four regions, has been analysed and compared to an analysis of the same regions in *Fermi*-LAT. The morphology seen with both instruments is highly consistent, suggesting a single population of cosmic rays across a wide range of energies. The spectral shape is best fit with a broken power-law, with a break at ~ 40 GeV when jointly fitting the 1 GeV to 10 TeV data set.

3.1.3 VERITAS follow-up of HAWC sources

The HAWC observatory's 2HWC catalog [10], resulting from a survey incorporating 507 days of observations, contains 39 sources, with 20 being associated with previously-detected TeV objects. A VERITAS study entailing a total of 218 hrs archival and dedicated follow-up observations of 14 of the objects without know counterparts was conducted and combined with the analysis 8.5 years for *Fermi*-LAT observations [11]. The VERITAS observations resulted in the detection of just one object, DA 495, a pulsar wind nebula coinciding with 2HWCJ1953+294. The *Fermi*-LAT analysis detected GeV emission from a known TeV pulsar wind nebula, SNRG54.1+0.3 (VERJ1930+188), and a 2HWC source, 2HWCJ1930+188. The lack of VERITAS detections of the other HAWC sources is possibly due to source extensions as the VERITAS analyses were limited to moderately extended sources with extensions $< 0.3^\circ$.

3.1.4 VERITAS observations of the Galactic Centre region

The Galactic Centre region is a high-priority target for VERITAS, which observes it at large zenith angles (typically $\geq 60^\circ$), resulting in an energy threshold of ~ 2 TeV and an increased effective area of $\sim 5 \times 10^5$ m² at energies above a few TeV. Observations are conducted offset 0.7° from the source ("wobble" mode) with dedicated off source observations $\sim 5^\circ$ away. The VERITAS observations have resulted in a detection of Sgr A* at $> 35\sigma$, consistent with a point source, with a spectrum best fit with a power law with exponential cut off at ~ 11 TeV. An analysis of the diffuse extended emission, using the regions as described in HESS [12] reveal a hard spectrum consistent with a power law up to the highest observed energy of ~ 40 TeV, supporting the hypothesis that the Galactic Centre region contains a PeVatron. A VERITAS publication detailing the latest results is in preparation.

3.2 Extragalactic Science Highlights

3.2.1 3C 264

3C 264 is an FR-I-type radio galaxy at redshift of $z = 0.0216$. It has a rapidly evolving knot structure as seen from radio and optical observations and is detected in MeV to GeV gamma-rays by *Fermi*-LAT

with an extrapolated flux at energies >200 GeV of 1.6% Crab. Ten hours of VERITAS observations in 2017 revealed a hint of a signal, prompting follow-up observations in 2018. These observations resulted in the detection of the 3C 264 by VERITAS initially at the 5.4σ level in 12 hours of data [13]. This detection prompted additional VERITAS and multi-wavelength observations, with VERITAS detecting it at the 8σ level. The observations revealed it have a flux of $\sim 0.5\%$ that of the Crab Nebula and to be weakly variable.

3.2.2 Ton 599

VERITAS observations of Ton 599, an FSRQ at redshift $z = 0.72$, were triggered by an exceptional period of outburst seen by the *Fermi*-LAT instrument in early November 2017 where its flux reached 20 times its 3FGL value [14]. While Ton 599 was initially at too low an elevation to be observed by VERITAS, the outburst seen at MeV-GeV energies persisted and went through a second exceptional enhancement in December 2017, prompting follow-up observations that resulted in the VERITAS detection of it at $\sim 8\sigma$ in two hours of observations, with a flux level of $\sim 12\%$ that of the Crab Nebula [15]. Ton 599 is the third-most-distant VHE gamma-ray source.

3.2.3 OJ 287

OJ 287 is a BL Lac object at redshift $z = 0.3056$ with quasi-periodic pairs of optical outbursts which have been interpreted as the accretion-disk crossings of a 150 million M_{\odot} black hole in a 12-year precessing orbit about an 18 billion M_{\odot} black hole [16]. In late 2016 the *Swift-XRT Monitoring of Fermi-LAT Sources of Interest* web site [17] revealed that OJ 287 was undergoing a period of enhanced activity. VERITAS conducted observations and detected OJ 287 at a level of $\sim 1.3\%$ Crab [18]. Copious multi-wavelength observations were taken, including radio observations that indicate the enhanced emission may coincide with emission from a new feature in the jet.

3.2.4 BL Lacertae

A very rare rapid flare from a low-peaked BL Lac (LBL) object was observed by VERITAS from BL Lacertae, with a rise time of ~ 2.3 hr. and a decay time of ~ 36 min. on 2016 October 5 [19]. The peak flux in 4-min. bins reached 180% that of the Crab Nebula. Contemporaneous multi-wavelength variability was also detected, with a possible superluminal feature passing the core of the jet identified in the VLBA observations at 43 GHz.

3.2.5 TXS 0506+056

The IceCube neutrino observatory detected a neutrino event of potential astrophysical origin directionally consistent with being from the blazar TXS 0506+056 on 2017 September 22, directly linking the acceleration of hadronic particles to the jets of active galaxies. Within 12 hours of the ICECUBE event VERITAS conducted one hour of observations under non-optimal weather conditions and no gamma-ray source detected. VERITAS conducted a further five hours of follow-up observations in the period 2017 September 28 to September 30 in response to the announcement that *Fermi*-LAT had detected TXS 0506+056 in enhanced gamma-ray state. While the VERITAS observations did not reveal a detection, MAGIC detected the source between 2017 September 28 and October 3. The results of the initial observations from IceCube, VERITAS and several other observatories were reported in [20]. VERITAS continued observations of the object over the next 5 months, accumulating 35 hours

of data, and achieved a detection at the 5.8σ significance level [21]. The source had an average integral flux above 110 GeV of 1.6% that of the Crab Nebula, consistent with being steady over the period of observation, with a spectrum fit by a power-law with index of 4.8 ± 1.3 . The broadband spectrum has a softening between the *Fermi*-LAT and VERITAS energy that cannot be explained by EBL absorption alone, which has implications for the distribution of the parent population of particles producing the electromagnetic emission [21].

3.3 Dark Matter and Cosmic Ray Highlights

3.3.1 Dark Matter Limits

Recent VERITAS observations and analyses of ~ 230 hours of data on five dwarf spheroidal galaxies (Boötes I, Draco, Segue I, Ursa Minor and Willman I) have been published in [22]. No evidence for gamma-ray emission was found from either galaxy individually, not from a joint analysis (Willman I excluded), and upper limits on the dark matter annihilation cross section are derived at 1 TeV for the bottom quark ($b\bar{b}$), tau lepton ($\tau^+\tau^-$) and gauge boson ($\gamma\gamma$) final states respectively of $1.35 \times 10^{-23} \text{ cm}^3 \text{ s}^{-1}$, $2.85 \times 10^{-24} \text{ cm}^3 \text{ s}^{-1}$ and $1.32 \times 10^{-25} \text{ cm}^3 \text{ s}^{-1}$. Work is in progress to analyse extensive data sets on Ursa Major II and the galactic centre region in the context of dark matter limits.

3.3.2 Cosmic Ray Electron Spectrum

Cosmic ray electrons at TeV energies detectable at the Earth should have been produced within one kpc since they lose energy rapidly. A recent analysis of ~ 300 hours of VERITAS data for energies between 300 GeV and 5 TeV determined that the spectrum cannot be fit with a single power law but requires broken power law with break energy at $710 \pm 40_{stat} \pm 140_{sys}$ GeV [23].

3.3.3 Cosmic Ray Iron Spectrum

A novel template-based analysis of 71 hours of VERITAS data utilising the direct-Cherenkov method has been used to derive an energy spectrum for cosmic ray iron nuclei in the energy range 20 TeV to 500 TeV [24]. The spectrum was well fit with power law of index $2.83 \pm 0.3_{stat}$, in agreement with partially overlapping measurements at lower energies, and extends the spectrum higher energies.

4 Summary and Conclusions

VERITAS is operating extremely well with excellent reliability, and the 2017-2018 observing season was its most efficient yet. The collaboration has a multi-faceted science program covering galactic, extragalactic and fundamental physics. A selection of recent science highlights have been presented here, and many more studies using already-obtained data are in progress. VERITAS is fully funded for operations through end of 2019 and in late 2018 will apply for operations through 2022.

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