PROCEEDINGS OF SCIENCE

Highlights from VERITAS

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VERITAS is one of the world's most sensitive detectors of astrophysical very-high-energy VHE (E > 100 GeV) gamma rays. This array of four 12 m imaging atmospheric Cherenkov telescopes, located in southern Arizona, USA, has operated for ~15 years. VERITAS science spans Galactic topics, including pulsar wind nebulae, binary systems, and supernova remnants; extra-galactic topics, including studies of blazars and radio galaxies, searches for gamma-ray bursts and fast radio bursts; multi-messenger science; and astroparticle physics topics including searches for dark matter. VERITAS has also pioneered the use of IACTs for optical astronomy, particularly via intensity interferometry and high time-resolution studies. Recent highlights from the VERITAS observing program and scientific results are presented.

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1. Introduction and Status

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is an array of four 12 m (diameter) imaging atmospheric Cherenkov telescopes (IACTs) for gamma-ray astronomy at energies $\gtrsim$ 100 GeV. VERITAS is located at the Fred Lawrence Whipple Observatory in southern Arizona at approximately 1,268 m above sea level. VERITAS entered full four-telescope operations in 2007 and has just completed its 15th year of operations. A prototype CTA Schwarzschild-Couder (pSCT) telescope is co-located at the site.

The VERITAS Collaboration has 97 members including 32 graduate students and 16 post-doctoral fellows plus approximately 20 actively participating Associate members. Operations and group funding primarily comes from the National Science Foundation (NSF) and the Smithsonian Astrophysical Observatory (USA), the Natural Sciences and Engineering Research Council (Canada) and the Helmholtz Association (Germany). In summer 2022 the VERITAS Collaboration received word that it has been successful in its application to NSF for operations funding through 2025. This award supplements two recent instrument upgrade awards from NSF.

The VERITAS Collaboration strives to be be an equitable, diverse and inclusive organisation and has recently implemented a code of conduct to emphasise the behaviour and ethical standard required of all members.

2. Outstanding Contribution Awards

VERITAS is a bespoke facility that was designed, built and is maintained and operated by the Collaboration members. In 2019 the Collaboration instigated a pair of awards to "...formally recognize the significant contributions of more early-career members of the Collaboration in the critical service work that enables scientific publications of VERITAS and, but do not result in any scientific publications directly". For 2021 the award scope was expanded to include contributions made to the development of the pSCT. The two awards are the Simon Swordy award for graduate students and the Trevor Weekes award for postdoctoral fellows.

The 2021 winner of the Simon Swordy award is Deivid Rebeiro from Columbia University for wide-ranging contributions to VERITAS and the pSCT including data analysis software, helping to implement remote-observing capability, contributions to the pSCT optics, mentoring and outreach. Dr. Qi Feng from Columbia University was awarded the 2021 Trevor Weekes award for numerous and ongoing contributions to both VERITAS and the pSCT including multiple innovations in the commissioning of the optics system for the pSCT, and playing a key role in the Zooniverse Muon Hunter outreach project. For more details of the awards and previous winners see the Oustanding Contribution Awards section of the VERITAS web site

3. VERITAS Performance and Operations

VERITAS operates in the energy range $\gtrsim$ 100 GeV to > 30 TeV with a peak effective area of $\sim 10^5$ m^2 at 1 TeV. The VERITAS cameras cover a field-of-view of 3.5° with a gamma-ray point-spread-function of $\sim$ 0.08° at 1 TeV providing source localisation accuracy of $\sim$ 50 arcseconds. Spectral reconstruction achieves an energy resolution at 1 TeV of $\sim$ 17%. Above 240 GeV a source with flux 10% that of the Crab Nebula can be detected at $> 5\sigma$ in 25 minutes while it takes 24 hours to detect a source with flux 1% that of the Crab Nebula. More details on the performance can be found on the specifications section of the VERITAS web site.

The mirror reflectivity of VERITAS changes with time due to weathering and re-coating; these changes are monitored and corresponding instrument response functions generated to account for them, allowing long-term stable spectral reconstruction and flux determination [1].

VERITAS typically obtains $\sim$ 950 hours of dark observations and $\sim$ 250 hrs of moderate moonlight (illumination 30-65%) per year. Additionally, VERITAS is now utilised extensively for Stellar Intensity Interferometry measurements during full moon. VERITAS has been operating with excellent efficiency, with $> 95\%$ full four-telescope participation.

The VERITAS Observatory was impacted by the COVID pandemic and ceased operations temporarily on 17 March 2020. The observatory recommenced operations in September 2020 facilitated largely by the implementation of a remote observing capability requiring only one on-site operator and allowing VERITAS scientists to operate the array from anywhere in the world with a reasonable internet connection. This has proved to be a popular option for observers even as travel restrictions were gradually lifted and the possibility for on-site in-person observing shifts returned.

4. VERITAS Science Program

VERITAS has a number of Science Working Groups (Blazar, Galactic, ATOMM - Astroparticle Transient Optical Multi-Messenger) each of which receive a dedicated time allocation annually for their long-term science programs. In addition, VERITAS members can apply through a competitive Time Allocation Committee scheme for observing time, and urgent observations can be made through the Director's Discretionary Time allocation, which may be up to 10% of the total available time. External scientists can collaborate with VERITAS members or apply for observing time through the Fermi Guest Investigator program. A significant portion of the observing program is reserved for Target-of-Opportunity observations, triggered by VERITAS observations or external alerts.

4.1 VERITAS Galactic Highlights

The search for Galactic PeVatrons has been one of the key science projects for the VERITAS Galactic Science Working Group. Observations of young supernova remnants included deep exposures on Tycho's SNR (147 hours) [3] and Cassiopeia A [4]. In both cases, when the VERITAS data were combined with those from Fermi-LAT, spectral breaks were found in the TeV energy range indicating that these are not current accelerators of protons to PeV energies. Deep studies with VERITAS of detected hard-index sources (MGRO J2019+37, MGRO J1908+06, SNR G106.4+2.7) are ongoing. VERITAS has also conducted follow-up observations of 14 HAWC sources from the 2HWC catalogue [5] with no known counterparts, resulting in the detection of a pulsar wind nebula, DA 495, (coincident with 2HWC J1953+294) but no other detections, indicating that the HAWC sources are possibly extended. More recently VERITAS has been conducting follow-up observations of LHAASO sources [7], in particular LHAASO J0341+5258 and LHAASO J2108+5157. Whilst the VERITAS observations of LHAASO J0341+5258 are still being processed, preliminary analysis of 35 hours of data on LHAASO J2108+5157 with both point-source and moderately extended angular cuts (0.25°) have revealed no detection and upper limits have been produced that constrain the hadronic model presented in [7]. Further details of the VERITAS search for PeVatrons is given by Park et al. in these proceedings.

The Galactic Centre region has been a long-term target for VERITAS, with observations mainly been taken at large zenith zenith angles (between 60° and 65°) due to small elevation at which the region transits at the VERITAS site. The consequence of the large zenith angle observations is to increase the energy threshold to > 2 TeV but also to significantly increase the effective area for the obsevations. VERITAS has recently published results from 125 hours of observations on the Galactic centre region [8] with the main results being the detection of Sagittarius A* at 38σ with a spectrum best-fit with a power law with exponential cut off (spectral index, $\Gamma = 2.12^{+0.22}_{-0.17}$, $E_c = 10$ TeV) and no evidence for variability, and detection of diffuse emission at the level of 9.5σ, with a spectrum best fit by a power law of index $\Gamma = 2.2 \pm 0.2$ up to 40 TeV.

VERITAS has conducted extensive studies of the binary systems PSR J2032+4127/MT91 213, HESS J0632 and LS I +61 303. VERITAS and MAGIC observations of PSR J2032+4127/MT91 213 have been jointly published with complex flux and spectral variations observed through the periastron phase of its 50 year orbit period [9]. The multiwavelength variability through the periastron phase requires sophisticated models, such as those by Chen & Takata [10]. The H.E.S.S., MAGIC and VERITAS collaborations have published joint gamma-ray combined with multi-wavelength observations of HESS J0632, with observations from the two regimes revealing a consistent orbital modulation of ~ 317 days and evidence for orbit-to-orbit variability [2]. VERITAS has also conducted multi-year observations of LS I +61 303, acquiring a total data set in excess of 180 hours, with ongoing studies of flux and spectral variability with orbital phase, multi-wavelength correlations and super-orbital modulation under way. For more information of VERITAS binary studies see Patel et al. in these proceedings.

4.2 Blazars and Radio Galaxies

Blazars and radio galaxies are key long-term targets for VERITAS with ~ 200 hours of observations obtained each year, many of which have simultaneous Swift XRT X-ray coverage. For the period 2022-2025 simultaneous observations of key targets with the Imaging X-ray Polarimetry Explorer (IXPE) will have high priority. The long data sets allow various studies to be conducted including an unbiased survey of High-synchrotron-Peaked BL Lacs (HBLs) with the ultimate goal of deriving the HBL VHE luminosity function, studies of HBL low-state spectra and variability (see Batista et al. in these proceedings), low-state observations of selected objects (e.g. H 1426+428), and, using nightly snapshots to search for repeating flaring patterns in Markarian 421 as perturbations propagate along the stationary shock structure. Deep studies of three flaring flat spectrum radio quasars (FSRQs) with Fermi-LAT and VERITAS have been published in [13], with PKS 1222+216 and Ton 599 detected by VERITAS while 3C 279 was not. The multiwavelength observations strongly constrain the jet Doppler factors and the emission region locations.

The VERITAS unbiased HBL study entails the study of 36 HBL objects selected from the 3HSP catalogue [11] incorporating more than 2,000 hours of archival data and new data to ensure at least 8 hours exposure on each object. The addition of new data has resulted in the detection of a new extreme HBL at VHE energies, RBS 1366 (RGB J1417+257), with synchrotron peak

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located at $\log \nu_{peak} \approx 17.2$. This object has been proposed as a TeV-peaked BL Lac [14] and a possible UHECR accelerator [15]. The VERITAS detection of this object has a (preliminary) flux of approximately 0.5% Crab and a power-law spectral index (preliminary) of -3.1 ± 0.5.

Of the six detected VHE radio galaxies [12] VERITAS has detected four: M87, NGC 1275, IC 310 and 3C 264. VERITAS conducts long-term monitoring of these objects as well as searching for VHE emission from additional objects; notable non-detections to date include 4C +39.12 (11 hrs. 0.17σ), 3C 303 (9.5 hrs, 1.2σ and B2 1113+29 (9.5 hrs, 0.9σ). VERITAS will soon publish the results of 8 years of VERITAS and multi-wavelength observations of NGC 1275.

4.3 Multi-Messenger and Transients Program

Multi-messenger observations are of highest importance and include follow-up observations of gravitational wave events, astrophysical neutrino events, gamma-ray bursts (GRBs), fast radio bursts (FRBs), tidal disruption events and super-luminous supernova. VERITAS provides critical coverage of a unique part of the sky where there is no additional IACT coverage.

4.3.1 Neutrino ToO Program

VERITAS automatically re-points and conducts observations of suitable IceCube neutrino alerts received through the GCN network. Since the detection of TXS 0506+056 as a neutrino blazar with contemporaneous elevated gamma-ray emission [6], VERITAS has performed 9 follow ups of real-time neutrino alerts and one additional follow up from the Gamma-ray Follow Up (GFU) program, with no detections. Since the VERITAS detection of TXS 0506+056 [16] VERITAS has accumulated a total of over 100 hrs of observations of the object, including multi-wavelength campaigns with NuStar and Swift, and a publication is in preparation.

4.3.2 Gamma-ray Burst Follow-up Program

GRB follow ups have the highest priority for VERITAS and suitable observable alerts override any observations currently under way. To date VERITAS has conducted follow-up observations of 211 GRBs, with the fastest time to data taking being 64 s and with the median time of 284 s. Of the 211 GRBs observed, 127 had locations within the VERITAS point-spread function and no individual detections were found - a stacked analysis of all of these bursts is currently under way.

4.3.3 Fast Radio Bursts: gamma-ray and optical observations

The Canadian Hydrogen Intensity Mapping Experiment (CHIME) observatory, located in British Columbia (Canada), has detected hundreds of fast radio bursts. VERITAS is uniquely located to be able to simultaneously observe with CHIME if VERITAS observes known repeater locations ~ 35 minutes after culmination. In addition to VHE gamma-ray observations VERITAS conducts optical observations using an enhanced current-monitoring system, to allow ms optical variations to be detected (more details below). To date gamma-ray observations on 11 FRB repeating objects with overlapping data on 21 bursts have been obtained, but due to technical issues none of these had VERITAS optical data. For more information on the VERITAS FRB program see Lundy et al. in these proceedings.

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5. VERITAS Optical Science

The VERITAS telescopes are large optical reflectors with sensitive and fast cameras and electronics, and in recent years the VERITAS Collaboration has been exploiting this optical capability for the study of optical transients, stellar intensity interferometry (SII), optical SETI and calibration by detecting optical pulses from LIDAR satellites.

The VERITAS enhanced current monitor measures 2-4 pixels in the camera at a rate of 1,200 - 2,400 Hz down to a magnitude limit of $\sim$ 12 mag. One of the first applications of this by VERITAS was to measure stellar diameters using asteroid occultation of stars [17]. Subsequent observations of additional occultations have been made and further studies are underway. As mentioned above, the enhanced current monitor is now routinely used for FRB observations as well. VERITAS has recently received funding from NSF to upgrade the data acquisition system to allow for continuous monitoring of all camera pixels on timescales from μs to 10s of seconds for optical transients.

The utilisation of IACTs to conduct digital offline SII has been pioneered by the VERITAS Collaboration achieving sub-milliarcsecond resolution at 400 nm [18]. The VERITAS SII group has been rapidly expanding, improving the technique and analysis methods, and developing a strong science program including a survey of stellar diameters and studies of cepheids and fast rotators. A recent NSF-funded upgrade will further enhance the SII capability and lead to additional science capabilities, such as enabling studies of limb darkening.

The fast optical capabilites of IACTs make them ideal instruments for detecting laser pulses from space. Such laser pulses were proposed as a mechanism for searching for extra-terrestrial intelligence and VERITAS conducted observations on a particular target, KIC 8462852 [19], leading to a subsequent joint project with the Breakthrough Listen foundation. This capability has recently been used to detect laser pulses from CALIPSO, a LIDAR satellite at an altitude of 700 km which produces 20 ns pulses at 532 nm with a pulse rate of 20 Hz. CALIPSO passes over the VERITAS site in dark time a few nights per month and in a one-minute exposure enough pulses can be detected to measure relative telescope efficiency. Potential applications of such measurements include characterising optical performance, monitoring time-dependent array efficiency and cross-calibration with other IACTs. The feasibility for conducting similar observations of additional LIDAR satellites is currently under investigation.

6. Summary and Conclusions

The VERITAS instrument continues to operate well and the VERITAS Collaboration has a strong and varied science program covering Galactic, extra-galactic and multi-messenger topics. VERITAS has pioneered the use of IACTs for optical applications and continues to innovate in this area. VERITAS has received funding from the NSF to continue operations through 2025, and has received two instrument upgrade awards to enhance the optical science capability. VERITAS has lots of data recorded, an ongoing and varied observing program, and welcomes collaboration and new members.

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