Recent results from VERITAS

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Abstract. VERITAS has been observing the northern sky at TeV energies with full sensitivity since 2007. Consisting of a ground based array of four 12 m imaging atmospheric Cherenkov telescopes, sited in southern Arizona, it is one of the world’s most sensitive detectors of gamma-rays between 85 GeV to 30 TeV. VERITAS maintains a broad scientific programme in many areas of astroparticle physics, including, but not limited to: studies of the acceleration, propagation and indirect measurements of cosmic rays and their spectra; searching for indirect detection signatures of dark matter candidates; and tests of fundamental physics, such as setting constraints on Lorentz invariance violation. There is also an active multi-messenger programme with partners in the electromagnetic, neutrino, and gravitational wave sectors. We review here the current status and some recent results from VERITAS and examine the prospects for future studies.

1. Introduction

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is composed of four 12 m diameter imaging atmospheric Cherenkov telescopes (IACTs) sited at the Fred Lawrence Whipple Observatory in southern Arizona (USA). Each dish is a tessellated reflector made up of 350 individual mirror facets in a Davis-Cotton configuration focused onto 499-pixel photomultiplier tube cameras for a total field of view of $3.5^\circ$. The primary field of research of VERITAS is in the ground based detection of very high energy (VHE, $E \geq 100$ GeV) gamma-rays.

In the ten years since its full phase operations began in 2007 VERITAS has undergone two major upgrades: the first, in 2009, was the relocation of the original prototype telescope to a more favourable location to give an approximately diamond-shaped layout with telescope separation of $\sim 100$ m; the second, in 2012, saw an update of the electronics with the replacement of all the pixels with higher quantum efficiency (super bi-alkali photocathode) PMTs and a new pattern selection trigger system. These upgrades respectively improved the angular reconstruction capabilities, and lowered the energy threshold whilst simultaneously improving the sensitivity of the array. As shown in Figure 1, in its current configuration VERITAS can detect the Crab nebula (the standard candle of the field) in under a minute and a source with 1% of the steady Crab nebula flux in under 25 hours (less than half of the exposure required in the original configuration).

The ability to detect faint Cherenkov emission above the night sky background is largely driven by the phase of the moon, with VERITAS’ annual total around 900 hours of dark, moonless, good weather data. However, VERITAS has also developed routine operations with a reduced PMT voltage to protect the PMTs which enables VERITAS to observe for lunar disk illuminations up to $\sim 60\%$. This provides up to an additional 40% in the number of hours,
Figure 1. The observing time needed for VERITAS to collect a $5\sigma$ measurement as a function of source strength, more details on the specifications are available from https://veritas.sao.arizona.edu/.

bringing the annual average observing yield to $\sim$1300 hours. In the decade since full-scale operations began VERITAS has accumulated over 10,000 hours of good weather exposure to a substantial fraction of the Northern Hemisphere sky.

The VERITAS source catalogue, shown in Figure 2 comprises 58 sources in 8 source classes, with additional measurements of other astroparticle phenomena such as the cosmic ray iron and electron spectra. Here we summarise some of the interesting results released in the last year.

2. Astroparticle

2.1. IGMF

An electron-positron pair cascade process occurs when multi-TeV gamma rays interact with extragalactic background light (EBL) photons. Subsequent inverse Compton scattering of cosmic microwave background light photons with the cascade particles will produce gamma rays once again. A non-zero intergalactic magnetic field (IGMF) will induce deflection of the electron-positron pairs, potentially producing a detectable broadening of the angular distribution of the cascade emission. Non-detection of such an effect in VERITAS detections of AGN lead us to exclude an IGMF strength around $10^{-14}$ G at the 95% confidence level, though the exact value can vary significantly depending on the assumed intrinsic source spectrum [1].
2.2. Iron Spectrum

IACTs can also detect the direct Cherenkov (DC) radiation from charged primary particles entering the atmosphere. The intensity of the DC light favours the detection of heavy nuclei through this technique. A template-based likelihood fit was used to improve reconstruction of the energy and geometry (arrival direction and core position) of iron nuclei between 20-500 TeV, in addition to Random Forest classifiers to reduce background, in 71 hours of good quality data taken between 2009 and 2012 \[3\]. The spectrum was well fit by a power law with index $\gamma = 2.82(\pm0.3_{\text{stat}})(^{+0.23}_{-0.25})_{\text{sys}}$ agreeing well with previous measurements and direct detection experiments. Future work could make it possible to extend the template library to include lighter elements and measure the composition of cosmic rays in the TeV-PeV range.

2.3. DM limits

If weakly interacting massive particles (WIMPs), candidates for dark matter (DM), self-annihilate or decay the secondary particles could include VHE gamma rays. Dwarf spheroidal galaxies (dSph) are mooted astrophysical candidates for the indirect detection of DM due to their large mass-to-light ratios and low number of stars implying that any gamma-ray signal would be unlikely to be due to any other astrophysical sources/processes. VERITAS has observed a number of dSph targets with no significant gamma-ray excess being measured \[4\]. By combining 216 hours of the individual target observations together, upper limits at the 95% confidence level were produced on the thermally-averaged annihilation cross section in the region $<\sigma v> \sim 10^{-29} - 10^{-25} \text{cm}^{-2}\text{s}^{-1}$, with the exact value depending on the various standard model particle branching ratio scenario and candidate particle mass \[5\].

Figure 2. The VERITAS source catalogue, as of June 2017, in galactic coordinates and where the shaded region indicates visibility to VERITAS above 55° elevation. Figure modified from TeVCat source (http://tevcat.uchicago.edu).
2.4. Multimessenger
The electromagnetic spectrum is but one domain with which to explore the high energy universe. VERITAS maintains active links with the multimessenger community to try and better identify and understand the astrophysical sources of neutrino and gravitational waves.

The detection of an astrophysical flux of high-energy neutrinos by the IceCube Observatory is an important step in the search for the acceleration sites of cosmic rays. There have so far been no identified neutrino point sources, nor significant correlation with known astrophysical objects that could reveal their location. Given the apparent isotropy of the astrophysical neutrino events an extragalactic origin would seem to be favoured. Interactions in, or near, these sites should also generate gamma rays through neutral pion generation and decay, so a correlated gamma-ray and neutrino flux would be expected. The typical $\leq 1^\circ$ error circle of neutrino “track” events can be covered in a single pointing within an IACT camera. VERITAS has taken 64 hours of observations on 28 IceCube high energy muon event locations, producing 99% confidence level upper limits on source flux at the 1-5% Crab nebula level above 100 GeV [6].

There are many transient sources of high energy emission, particularly amongst extragalactic objects. Alerts from IceCube on potential astrophysical neutrino events broadcast on the GCN allow rapid follow-up of detected neutrino emission. Again, no gamma-ray emission has currently been detected within the neutrino error circle at the few percent Crab level [6]. These correspond to upper limits at a level of $\sim 0.1\%$ of the all-sky astrophysical neutrino flux, though the precise limit will depend on the exact source spectrum and distance to the source as the gamma-ray signal of high redshift sources will be attenuated via pair production on the EBL. VERITAS also joined in the follow-up observation campaign of a “neutrino triplet” where three closely grouped neutrino events were detected within 100 s. Due to observing constraints caused by the moon position and the weather, VERITAS could not observe the region until 8 days after the event, but it is not unusual for AGN flaring activity to last for such extended periods. The dataset showed no indications for a persistent VHE gamma-ray source, nor a high state of RGB J0136+391 which could be associated with the triplet region [7].

VERITAS is also part of the gravitational wave (GW) follow-up community. The $\sim 10$ deg$^2$ camera field of view can be used to observed the O(100 deg$^2$) error region of the GW alert in 5 minute tiled pointings. Under ideal conditions this would be sensitive to a 0.5 Crab source at $E \geq 100$ GeV. VERITAS has employed this strategy to observe LIGO/Virgo G268556, though due to a combination of poor weather and only three telescopes of the array being available the sensitivity of the observations was less than ideal [8].

3. Extragalactic
The last 12 months proved very fruitful for observations of active galactic nuclei (AGN) with alerts on unprecedented flaring activity from BL Lac and NGC 1275 and first time detections of VHE emission from RGB J2056+496 and OJ 287. The detection of OJ 287 [9] is particularly interesting, the optical data on this object, spanning over a century of data, shows a regular double-peaked 12 year periodicity to the light curve that has been interpreted as evidence for a binary supermassive black hole system, though it could also be due to precessing jets. The VHE emission occured between the expected maxima, but coincident with a record high X-ray state as measured by the Swift satellite.

4. Galactic
Supernova remnants (SNRs) are key galactic targets for observations with VERITAS, as precise measurements of their gamma-ray morphology and spectra can be used in modelling of cosmic-ray acceleration and diffusion. The VERITAS exposure of Tycho’s SNR has effectively doubled

1 Gamma-ray Coordination Network, https://gcn.gsfc.nasa.gov/
over the prior published data that informed the development of several theoretical models proposed to explain its broadband emission. The updated VERITAS results extend the energy range and, whilst consistent with previous results giving a SNR shell origin of the emission, show a softer spectrum and point to a lower maximum particle energy being attained than has been suggested previously [10].

The accumulated exposure of ten years of VERITAS operations makes for a large archive of data. The release of the 2nd HAWC catalogue showed VERITAS had taken 187h of observations on 13 of the 39 sources which, in addition to the already known TeV sources, resulted in the detection of 2HWC J1953+294 [11] and its likely association with the ageing pulsar wind nebula DA 495.

5. Summary
VERITAS is a ground based detector of astrophysical VHE gamma rays and observes the Northern Hemisphere sky at the highest sensitivity to date. Since 2007, the array has been used to collect over 10,000 hours of good quality data. This allows an active programme of research in areas of galactic, extragalactic and also astroparticle science in addition to strong multi-wavelength and multi-messenger links. Operational funding for VERITAS is secure, and the collaboration plans to continue observing with the array until at least 2019.

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