Observing the Energetic Universe at Very High Energies with the VERITAS Gamma Ray Observatory

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Abstract

Very high energy gamma-ray observations offer indirect methods for studying the highest energy cosmic rays in our Universe. The origin of cosmic rays at energies greater than $10^{18}$ eV remains a mystery, and many questions in particle astrophysics exist. The VERITAS observatory in southern Arizona, USA, carries out an extensive observation program of the gamma-ray sky at energies above 85 GeV. Observations of Galactic and extragalactic sources in the TeV band provide clues to the highly energetic processes occurring in these objects, and could provide indirect evidence for the origin of cosmic rays and the sites of particle acceleration in the Universe. VERITAS has now been operational for ten years with the complete array of four atmospheric Cherenkov telescopes. In this review, we present the status of VERITAS, and give few results from three of its key scientific programs: extragalactic science, Galactic physics, and study of fundamental physics and cosmology.

Keywords: Gamma-ray, TeV, Imaging Atmospheric Cherenkov Telescopes

1. Introduction

VERITAS (Very Energetic Radiation Imaging Telescope Array System) is an array of four imaging atmospheric Cherenkov telescopes (IACTs), located at the base camp of the Fred Lawrence Whipple Observatory (FLWO) in southern Arizona. VERITAS uses ground-based detection techniques to explore the Universe at very high energy (VHE) gamma rays from 85 GeV to 30 TeV. High energy gamma-rays from astrophysical sources emitted in the direction of Earth, interact with the Earth’s atmosphere, producing electromagnetic cascades which generate short-lived but bright flashes of Cherenkov
radiation, at a characteristic angle. IACTs are capable of detecting these brief flashes of Cherenkov light in the visible and UV range, and thus indirectly function as gamma-ray telescopes. However, at a much higher rate than gamma-ray showers, cosmic rays also produce showers of charged particles and Cherenkov radiation, which constitute the principal source of background for gamma-ray telescopes. IACTs such as VERITAS utilize the Cherenkov light emitted from air showers to form an image on the camera-plane of the longitudinal and lateral development of the air shower. The imaging technique can reject 99.7% of the cosmic-ray background using statistical analysis methods, while retaining > 50% of the gamma-ray signal. Shower images can be modeled as an ellipse whose semi-major axis points back to the origin of the shower. Second-moment parameters, or Hillas parameters (Hillas, 1996), characterizing the length, width and asymmetry of the image are calculated and used to discriminate between primary particle types. By employing multiple telescopes in combination (four in the case of VERITAS) to increase the collection area and obtain a stereoscopic image of the particle showers in order to reduce cosmic ray background, VERITAS operates at a sensitivity an order of magnitude better than the previous generation of telescopes (Horan & Weekes, 2004). At the present time, in addition to VERITAS, the other major IACTs in operation are MAGIC (Aleksic et al., 2016a) and H.E.S.S. (Aharonian et al., 2006a). FACT (First G-APD Cherenkov Telescope), a new telescope using advanced technology in the form of a camera comprised of Geiger avalanche photo diodes, has been successfully monitoring blazars at TeV energies since 2011 (Anderhub et al., 2013).

The VERITAS telescopes are of Davies-Cotton design, each with a diameter of 12 m. Each telescope has a camera at its focal plane comprising 499 photomultiplier tubes (PMTs) arranged in a hexagonal pattern with a field of view of diameter 3.5°. Figure 1 is a photograph of the VERITAS observatory, showing the array of four telescopes. Figure 2 shows a detail of the VERITAS camera focal plane and an image of a gamma-ray event recorded by all four telescopes. Further details of the VERITAS telescopes including image analysis, telescope specifications, background rejection techniques and scientific analysis of data may be found in *VERITAS: Status and Highlights* (Holder, 2011).

VERITAS has been operating with the complete four-telescope array since 2007. In the past decade, there have been several upgrades and improvements to VERITAS, such as the relocation of one of the telescopes in
order to obtain a more symmetric array layout in 2009 (Kieda, 2013), imple-
mentation of a new alignment system which improved the instrument point
spread function (McCann, 2010) and allowed for a 30% improvement in sen-
sitivity, and a complete upgrade of the VERITAS cameras with new photo-
multiplier tubes in the summer of 2012 (Otte, 2011). These new PMTs, with
super bialkali photocathode material, allowed a peak quantum efficiency of
greater than 32%, leading to an increase of the photon detection efficiency of
each camera by approximately 50%. VERITAS is now able to detect a source
with a Crab Nebula-like spectrum and a flux of 1% Crab Nebula strength
in about 25 hours in less than half of the exposure required for the original
array configuration from 2007. VERITAS has an angular resolution of less
than 0.1° (68% containment) at 1 TeV and an energy resolution of 15% to
20%. Figure 3 shows the differential sensitivity of VERITAS for the three
different sets of “cuts” (Park, 2015). Soft cuts provide the highest sensitivity
at approximately 100 GeV, while the hard cuts are optimized for energies
greater than 600 GeV. VERITAS now typically collects approximately 1300
hours of data per year, including 200 hours taken in moderate moonlight
with the lunar disk up to 50% illuminated.

The scientific program of VERITAS includes the study of extragalactic
sources such as blazars, galactic systems such as pulsars, supernova remnants,
pulsar wind nebulae, binary systems, and studies of fundamental physics
and cosmology. Together with the Fermi Large Area Telescope (Fermi-
larger and less uniform, and lies on an axis which does not point to the center of the camera. The most persistent source of background for a single IACT comes from local muons passing above the telescope, as partially imaged muon rings can approximate the size and shape of gamma-ray showers.

By using an array of four telescopes, with multi-telescope trigger, the VERITAS array configuration eliminates the local muon background, provides a larger collection area and lower energy threshold. Stereoscopic imaging of showers from multiple viewing angles allows the determination of the shower main axis and location relative to the array using simple geometric reconstruction techniques, which rely on the fact that the major axes of the shower images are projections of the shower axis. Superimposing the four images into the same field of view, the major axes of the elliptical images intersect at the location of the shower core. The stereoscopic approach also offers new techniques to improve the efficiency of gamma-hadron separation, and provides a further increase in sensitivity and angular and energy resolution. VERITAS data are generally taken using the full four-telescope array. The array-level trigger requires Cherenkov images in at least two telescopes, coincident within a narrow time window. The signals in all pixels are then read out using a 500 Megasamples/s Flash-ADC data acquisition system for each PMT. Details of the VERITAS telescopes and instrument are provided elsewhere [15, 16].

VERITAS started four-telescope operations in 2007, but in 2009 relocated one of the telescopes to provide a more symmetric array layout. This rearrangement together with a new alignment system, which improved the instrument point spread function [17], allowed for a 30% improvement in sensitivity. VERITAS is able to detect a source with a Crab Nebula-like spectrum and a flux of 1% Crab Nebula strength in about 25 hours. VERITAS has an angular resolution of <0.1° (68% containment) and an energy resolution of 15 - 20% for energies >200 GeV. In the summer of 2012 the VERITAS cameras were replaced with new photomultiplier tubes with high-quantum efficiency of greater than 32% [18] that increased the photon detection efficiency of each camera by approximately 50%. This is part of a series of upgrades and improvements that have been implemented on the VERITAS observatory since 2007 (see [19] for details on the gamma-ray detection sensitivity of the upgraded VERITAS observatory). VERITAS now typically collects more than 1300 hours of data per year (including 200 hours data taken in moderate moonlight).

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LAT) (Atwood, 2009), the High Altitude Water Cherenkov (HAWC) Experiment (Abeysekara et al., 2017a), and the IceCube neutrino observatory (IceCube website, 2017), VERITAS offers the chance to use neutral messengers to directly probe cosmic accelerators. With the detection of astrophysical neutrinos by IceCube (Aartsen et al., 2013) and reports of the first gravitational wave localizations by LIGO (Abbott et al., 2016) and VIRGO (VIRGO website, 2017), VERITAS has the potential for multi-messenger complementarity, and could detect electromagnetic counterparts for observations made by LIGO/VIRGO or IceCube. The first-ever detections of electromagnetic counterparts to a gravitational wave was recently made for the LIGO event 20170817 (Abbott et al., 2017b) by Fermi-GBM and INTEGRAL (Abbott et al., 2017a), demonstrating the promise of multi-messenger astronomy. With its superior angular resolution, and its ability to follow up on transient trig-
gers alerts, VERITAS therefore plays a critical role in multi-messenger astrophysics.

In the past three years VERITAS has been functioning as a robust observatory, with a steady observing program, and the scientific output of VERITAS has remained strong. The VERITAS source catalog, as of this publication, is shown in Fig. 4. The source count stands at 59 sources and is composed of eight different source classes. As of this writing, a comprehensive set of VERITAS results were presented at the 35th International Cosmic Ray Conference (ICRC) (VERITAS Collaboration ICRC, 2017). In the following we present a very brief summary of a few selected results on individual sources. We note that the field of very high energy astrophysics has been enriched with the results from all three major IACTs, H.E.S.S., MAGIC and VERITAS. However, in this review we focus just on the VERITAS results.

Figure 3: VERITAS current differential sensitivity estimated by using Crab Nebula data. Differential sensitivities give the strength of a source VERITAS can detect with a significance of 5 sigma, assuming an exposure time of 50 hours. The source is assumed to be at elevations above 70 degrees (Park, 2015). The latest VERITAS sensitivity curves are available on the VERITAS website (VERITAS website, 2017).

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2. Extragalactic Source Studies with VERITAS

The majority of the sources detected by VERITAS, as seen in Fig. 4, are active galactic nuclei (AGN) of the blazar class, with gamma-ray emission originating in their relativistic jets. TeV observations of AGN help us constrain models of particle acceleration and energy dissipation in blazar jets, and help us determine the size and location of the gamma-ray emission region. Blazars are also important probes of the extragalactic background light (EBL), which absorbs their TeV photons traveling cosmological distances. Furthermore, studies of blazars at the highest energies may be used to explore and constrain the weak intergalactic magnetic fields (IGMF), and test the validity of the Lorentz Invariance principle at high energies. Blazars observations constitute a key component of the VERITAS observation program. Over the past decade the VERITAS observatory has carried out a combination of dedicated blazar observations, long term studies of certain historical blazars, a discovery program for detecting new TeV blazars, and target-of-opportunity observations for flaring sources (Benbow, 2017).

Figure 4: VERITAS skymap (October 2017). The shaded area shows the region of visibility for VERITAS, which is located in the Northern Hemisphere. Different source types are represented as follows: blazars (red), pulsar wind nebulae (magenta), binaries (yellow), supernova shells (green), starburst galaxies (orange), and dark/unidentified (grey). Figure modified from TeVCat (TeVCat, 2017).
Table 1 lists all the extragalactic sources detected by VERITAS as of October 2017. Except for the two FR I type radio galaxies, M87 and NGC 1275, and the starburst galaxy M82, all the extragalactic sources are active galaxies of the blazar class. It is not surprising that of the 36 sources shown in the table, 23 are high-frequency-peaked BL Lac objects (HBLs). As we have learnt, the TeV blazar population is largely dominated by high-frequency peaked BL Lacs, in which the peaks in the spectral energy distribution (SED) lie in the X-ray and TeV bands (TeVCat, 2017). These blazars exhibit strongly correlated TeV and X-ray emission on many occasions, suggesting that the low-energy peak is explained by synchrotron emission from a population of ultra relativistic electrons, and that the high-energy peak arises from inverse-Compton scattering of the synchrotron photons by the same population of electrons. So called “SSC,” or 1-zone synchrotron self-Compton models of blazar emission (Maraschi & Tavecchio, 2003), have been found to be largely successful in explaining TeV emission in blazars. In addition to HBLs, VERITAS has also detected high energy emission from other blazar classes, such as intermediate- and low-frequency-peaked BL Lacs (IBLs/LBLs), with gamma-ray emission peaking at lower frequencies, flat spectrum radio quasars (FSRQs), and radio galaxies. Typically, FSRQs are only detected during flaring episodes. As the catalog of TeV LBLs, IBLs and FSRQs grows, it will be possible to carry out studies of blazar populations, and the study of jet properties in systems with different supermassive black hole (SMBH) masses and accretion rates than the commonly observed HBLs.

The blazars detected by VERITAS are predominantly nearby, with the range of redshifts from 0.03 to at least 0.939. It is interesting to note that all VERITAS AGN are also detected by the Fermi-LAT at lower energies. This could possibly be due to observational bias, since the strategy of the VERITAS observations has been to follow up on hard-spectrum Fermi-LAT sources, or flaring Fermi-LAT blazars, as well as X-ray selected HBLs, which have also been detected at GeV energies. Only a handful of TeV detected blazars are not seen at Fermi-LAT energies. One example is the HBL 1ES 0347-121 (TeVCat, 2017), and some studies have used this non-detection to place interesting limits on the IGMF (Neronov & Vovk, 2010). VERITAS observations are supported by simultaneous multi-wavelength data that has helped in modeling studies of the blazar SEDs.
2.1. *Flat-Spectrum Radio Quasars and the Distant Blazar PKS 1441+25*

There are only 6 FSRQs known to be TeV emitters as of date (TeV-Cat, 2017), and only two detected by VERITAS, namely, PKS 1441+25 and PKS 1222+216. At a redshift of 0.939, PKS 1441+25 is the most distant source in the VERITAS catalog. FSRQs are believed to host radiatively efficient disks that enrich the environment of the supermassive black hole with ultraviolet-to-optical photons. In FSRQs, $\gamma\gamma$ interaction of TeV photons with the ultraviolet-to-optical photon field from the disk, the reprocessed emission from the clouds of the broad line region (BLR), or the infrared radiation (IR) from the “dusty torus” can make the environment opaque to TeV gamma rays from the base of the jet (Donea & Protheroe, 2003). VERITAS detected gamma-ray emission from PKS 1441+25 from about 80 GeV up to 200 GeV in 2015 April, a period when the source was highly active across all wavelengths. The observation results are summarized in the *Astrophysical Journal Letters* (Abeysekara et al., 2015), which was simultaneously published with the MAGIC detection of the source at the same time (Ahnen et al., 2015).

Figure 5a shows the broadband SED of PKS 1441+25 from X-ray to TeV gamma rays. A stationary model was used to reproduce the data, using the numerical code of Cerruti, Boisson & Zech (2013), and assuming the EBL model of Gilmore et al. (2012). The fact that the week-long TeV and X-ray enhanced activity was detected during a half-year long period of simultaneous brightening in the radio, optical, and GeV bands suggest that all emissions come from the same region, located $\sim 10^4$ to $10^5$ Schwarzschild radii away from the black hole, which would point to large-scale emission in PKS 1441+25. This is the first detailed photometric and polarimetric picture of a TeV FSRQ consistent with a single region being responsible for the multi-band flare.

The detection of gamma-ray emission from PKS 1441+25 also sets a stringent upper limit on the near-ultraviolet to near-infrared intensity of the EBL, as shown in Figure 5b. The VERITAS and MAGIC results imply that galaxy surveys have resolved most, if not all, of the sources of the EBL at these wavelengths. Catching a TeV gamma-ray outburst from a quasar provides an excellent opportunity for placing constraints on the diffuse extragalactic background radiation, and offers insights on the relativistic jets of blazars.
2.2. Extreme Variability in Flux

Blazars are characterized by extreme and episodic flux variability across all wavelengths, and observations of bright blazar flares result in tighter constraints on the size and location of the gamma-ray emitting region (e.g. Begel-
A bright, short-lived flare in BL Lacertae was measured by VERITAS in June 2011, the first detection of minute-scale variability in a low-frequency peaked BL Lac object. In this observation, the flux from the source was found to decay by a factor of $\sim 10$ in $13 \pm 4$ min, thus constraining size of emission region to $\sim 2.2 \times 10^{13} \delta$ cm, where $\delta$ is the Doppler factor of the jet (Arlen et al., 2013). At the time of the TeV flare, the source was active and variable in GeV gamma rays as detected by the Fermi-LAT. Observations with VLBA at 43 GHz also noted the emergence of a radio knot, resolved as moving downstream in the jet, that is likely to be linked to the gamma-ray flare (Arlen et al., 2013).

Recently, in 2016 October, a fast TeV gamma-ray flare was detected again from BL Lacertae by VERITAS, with a rise time of about 2.3 hours and a decay time of about 36 minutes. Figure 6a shows the VERITAS light curve above 200 GeV for this flare, plotted with a 4-minute binned light curve. The peak flux from BL Lacerate during this flare was measured to be roughly 180% the Crab Nebula flux (Feng, 2017).

Another AGN that has exhibited several flares at TeV energies is the radio galaxy M 87. Radio galaxies offer an unique opportunity to study VHE emission in close proximity to a super-massive black hole, since they exhibit
weak-to-moderate beaming, with jets at larger angles compared to blazar jets. Only two radio galaxies have been detected by VERITAS, M 87 and NGC 1275. Figure 6b shows a bright and isolated VHE flare recorded from M 87 in 2010 by all three IACTs, VERITAS, MAGIC and H.E.S.S. (Abramowski et al., 2012). The flare is characterized by a two-sided exponential function with a rise time of near 1.7 days and fall time of approximately 0.6 days.

No two blazar flares are similar. VERITAS measured an isolated gamma ray flare in February 2014 from B2 1215+30 that was remarkable because of its extreme luminosity, with the TeV flux reaching 2.4 times the Crab Nebula flux with a variability timescale of less than 3.6 h. The measured flux above 0.2 TeV corresponded to an isotropic luminosity $L_\gamma = 1.7 \times 10^{46}$ erg s$^{-1}$, which was one of the highest to be ever observed from a TeV blazar. The VERITAS observations imply a Doppler factor $\delta > 19$ and place the emitting blob beyond the broad-line region (Abeysekara et al., 2017c). The short timescale flux variability observed in B2 1215+30 may be explained as particle acceleration in relativistic shocks or through magnetic reconnection (Sironi & Spitkovsky, 2009; Giannios, 2013). These observations suggest a hard spectrum for the electron population with index $p \sim 1.9$, and are consistent with a scenario of magnetic reconnection events in the blazar jet.

2.3. Understanding Blazar Spectral Energy Distributions

Multitwavelength (MWL) observations of blazars provide critical input to modeling blazar SEDs and understanding their particle acceleration and radiation. The key to a successful model calculation is contemporaneous and complete coverage across a broad wavelength range, which has often proved difficult. Dedicated blazar MWL campaigns in recent times have allowed us to make some progress in this area. It is generally found that the SEDs of HBLs are better explained by a one-zone synchrotron self-Compton emission model, although with some degeneracies (for example, see Böttcher et al. (2013) for a review of blazar emission models). Observations of 1ES 0229+200 with VERITAS over a three year period from 2009 to 2012, provided an SED data set that allowed extensive modeling studies. In particular, with the availability of Swift, Fermi-LAT, and VERITAS data, it was possible to constrain both the low-energy and high-energy peaks of the SED of the blazar. The SED of the HBL 1ES 0229+200 was found to be compatible with an SSC model, and the data allowed constraining the SSC parameter space, using an algorithm as described by Cerruti et al. (Cerruti, Boisson & Zech, 2013). Figure 7 shows the relationship between the Doppler factor
Figure 7: (Left) Constraining the magnetic field $B$ and Doppler factor $\delta$ parameter space obtained from model calculations for the broad band SED of the HBL 1ES 0229+200. (Right) Particle and magnetic energy densities ($U_e$ and $U_B$) parameter space in the model calculation of the SED of 1ES 0229+200. The slanted lines are equipartition contours ($U_e/U_B$). In both plots, the color scale is arbitrary and the most extended contour represents the 1σ region (Aliu et al., 2014b).

$\delta$, with the tangled homogeneous magnetic field $B$, and the energy densities contained in the particles and magnetic field ($U_e, U_B$). The latter indicates that the equipartition factor $U_e/U_B$ is between $2 \times 10^4$ and $10^5$, implying an emission region significantly out of equipartition (Aliu et al., 2014b).

On the other hand, some blazar SEDs are not well modeled with a simple one zone SSC scenario. For example, observations of the BL Lac object PKS 1440+122 with Fermi-LAT, Swift, and VERITAS showed that while a synchrotron self-Compton model produces a good representation of the multi-wavelength data, adding an external-Compton or a hadronic component also adequately describes the data (Archambault et al., 2016). In general, HBL-like SEDs can be modeled by SSC, SSC+EC and lepto-hadronic models. The VERITAS blazar “long term” program continues to build up a database of SEDs from a variety of blazars, which will enable focused modeling studies in the future (Benbow, 2017). As we build up an archival data set on VHE blazars, it is possible that high-resolution measurements of blazar spectra at GeV and TeV energies, and variability studies of blazar flares, may help resolve degeneracies between blazar models.
2.4. New Discoveries: OJ 287

The TeV sky is rapidly changing, and the very high energy source catalogue continues to grow. In February 2017, VERITAS reported the detection of the iconic optically bright quasar blazar, OJ 287 (Mukherjee et al., 2017) that shows an interesting 12-year cycle quasi-periodicity in the optical band (Shi, Liu & Song, 2007). OJ 287 is believed to host a binary black hole system at its core (Valtonen et al., 2006), and was known previously to be a gamma-ray emitter at GeV energies, with strong flares detected by Fermi-LAT. Strong gamma-ray flares are believed to originate from either the “core” region or further downstream in the jet (Hodgson et al., 2017), but this was the first evidence of VHE emission from the source. Studies are currently underway to understand the TeV emission in the context of multi-wavelength models (O’Brien, 2017).

3. Galactic Astrophysics with VERITAS

The VERITAS Galactic program encompasses a variety of topics such as the survey of the Cygnus region, study of supernova remnants including non-thermal shells, shell-molecular cloud interactions, and the observation of TeV pulsar wind nebulae (PWNe) associated with high $E_{\text{dot}}/d^2$ pulsars, observations of gamma-ray binaries and binary candidates, follow-up of unidentified gamma-ray sources, and focused observations of the Galactic Center. In the following subsections, we highlight a few results from VERITAS.

3.1. Supernova Remnants

Supernova remnants are a key component of the VERITAS long term observation plan, since gamma-ray emissions from SNRs offer an opportunity to study cosmic-ray acceleration in Galactic sources. These objects are one of the most violent events in our Universe, with expanding shock waves likely to be capable of accelerating cosmic rays up to multi-TeV energies through diffusive shock acceleration. Young shell-type SNRs are expected to release a significant fraction of their non-thermal output at TeV energies, and several have been detected by current IACTs. Figure 8 shows a skymap of the SNR shells detected at TeV energies in the last several years, by H.E.S.S., MAGIC and VERITAS (TeVCat, 2017). All the SNRs detected at TeV energies are remnants of recent supernova explosions, less than a few 1000 years old, except for IC 443 which is a middle-aged remnant. Several of the TeV SNRs have been resolved in VHE gamma rays, and H.E.S.S. has detected at least
five SNRs with shell type morphology (de Naurois, 2013), RX J0852.0−4622 (Vela Junior), SN 1006, HESS J1731-347, RX J1713.7-3946, and RCW 86. In each case, there is clear correlation between non-thermal X-ray and VHE gamma-ray emissions, giving us the chance to investigate sites of CR acceleration. Fermi-LAT data show that SNRs are firmly established as sources of cosmic rays, with the spectrum peaking in the GeV range, and consistent with a pion-bump. Figure 9 shows the gamma-ray spectrum of IC 443 measured with Fermi-LAT, with TeV data from MAGIC, and VERITAS overlaid (Ackermann et al., 2013). The Fermi-LAT SED shows the characteristic cutoff around 200 MeV, which is a direct evidence of hadronic interactions, with the gamma-ray spectrum tracing the source spectrum of cosmic rays.

Cas A and Tycho are two SNRs detected by VERITAS. Both sources are unresolved but comparatively bright at TeV energies. With long exposures, VERITAS has been able to make precise spectral measurements for both sources (Holder, 2016). The Tycho SNR provides a particularly good target for investigating hadronic cosmic-ray interactions as it is located in a relatively clean environment, and because it is a young type Ia SNR that is well studied in other wavelengths. The Canadian Galactic Plane Survey (CGPS) shows evidence of a molecular cloud in the north east corner of the remnant.

Figure 8: Skymap showing the SNR shells detected at TeV energies by all three major IACTs, as of October 2017. The shaded areas show the visibility regions for the northern and southern IACTs; blue for MAGIC/VERITAS and magenta for H.E.S.S. Figure compiled from TeVCat (2017).
providing a target for possible hadronic interactions (Ishihara et al., 2010). At X-ray energies of 4.0 to 6.0 keV, Chandra data show non-thermal emission features and shock fronts, with evidence for electrons with energies up to 100 TeV.

VERITAS recently reported results from 147 hours of observations on Tycho’s SNR, spanning data from 2008 to 2012 (Archambault et al., 2017b), which is detected as a point source at VERITAS energies. Enhanced sensitivity of the upgraded VERITAS cameras allowed the measurements to extend down to near 400 GeV. The spectrum of Tycho measured by VERITAS is consistent with a power-law with a gamma-ray photon index $\Gamma = 2.92 \pm 0.42_{\text{stat}} \pm 0.20_{\text{sys}}$. A broad band study of the SED of Tycho was carried out, including data at MeV and GeV energies from Fermi-LAT. Figure 10 shows the SED of Tycho at VERITAS and Fermi-LAT energies. The VERITAS spectrum is found to be softer than that measured at Fermi-LAT energies, and the current VERITAS results indicate that the maximum par-
particle energy in Tycho may be lower than previously suggested. Since the first TeV detection of Tycho (Acciari et al., 2011), several emission models have been proposed to explain its high energy behavior (see for example Slane (2014)). Fig. 10 shows some of these model calculations overlaid on the new VERITAS data, and are found to be inadequate in explaining the new VERITAS data. One of the models in Fig. 10 “Morlino & Blasi 2015” presents a good fit to the data, assuming the presence of neutral hydrogen close to the shock and that the gamma-ray emission is largely in the dense northeastern region of the remnant (Morlino & Blasi, 2016).

IC443 is an older SNR and is one of the classic examples of a supernova remnant interacting with a molecular cloud in an inhomogeneous environment. VERITAS has recently been able to resolve the gamma-ray emission from the entire shell of the remnant, as shown in Figure 11 (Humensky, 2015), after a deep observation campaign. The spatial morphology of the VERITAS emission correlates well with the GeV emission from Fermi-LAT (Ackermann et al., 2013), and shows gamma-ray emission at the position of the brightest maser as well as from the entire northeast lobe. Along with the SNR W51C, detected by MAGIC (Aleksic et al., 2012), in the W51 complex, IC 443 is one of two extended northern SNR to be resolved at gamma-ray energies.
IC 443 offers the opportunity to study a system where the expanding shock wave is interacting with gas and clouds. The spatial resolution of IC 443 by VERITAS has been one of the highlight results from VERITAS. Other resolved TeV SNRs are in the southern hemisphere, and have been detected at TeV energies by H.E.S.S. (Abdalla et al., 2016).

3.2. VERITAS Studies of Gamma-Ray Binaries

Binaries are the only variable and point-like sources in our galaxy, and whether the particle acceleration in these systems happens in jets or colliding winds is still an open question. TeV emission probes the highest energy particles accelerated. VERITAS recently reported on the long-term TeV observations of the gamma-ray binary HESS J0632+057 (Maier, 2015), a source that has now been observed nearly ten years by H.E.S.S., MAGIC and VERITAS. The source was found to have a period of 315 ± 5 days, derived from X-ray data (Bongiorno et al., 2011), and VERITAS has observed the source through nearly its entire orbital period. VERITAS and Swift observations show that the gamma-ray and X-ray fluxes are correlated (Fig. 12a), which can be explained by a simple one-zone leptonic emission model, where relativistic electrons lose energy by synchrotron and inverse Compton
Another well-studied binary at gamma-ray energies is the high-mass X-ray binary (HMXB) LS I+61°303, which has been detected across all wavelengths from radio to TeV, and has been found to exhibit a high degree of flux modulation over a single orbit of period approximately 26.5 days (Kar, 2017). The system consists of a massive B0 Ve star and a compact object, but the nature of the central object, whether it is a black hole or a neutron star has not yet been resolved. A search for pulsations at radio, X-ray, or GeV bands has not found any evidence of pulsed emission. LS I +61° 303 has been extensively observed by VERITAS. Figure 12b shows skymaps of LS I +61° 303 obtained from ten years of VERITAS observations of the source, for ten different phase bins, showing maximum flux in the 0.55 to 0.65 phase range, during its apastron pasage. This data set of more than 200 hours will be useful in determining the nature of the unknown compact object (neutron star or microquasar) in the source. It has been suggested that the baseline TeV emission and VHE outbursts near apastron could be explained by the
so called neutron star flip flop model (Torres et al., 2012). It is interesting to note that LS I+61° 303 also exhibits a super-orbital period of about 4.5 years in radio, X-ray and GeV emission, and TeV gamma rays (Ahnen et al., 2016). The cause of the super-orbital periodicity is not completely known, but the detection of TeV emission is consistent with the predicted long-term behavior of the flip-flop model (Ahnen et al., 2016).

The VHE binary population remains small, with only 6 binaries known to emit at TeV energies (TeVCat, 2017). TeV J2032+4130 may turn out to be a new TeV binary, associated with the pulsar/Be-star binary system PSR J2032+4127/MT91 213, with the pulsar assumed to be in a long period (45-50 years), highly eccentric orbit with MT91 213 (Lyne et al., 2015). With the predicted periastron in November 2017, VERITAS and MAGIC observations were carried out in Fall 2017, and both collaborations recently announced the detection of a point source VER J2032+414 at the location of PSR J2032+4127 (Holder, 2017). This observing campaign is just beginning, and it will be interesting to see if targeted observations continue to find enhanced VHE emission.

### 3.3. The Galactic Center

The Galactic Center is at large zenith angles for VERITAS, and so VERITAS is able explore the region at energies greater than 2 TeV. This is a rich region for gamma-ray studies, revealing diffuse emission, as well as the composite supernova remnant G0.9+0.1, and the supermassive black hole Sgr A*. Recent studies by H.E.S.S. show diffuse gamma-ray emission in the Galactic Center region, suggesting a source accelerating cosmic particles to PeV ($E > 10^{15}$ eV) energies (Abramowski et al., 2016). Figure 13a shows the skymap from VERITAS, following a deep observing program of the region between 2010 and 2014. Diffuse emission along the Galactic ridge is evident, after the point sources SgrA* and SNR G0.9+0.1 are subtracted out (Archer et al., 2016). The VERITAS data, as shown in Fig. 13b, offer improved statistics at multi-TeV energies (as a result of larger effective areas for large zenith angle observations), and together with the H.E.S.S. measurements with excellent statistics at lower energies, provide a rich data set for joint spectral studies between 0.2 to 50 TeV. VERITAS also reported on the detection of a new source VER J1746-289 at > 2 TeV along the Galactic plane, which looks point-like (Fig. 13a, top panel), and could be related to a combination of local enhancement in the diffuse emission near the Galactic Center and a known H.E.S.S. source in the region (Abramowski et al., 2016).
One of the outstanding questions about this region is a definitive explanation of the gamma-ray emission from Sgr A*. Further studies of this region will help resolve some of these outstanding questions.

3.4. The Cygnus Region

VERITAS carried out an observation of the Cygnus region from 2007 through 2012, accumulating more than 300 hours of data. The Cygnus region is a natural laboratory for the study of cosmic rays and their origins, as it is the largest and most active region of creation and destruction of massive stars in the Milky Way. A comprehensive report on the Cygnus region by VERITAS is under preparation, and preliminary results have been presented at the 35th ICRC (Popkow, 2015). Figure 14 shows a skymap of TeV emission measured by VERITAS of this complex region, showing four VERITAS sources VER J2019+407, VER J2031+415, VER J2016+371, and VER J2019+368 (Bird, 2017). The VERITAS survey of the Cygnus region has roughly similar sensitivity as the H.E.S.S. Galactic plane survey (GPS) (Aharonian et al., 2006b). An analysis of seven years of Fermi-LAT data was also carried out to compare with the VERITAS results. A multi-wavelength interpretation of these results is currently under way (Bird, 2018).

3.5. The Crab Pulsar

The MAGIC Collaboration reported the first detection of pulsed gamma-ray emission above 25 GeV from the Crab pulsar (and the first detection of a pulsar > 25 GeV), suggesting that the emission zone is far out in the pulsar magnetosphere (Aliu et al., 2008). The first detection of pulsed emission above 100 GeV from the Crab pulsar was reported by VERITAS, a result that was difficult to explain on the basis of present pulsar models (Aliu et al., 2011). The VERITAS data indicate that the very high energy gamma-ray emission above 100 GeV is unlikely to be primarily due to curvature radiation. These results imply that the gamma rays are not produced at the inner acceleration gap, but rather close to or outside the light cylinder, beyond 10 stellar radii from the neutron star. Furthermore, MAGIC reported the first detection of pulsed emission from the Crab pulsar above 400 GeV with the spectrum reaching up to 1.5 TeV (Ansoldi et al., 2016), challenging emission models. An updated VERITAS analysis on the Crab pulsar was presented by Nguyen (2015) using 194 hours of quality-selected data from VERITAS, searching for pulsed emission beyond 400 GeV, but there was no significant detection. Studies of terraelectronvolt pulsed emission from
Figure 13: (a) Top: The VERITAS $>2$ TeV significance maps of the Galactic Center region after subtracting excess emission from Sgr A* and G 0.9+0.1. The top panel shows the locations of the subtracted point sources as well as the VERITAS source VER J1746-289. VLA 20cm radio contours are shown in the middle panel, with H.E.S.S. excess event contours and Fermi-LAT 3FGL sources shown in the bottom panel. (b) Bottom: The differential energy spectrum of Sgr A*, as measured by VERITAS and H.E.S.S.. The lines describe various power-law model fits. Figures and captions are from Archer et al. (2016).
pulsars may provide the opportunity to probe physics at the Planck scale and constrain LIV (Lorentz Invariance Violation) effects (see for example Otte (2012). A study constraining LIV using the TeV Crab pulsar emission was recently carried out by MAGIC (Ahnen et al., 2017).

4. Fundamental Physics Studies and Cosmology

VERITAS data has contributed to our understanding in several areas of fundamental physics and cosmology. We highlight a few particular areas of study in the following subsections.

4.1. Dark Matter

VERITAS has carried out a program for indirect dark matter searches to look for weakly interacting massive particles (WIMPs) in the mass range of \( \sim 100 \) GeV to 10 TeV. WIMPs are well motivated dark matter candidates in extensions of the Standard Model of particle physics (supersymmetry, Kaluza-Klein). The neutralino, the lightest SUSY particle, could self-annihilate to

![Figure 14: VERITAS VHE gamma-ray significance map of the Cygnus region at energies > 100 GeV (Bird, 2017). The survey region is a 15° by 5° portion of the Cygnus region centered on \( (l = 74.5°, b = 1.5°) \).](image-url)
produce gamma rays. Dwarf spheroidal galaxies (dSphs) are attractive targets for indirect dark matter searches as they are nearby (20 to 200 kpc) and have large mass to light ratios. Additionally, these sources are not known to be high energy gamma-ray sources, and therefore are not expected to produce a confusing astrophysical signal. IACTs such as H.E.S.S., MAGIC or VERITAS are able to put stringent constraints at the high mass range ($\geq 1$ TeV), where instruments such as Fermi-LAT do not have significant sensitivity. VERITAS recently published results on 230 hours of data taken on five dwarf galaxies, Boötes I, Draco, Segue I, Ursa Minor, Willman I, observed between 2007 and 2013 (Archambault et al., 2017a), presenting constraints on the annihilation cross section of WIMP dark matter. VERITAS data show no evidence of gamma-ray emission from any individual dwarf spheroidal galaxy, nor from a joint analysis of the four dwarfs Boötes I, Draco, Segue I and Ursa Minor. Willman I was not included in the joint analysis, since some studies have shown evidence of irregular kinematics in the stellar population of Willman I, and its $J$ factor cannot be reliably calculated (Willman et al., 2011). The paper quotes the following result: The derived upper limit on the dark matter annihilation cross section from the joint analysis is $1.35 \times 10^{-23}$ cm$^3$s$^{-1}$ at 1 TeV for the bottom quark ($b\bar{b}$) final state, $2.85 \times 10^{-24}$ cm$^3$s$^{-1}$ at 1 TeV for the tau lepton ($\tau^+\tau^-$) final state, and $1.32 \times 10^{-25}$ cm$^3$s$^{-1}$ at 1 TeV for two photon final state (Archambault et al., 2017a). MAGIC has also recently published results on annihilation cross section limits using 160 hours of data on one dwarf spheroidal galaxy Segue 1, for the $b\bar{b}$ and $\tau^+\tau^-$ channels, which are the most constraining limits to date (Aleksic et al., 2014). Figure 15 shows the expected median velocity-weighted annihilation cross section limits from the joint analysis of all five dwarf galaxies for all different possible channels. As shown in the figure, the strongest continuum constraints are from a heavy lepton final state. The current upper limits on the annihilation cross section are still about two orders of magnitude away from the value of the relic abundance. One hopes that future improvements in instrumental sensitivity might bridge the gap.

4.2. Constraints on the intergalactic magnetic fields

VERITAS has carried out a search for magnetically-broadened emission from blazars, which could potentially be detected if there is a non-zero magnetic field in the intergalactic medium. Such an intergalactic magnetic field (IGMF) could lead to cascade emission in blazars, particularly for the extreme-HBLs with hard spectrum. Characterizing the IGMF could help
understand the origin and evolution of the primordial magnetic fields. A recent study presented the latest VERITAS results on the search for extended gamma-ray emission. Based on observations on a number of strongly-detected TeV blazars at a range of redshifts (Archambault et al., 2017c), the research found no indication of angularly broadened emission. In particular, for the hard-spectrum blazar 1ES 1218+304, an IGMF strength of $5.5 \times 10^{-15}$ G to $7.4 \times 10^{-14}$ G was excluded at the 95% CL, assuming an EBL model of Gilmore et al. (2012), spectral index $\Gamma = 1.66$ and cutoff energy $E_C = 10$ TeV. Results have also been published by the H.E.S.S. Collaboration, excluding IGMF strengths of $(0.3 - 3) \times 10^{-15}$ G at the 99% confidence level, using data from three blazars 1ES 1101-232, 1ES 0229+200 and PKS 2155-
4.3. Electron Spectrum

At TeV energies, cosmic-ray electrons provide a direct measurement of local cosmic-ray acceleration and diffusion in our Galactic neighborhood since they lose energy quite rapidly via inverse Compton scattering and synchrotron processes. VERITAS, similar to the other IACTs, is able to measure the combined spectrum of the cosmic-ray electrons and positrons beyond the energy range explored by Fermi-LAT and AMS, although it is not able to distinguish between electrons and positrons. Figure 16 shows the preliminary VERITAS cosmic-ray electron energy spectrum in the energy range from 300 GeV to about 5 TeV (Staszak, 2015). The spectrum is best fit with a power-law of two indices, $-3.1 \pm 0.1_{\text{stat}}$ below, $-4.1 \pm 0.1_{\text{stat}}$ above, and a break energy of $710 \pm 40$ GeV. Note that the uptick in the final VERITAS data point is within $2\sigma$ of the best fit line, and should therefore not be over-interpreted. The H.E.S.S. data are also within their systematic limits (not shown here), and are consistent with the VERITAS results. Recently H.E.S.S. has reported the detection of electron-like events extending to about 20 TeV, the highest energies detected to date. These results, reported at the 2017 ICRC, show a spectrum that can be fitted with a smooth, broken power law, with no features seen up to the highest energies (Kerszberg, 2017).

5. Multimessenger & New Partners

As of this writing, VERITAS has started collaborative work with both the HAWC and IceCube Collaborations, and has actively followed up on LIGO/VIRGO alerts. These joint studies provide new avenues using multimessenger techniques to explore the highest energy events in the Universe.

VERITAS has carried out follow up studies of TeV gamma-ray sources from the second HAWC catalog (Abeysekara et al., 2017b), that lists thirty nine very high energy gamma-ray sources based on 507 days of exposure time. VERITAS and Fermi-LAT observations of these fields have seen recently been reported by Park (2017). VERITAS has also carried out a search for TeV gamma-ray emission associated with IceCube high-energy neutrinos, in the hope of finding hadronic cosmic-ray accelerators, which would be sources of both gamma rays and neutrinos. Over the last two years, VERITAS has carried out observations of several muon neutrino events, since they have better angular reconstruction uncertainty ($< 1^\circ$) than other neutrino events.
Figure 16: A preliminary cosmic-ray electron spectrum as a function of energy measured by VERITAS. The VERITAS data are shown as solid blue circles. For comparison, archival data from other experiments in the same energy range are included. The systematic uncertainty of the VERITAS measurements is shown as a gray band. See Staszak (2015) for references.

Figure 17a shows the sky map of high-energy neutrino events as measured by IceCube (Aartsen et al., 2014). VERITAS can view the northern sky (shown in blue). The positions of the IceCube contained muon tracks are highlighted with red circles (C5, C13, and C37). VERITAS carried out observations of the three muon track events, but did not see a gamma-ray excess. Figure 17b shows the skymap of VERITAS observations of C5 (see Santander (2015) for details). VERITAS has also carried out target-of-opportunity observations on the blazar TXS 0506+056, seen flaring in Fermi-LAT (Tanaka et al., 2017), within the localization region of the IceCube neutrino IC 170922A (Kopper & Blaufuss, 2017). It is interesting to note that MAGIC reported on detecting this blazar during the time window of the Fermi-LAT observations (Mirzoyan, 2017).

Responding to transients alerts is of the highest priority for VERITAS, and the goal is to search for sources that emit in two or more “cosmic messenger” channels (photons, neutrinos, cosmic rays, and gravitational waves). VERITAS has carried out prompt follow-up observations of LIGO/VIRGO.
alerts, when possible. Recently, VERITAS reported follow up observations of
the localization region for the gravitational-wave candidate G268556 in January
2017 (Williams, 2017). Thirty nine consecutive exposures were taken
to tile the localization region of the northern section of the 50% contain-
ment region for the event, which was observable at $> 50^\circ$ elevation from
the VERITAS site. The exciting LIGO/VIRGO event GW170817 in August
2017 (Abbott et al., 2017b), for which there were detections of electromag-
netic counterparts, was unfortunately not unobservable for VERITAS due
to its location in the southern hemisphere. (VERITAS is also shut down in
August due to the monsoon season in Arizona). In the future VERITAS will
make it a priority to follow up such events in its field of view.

6. Summary

This review presents some of the highlights from VERITAS in the last
ten years. VERITAS recently marked ten years of successful operations with
its full four-telescope array with a celebration and conference in Arizona in
2017 June (see the conference website (VERITAS 10-Year Conference, 2017)
for a set of talks highlighting the history and scientific accomplishments of

![Figure 17: Left: (a) IceCube sky map of contained high-energy neutrino events. The positions of the IceCube contained muon tracks (C5, C13, and C37) have been circled in red. Figure from Aartsen et al. (2014). Right: (b) Preliminary VERITAS skymap showing significance of detection at the position of C5. The dashed circle represents the angular uncertainty in the neutrino position as estimated by IceCube. Figure and caption from Santander (2015).](image-url)
VERITAS, as well as an overview from partner IACTs and multi-messenger observatories). The outlook in the field of very high energy astrophysics, with the upcoming Cherenkov Telescope Array is excellent (Acharya et al., 2017), and synergies with multi-messenger instruments such as IceCube, HAWC, and LIGO and VIRGO look promising. With its superior angular resolution, VERITAS is able to follow up on any new discoveries announced by multi-messenger partners in the Northern Hemisphere, with the potential of finding an electromagnetic counterpart in the energy range 85 GeV to 30 TeV. The recent detection of gamma rays from the flaring blazar TXS 0506+056 (Mirzoyan, 2017; Tanaka et al., 2017), in the field of the IceCube neutrino 170922A (Kopper & Blaufuss, 2017) was an exciting event, opening up new avenues in multi-messenger astronomy. The first-ever detections of electromagnetic counterparts to the LIGO event 20170817 has demonstrated the promise of multi-messenger astronomy (Abbott et al., 2017a) and new avenues for exploring the Universe have opened up using neutrinos and gravitational waves.

Figure 18 shows the differential sensitivities of the different gamma-ray experiments currently in use and planned for the future (CTA Observatory, 2017). The combined sensitivities from approximately 10 GeV to 100 TeV will allow deep studies to probe particle astrophysics processes in the cosmos. Future synergies will provide access to the high energy Universe using multiple messengers, not only with photons and cosmic rays, but also gravitational waves and neutrinos.

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| Source Name | Class     | Redshift z |
|------------|-----------|------------|
| Mrk 421    | HBL       | 0.031      |
| Mrk 501    | HBL       | 0.034      |
| 1ES 2344+514 | HBL   | 0.044      |
| 1ES 1959+650 | HBL   | 0.048      |
| 1ES 1727+501 | HBL   | 0.055      |
| BL Lacertae | LBL     | 0.069      |
| 1ES 1741+196 | HBL   | 0.084      |
| W Comae    | IBL      | 0.102      |
| RGB J0521.8+112 | IBL/HBL | 0.108      |
| RGB J0710+591 | HBL   | 0.125      |
| H 1426+428 | HBL      | 0.129      |
| B2 1215+303 | IBL/HBL | 0.131      |
| S3 1227+25  | LBL      | 0.135      |
| 1ES 0806+524 | HBL   | 0.138      |
| 1ES 0229+200 | HBL   | 0.140      |
| 1ES 1440+122 | IBL/HBL | 0.163      |
| RX J0648.7+1516 | HBL | 0.179      |
| 1ES 1218+304 | HBL   | 0.184      |
| RBS 0413   | HBL      | 0.190      |
| 1ES 0647+250 | HBL   | 0.203?     |
| 1ES 1011+496 | HBL   | 0.212      |
| MS 1221.8+2452 | HBL | 0.218      |
| 1ES 0414+009 | HBL   | 0.287      |
| 1ES 0502+675 | HBL   | 0.34       |
| 1ES 0647+250 | HBL   | ~0.45      |
| PG 1553+113 | HBL      | 0.43 < z < 0.58 |
| 3C 66A     | IBL      | 0.33 < z < 0.41 |
| PKS 1222+216 | FSRQ   | 0.432      |
| 1ES 0033+595 | HBL   | 0.467?     |
| PKS 1424+240 | IBL/HBL | 0.604      |
| M87        | FR I     | 0.0044     |
| M82        | Starburst | 3.9 Mpc   |
| HESS J1943+213 | HBL?   | ?          |
| RGB J2056+496 | HBL   | ?          |
| RGB J2243+203 | IBL/HBL | >0.39      |
| PKS 1441+25 | FSRQ     | 0.939      |

Table 1: Extragalactic sources of TeV gamma-ray emission detected by VERITAS. Some redshifts are considered uncertain.
Figure 18: Differential sensitivities of the current generation of gamma-ray instruments. The curves for and HAWC are scaled by a factor 1.2 to account for the different energy binning. The curves shown above give only an indicative comparison of the sensitivity of the different instruments, as the method of calculation and the criteria applied are different. A comparison with CTA is shown. Figure and caption from the CTA Observatory website CTA Observatory (2017).

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