VERY HIGH ENERGY ASTRONOMY WITH VERITAS*

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The Very Energetic Radiation Imaging Telescope Array System (VERITAS) consists of four atmospheric Cherenkov telescopes fully operating in the northern hemisphere since 2007. It is located at the Fred Lawrence Whipple Observatory in southern Arizona, USA and is sensitive to gamma rays from 85 GeV to 30 TeV energy range. One of the major focuses of the broad science topics of the multinational VERITAS Collaboration is indirect measurements of cosmic rays and their spectra via the study of very high energy gamma-ray emission. So far, the gamma-ray observation has resulted in detection of 23 galactic and 41 extragalactic sources, which include supernovae remnants, pulsar wind nebulae, gamma-ray binaries, active galactic nuclei, gamma-ray bursts, starburst galaxies, *etc*. VERITAS participates in multi-wavelength studies with several observatories and maintains an active multi-wavelength campaign with HAWC and LHAASO. Additionally, there is also a multi-messenger program with multiple collaborations to follow up on gravitational waves and high-energy neutrino signals originating from the very energetic regions of the Universe. In this presentation, we summarize the recent results from VERITAS in gamma-ray physics along with the multi-wavelength and the multi-messenger efforts.

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1. Introduction

VERITAS is a ground-based gamma-ray observatory located at the Fred Lawrence Whipple Observatory in southern Arizona, USA. It consists of four 12 m diameter imaging atmospheric Cherenkov telescopes (IACTs), each of which covers a field of view of 3.5° using a 499-pixel photomultiplier tube (PMT) camera. The VERITAS gamma-ray instruments started the full-phase operations in 2007. Since then, there have been two major upgrades

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which include the relocation of the original prototype telescope in 2009 and an upgrade of the PMTs in 2012. In the present configuration, the VERITAS gamma-ray instruments can detect 1% Crab flux in 24 hours as shown in Fig. 1. VERITAS is sensitive to gamma-ray emission from $\sim$ 85 GeV to beyond 30 TeV and its angular resolution for a point source is 0.08° at 1 TeV as shown in Fig. 1.

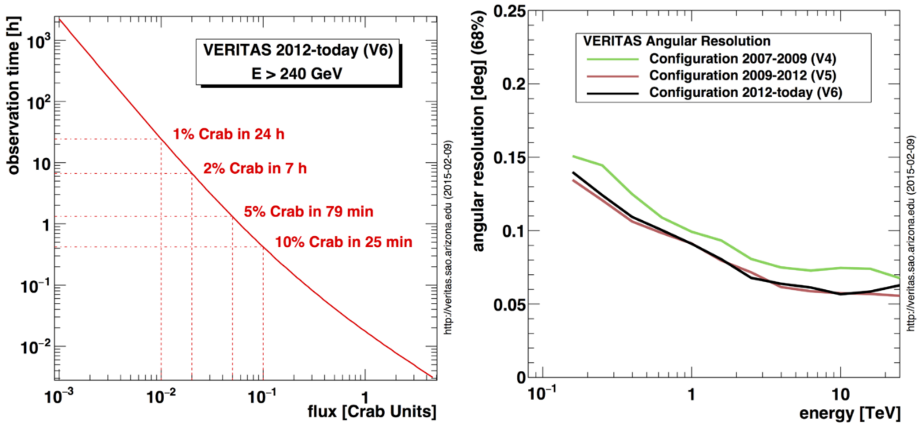


Fig. 1. Left: The VERITAS observation time *versus* source strength to detect a 5σ signal. Right: Angular resolution as a function of gamma-ray energy for the VERITAS configuration prior to two major upgrades and for the current configuration. The specifications of the VERITAS gamma-ray instruments are provided at https://veritas.sao.arizona.edu/

VERITAS typically collects about 70 to 100 hours of data per month from September to June. The observation is closed during July and August due to unfavorable weather conditions (monsoon season). The VERITAS observations require clear, dark skies. However, it is possible to observe with a reduced PMT voltage which enables VERITAS to observe during the moonlight period with up to 60% illuminated moon. The VERITAS observation of the Northern Hemisphere sky since its operation has resulted in 64 gamma-ray sources. Out of the total sources detected, 23 are galactic sources and 41 are extragalactic sources. Additionally, VERITAS is also an active member of multi-messenger follow-up campaigns and also maintains successful optical campaigns. These proceedings summarize some highlights from the VERITAS very high energy science results and multi-messenger follow-up campaigns.

2. Galactic science highlights

The galactic science is driven by our goals to understand particle acceleration in our Galaxy which include exploring the origin of galactic PeV cosmic rays (CRs) by probing very high energy gamma-ray emission, and morphological and spectral studies of the gamma-ray sources to understand the physics in very high energy regime. The VERITAS galactic science program has resulted in detection of multiple source types such as supernovae remnants (SNRs), pulsar and pulsar wind nebulae (PWNe), and gamma-ray binaries. The program also includes follow-up of the sources detected by the wide field of view observatories such as HAWC and LHAASO. Below, there are a few of the recent highlights of the various source types detected by VERITAS.

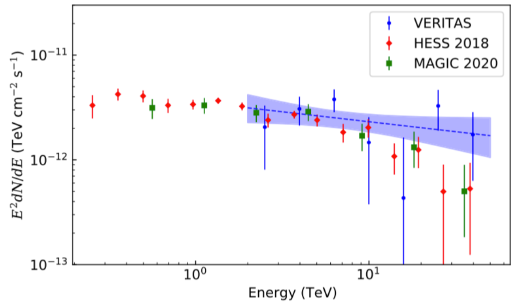
2.1. Galactic plane

The galactic center (GC) region consists of a number of particle accelerators, massive cloud complexes, and astrophysical sources such as the supermassive black hole Sagittarius A*. The diffuse spectrum measured by the HESS observatory for the GC continues up to tens of TeV with no evidence of a cutoff indicating a possible acceleration of protons up to PeV by Sagittarius A* [1]. The VERITAS observation of the region resulted in 125 hours of good data collected between the year 2010 and 2018. The results of the study above 2 TeV in the direction of the GC were published in [2].

The VERITAS source VER J1745+290, co-located with Sagittarius A*, is detected at a significance of 38σ. The spectral energy distribution is described by a power-law spectrum with an exponential cutoff, with a spectral index of 2.12 and a cutoff energy of 10.0 TeV. The spectral measurements are in agreement with the measurements by HESS and MAGIC within the quoted uncertainties [1, 3]. The VERITAS spectrum for the diffuse emission near the GC spanning $-0.7°$ to $+1.3°$ in galactic longitude is derived by combining data from multiple regions along the GC ridge [2]. The diffuse GC ridge has a cumulative significance of 9.5σ and is best fit by a power-law spectrum with a hard index of 2.19 with no evidence of a cutoff up to 40 TeV as shown in Fig. 2. This further strengthens the evidence for presence of a potential PeV CR accelerator in the GC.

2.2. Cas A SNR

SNRs are the major galactic CR accelerators and have the energy budget to explain the CR energy flux in our Galaxy. However, the observations of the SNRs have yet to reveal conclusive evidence of PeV acceleration of CRs. Cassiopeia A (Cas A) is an ideal source to explore the theory of PeV CR



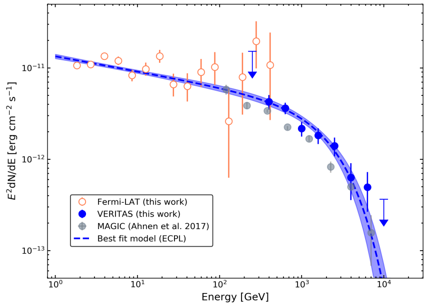


Fig. 2. (Color online) Left: The differential energy spectrum of the diffuse ridge emission reported by VERITAS in [2] (blue dots). The measurements by HESS [1] and MAGIC [3] are shown in red diamonds and green squares, respectively. Right: Spectral measurements of Cas A SNR using combined *Fermi*-LAT (red circles) and VERITAS (blue dots) data [4]. The blue curve is GeV to TeV spectrum described by a power law spectrum with an exponential cutoff [4].

acceleration by SNRs as it is one of the youngest galactic SNR, only about 350 years old. Cas A SNR has been observed from radio to gamma-ray bands. VERITAS has collected about 65 hours of good data on Cas A SNR during 2007–2012 observation period. The VERITAS analysis of the spectral energy distribution of Cas A above 200 GeV favors a power-law spectrum [4]. The spectral analysis in an energy range of (0.1–500) GeV was also performed using the *Fermi*-LAT data set. A spectral break observed at 1.3 GeV in the GeV spectrum is a signature of hadronic origin of gamma-ray emission via pion decay. The joint spectrum from *Fermi*-LAT and VERITAS shown in Fig. 2 favors a simple power-law spectrum with an exponential cutoff at 2.3 TeV [4]. This provides evidence of TeV acceleration of protons since at least 6 TeV protons are required to explain the GeV to TeV spectrum.

2.3. HESS J0632+057

The gamma-ray binary source class consists of a massive star in an orbit with a compact object. The massive star can be a Be-type star or O-type star, and the compact object can be either a pulsar or a black hole. While the nature of the massive star is known in almost all cases, the nature of the compact object is mostly unknown except in the case of a few binary systems. VERITAS has been monitoring for long a couple of binary systems which include HESS J0632+057. The light curve of HESS J0632+057 with more than a decade of observation by VERITAS above 350 GeV is shown in Fig. 3.

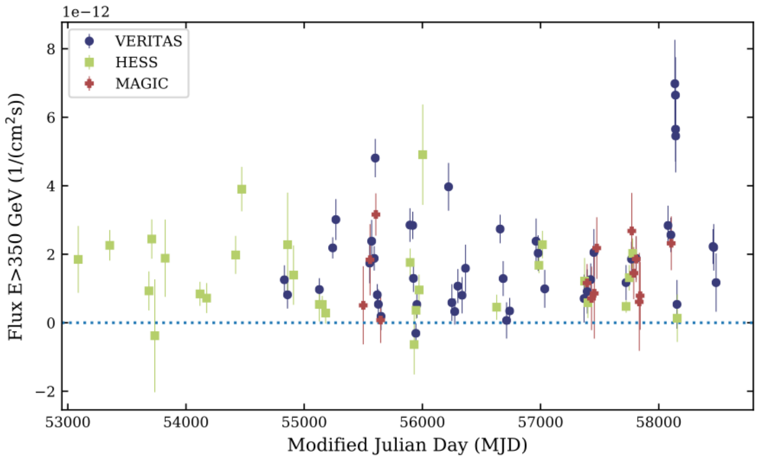


Fig. 3. (Color online) Gamma-ray light curves of HESS J0632+057 with HESS (green squares), MAGIC (red crosses) and VERITAS (blue dots) from [5]. The vertical lines are 68% statistical uncertainties [5].

The orbital period of 316.7 days was reported for the first time for this binary system at TeV energies which is in close agreement with the 317.3 days reported by the X-ray measurements. The phase-folded light curve at TeV energies resulted in two maxima at the orbital phase of 0.3 and 06–0.8, with a more prominent first maxima. The period of enhanced activities with increased flux was observed in January 2011 and January 2018. A short flux decay time of 20 days or less was reported in the multi-wavelength studies for these two outburst periods. A strong correlation between the X-ray and gamma-rays was observed which suggests a single-particle population origin for the X-ray and gamma-ray emission. The studies of the full data set observation by HESS, MAGIC, and VERITAS, and the other multi-wavelength results indicate orbit-to-orbit variability [5].

2.4. Pulsars and pulsar wind nebulae

Another powerful particle accelerators, with possible lepton acceleration up to a few PeV, are pulsars. PSR J2032+4127 is one of such pulsars, which is capable of powering a TeV PWN. This pulsar is a part of a binary system with a Be star with a period of 50 yr, which makes it a rare gamma-ray binary in which the nature of the compact object is known. The binary system reached periastron on November 13, 2017. The MAGIC and VERITAS observations of the binary system from 18 months prior to periastron to one month after the periastron reported a new gamma-ray source co-located with PSR J2032+4127/MT91 213 [6]. The new gamma-ray source, VER J2032+414, associated with the pulsar/Be star binary system is detected with a significance of 21.5σ with VERITAS in the energy range of 100 GeV to 20 TeV using 181.3 hours of observation. This binary system is also the first binary system with a PWN (TeV J2032+4130) possibly associated with it.

Emission from the PWNe powered by pulsars has been reported from radio to TeV energies. While the production mechanism of radio and MeV emission is via synchrotron processes of the accelerated leptons, the GeV and TeV emission is due to inverse Compton scattering processes. Due to the comparatively longer cooling time of the particles emitting inverse-Compton radiation at GeV/TeV energies ($\sim$ 10–100 kyr, assuming a typical interstellar medium photon density), PWNe in theory can extend to larger scales in the TeV energies. However, the supersonic PWNe with long tails reported in radio and X-rays have not been detected at TeV yet. The VERITAS study of the three supersonic pulsars (PSR B0355+54, PSR J0357+3205, and PSR J1740+1000) tails region provided the upper limit on the TeV flux and luminosity [7]. Based on the results, there is a possibility of TeV detection of PSR B0355+54 tail with the 2–3 times more sensitive gamma-ray instruments than VERITAS. The next-generation IACT observatory [8] with greatly improved sensitivity will likely be able to detect such pulsar tails at TeV.

3. Extragalactic science highlights

The extragalactic science is driven by our goals to discover new very high energy sources and to understand the spectral energy distribution and periodic behavior of the sources. The majority of the gamma-ray sources detected by VERITAS are extragalactic sources which include BL Lac objects, starburst galaxy, and radio galaxies. 41 active galactic nuclei (AGN), which include radio galaxies and blazars, have been detected by VERITAS so far. 37 of the 41 detected AGN are blazars. The emission observed from these AGN is highly variable in multi-wavelength bands. The time scale of variability could be as short as minutes. Hence, to understand the physics environment in these regions and the variability patterns, the multi-wavelength observation campaigns are required. Below are some of the science highlights of the AGN studies with VERITAS and the multi-wavelength instruments.

3.1. 3C 264

3C 264 is the most distant radio galaxy detected at TeV. VERITAS reported detection of 3C 264 in 2018 at 5.4σ using 12 hours of data. The spectral energy distribution is well fit by a power-law spectrum with a hard index of 2.2. This detection was followed by additional VERITAS and multi-wavelength observations. Using 57 hours of observation from 2017 to 2019, VERITAS detected the radio galaxy with 7.8σ [9]. The very high energy flux is variable on monthly time scales and a modest elevation in TeV flux was observed in 2018 as shown in Fig. 4. The source of the observed elevated flux is unclear. The comparison of 3C 264 and another radio galaxy M87 shows many similarities, especially in the radio wavelength.

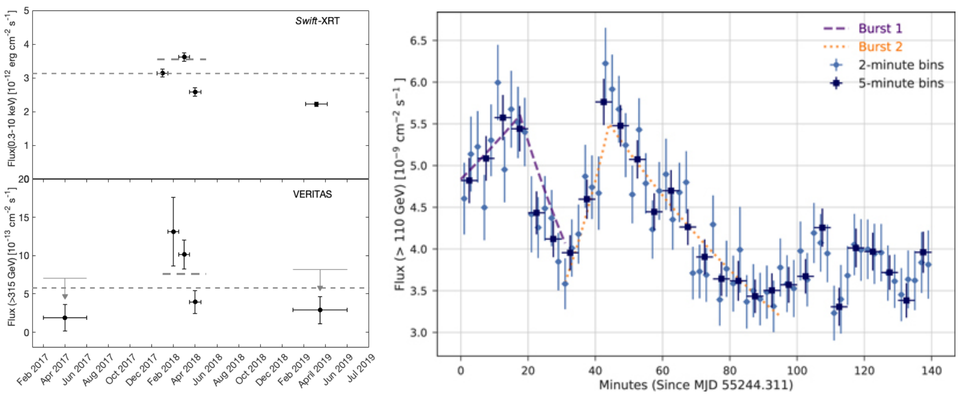


Fig. 4. Left: 3C 264 light curve measurements with VERITAS from [9]. Right: Mrk 421 light curve with two bursts observed by VERITAS during the first 2.33 hours of observations on MJD 55244 from [10].

3.2. Mrk 421 flare

In contrast to the modest enhanced flare of 3C 264, an extraordinary flaring episode was observed for Mrk 421 in February 2010 [10]. The highest flux observed at TeV energies for this source was recorded then with the flux of about 27 Crab Units above 1 TeV during February. It is not clear if the flare is a result of a different behavior state for Mrk 421 or if it is the extreme behavior of the previously assumed underlying processes. The variable emission observed on February 17 could be characterized by two burst peaks, with a faster rise time and slower decay for the second peak as shown in Fig. 4. Using this faster time variability of the TeV flux, the limits on the Doppler factor were derived [10]. A coordinated campaign across multiple instruments allowed the cross-correlation studies spanning optical to TeV band. The studies revealed a time lag of $\sim$ 25–55 minutes for optical emission, the first inter-band correlation on such a short timescale.

3.3. 1ES 1215+303

Another blazar with multi-wavelength variability is 1ES 1215+303. A detailed analysis of the light curves and spectra from radio to TeV bands was presented in [11] which includes more than a decade of observation in gamma-ray energies and 15 years of data for optical and radio energies. The paper [11] reported a continued flux increase from August 2011 up to 2017. This steady enhancement was significantly observed in GeV and optical light curves. This behavior is not well understood yet, however, it could be due to a perturbation within the accretion disk. Based on the multi-wavelength light curves, this blazar is the first example of the blazar capable of changing from one category to another, *i.e.* in this case, from intermediate frequency peaked BL Lac to high frequency peaked BL Lac. The explanation behind the change is unclear and needs more exploration.

3.4. Extragalactic background

As previously mentioned, the VERITAS extragalactic sky is dominated by blazars. The spectral measurements of blazars above 100 GeV can help us to constrain the spectral energy distribution of the extragalactic background light (EBL). The gamma rays originating from distant blazars on their way to the Earth interact with the EBL producing electrons and positrons. The energy- and distance-dependent attenuation of the photons reaching Earth can provide us information to reconstruct the EBL spectrum. VERITAS reported on the EBL spectrum in the wavelength from 0.56 to 56 microns using the spectral measurements of 14 blazars [12]. The observed spectral energy distribution of EBL by VERITAS agrees with the previously reported measurements as shown in Fig. 5.

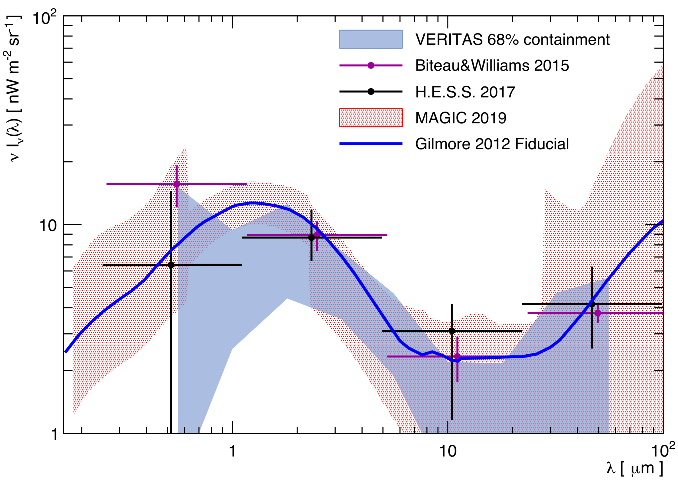


Fig. 5. (Color online) Extragalactic background light intensity as a function of wavelength from [12] by VERITAS (gray/blue bands) and other measurements.

4. Astroparticle science highlights

In addition to gamma-ray astronomy, the VERITAS instruments also have astroparticle applications deriving for example the spectrum of the EBL as mentioned in the previous section. Some of the other astroparticle applications using VERITAS instruments are discussed below.

4.1. Cosmic ray spectrum

During the gamma-ray observations, the VERITAS instruments also collect CR electrons (CREs) and positrons, the information from which can be used to provide the spectral measurements of the CREs. The propagation distance of the CREs is constrained by the rapid loss of energy via synchrotron and inverse-Compton scattering processes. This allows us to determine the possible limit on the distance for the CREs production sites. The TeV CREs detected on the Earth should have been produced within one kpc. This leads to two main possible sources for the TeV CREs detected on the Earth. They are either produced by the astrophysical objects within one kpc distance which are capable of accelerating electrons to such high energies or they are the products of the annihilation/decay of heavy dark matter (DM) particles.

Using 300 hours of data in the energy range from 300 GeV to 5 TeV, VERITAS studied the spectral energy distribution of the CREs detected by the observatory [13]. The VERITAS spectral measurement of the CREs as shown in Fig. 6 favors a spectral shape with curvature in comparison to a simple power-law spectrum. While the power-law spectrum with an exponential cutoff has not been ruled out, the spectrum is also well described by a broken power-law spectrum with a break energy at 710 GeV. The precise

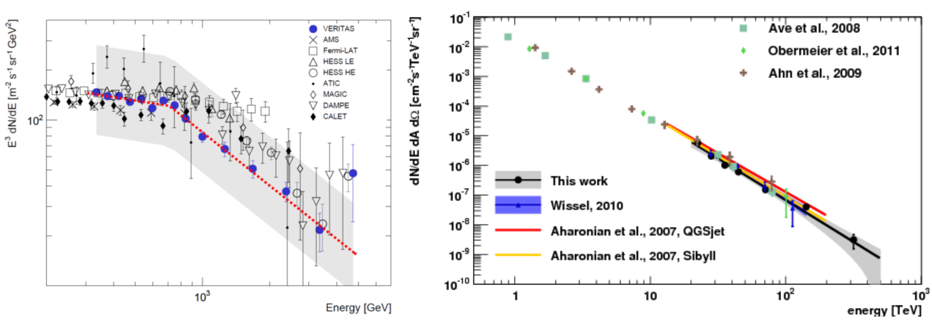


Fig. 6. (Color online) Left: Spectral measurements of the CREs from [13] in the energy range from 300 GeV to 5 TeV by VERITAS (blue/black dots) and other observatories. Right: Spectral measurements of iron nuclei from [14] in the energy range from 20 TeV to 500 TeV with VERITAS (black dots) and other instruments.

measurement of the break energy is important to understand the local CRE environment. The VERITAS results are in agreement with the previous published measurements.

4.2. Iron spectrum

The detection of direct Cherenkov radiation from charged primary particles interaction with the atmosphere by VERITAS can be used to derive the spectrum of CR spectrum especially, heavy nuclei. Using 71 hours of data and utilizing a novel template-based likelihood fit, VERITAS published an updated energy spectrum of CR iron nuclei in an energy range from 20 TeV to 500 TeV [14]. This new template-based analysis is able to account for the images greater than the field of view of the camera, thus improving the sensitivity at the highest energies and extending the spectral measurements up to 500 TeV. The spectral-energy distribution in the TeV energy as shown in Fig. 6 is well described by a power-law spectrum with an index of 2.82. This result agrees with the previous published measurements. Future work could make it possible to measure the spectra of more elements in the TeV–PeV range.

4.3. Dark matter constraints

We are still unaware of 95% of the composition of our Universe. It is assumed that the unknown Universe is composed of dark matter ($\sim 27\%$) and dark energy. VERITAS dark matter program searches for high energy and very high energy gamma-ray emission due to dark matter annihilation or decay. The search for the gamma-ray signatures of dark matter is divided into the four potential dark matter candidate classes, which include the Galactic Center, Galaxy Clusters, Dwarf Spheroidal Galaxies, and *Fermi*-LAT Unassociated Sources. The dwarf spheroidal galaxies, which supposedly have high dark matter content, are located at about 20–200 kpc distance. VERITAS has collected about 230 hours of data on five such dwarf spheroidal galaxies: Boötes I, Draco, Segue I, Ursa Minor, and Willman I. The analyses of data on these five of dwarf spheroidal galaxies were published in [15]. A joint statistical analysis was performed using data on four galaxies excluding Willman I. The study did not find evidence for gamma-ray emission in the individual galaxy analysis as well as in the joint analysis [15]. The paper [15] reported on the upper limits on the dark matter annihilation cross section from the joint analysis. The limits derived at 1 TeV for the bottom quark, the tau lepton, and the gauge boson final states are 1.35×10^{-23} cm^{3}s^{-1}, 2.85×10^{-24} cm^{3}s^{-1}, and 1.32×10^{-25} cm^{3}s^{-1}, respectively [15].

5. Multi-messenger programs

In addition to all the above-mentioned programs, there are additional domains to explore the high-energy universe such as neutrino and gravitational waves. VERITAS is an active member of the multi-messenger community and our multi-messenger programs aim to identify and understand the astrophysical sources of neutrino and gravitational waves.

5.1. Neutrino follow-up

In addition to gamma-rays, the high-energy astrophysical neutrinos detected by the IceCube Observatory are the other messengers from the CR acceleration sites. These neutrino events are believed to have extragalactic origin due to the observed isotropy of the events. The interactions which generate these neutrinos in/near their site of origin should also generate gamma rays via neutral pion production and decay. Hence, a correlated gamma-ray and neutrino flux would be expected. VERITAS has participated in several prompt follow-ups after alerts from IceCube on potential astrophysical neutrino events as well as long-term monitoring activities of the alert regions to search for the associated gamma-ray emission.

5.1.1. TXS 0506+056

The follow-up of the IceCube neutrino event, IC 170922A, announced on September 22, 2017 by the IceCube Neutrino Observatory from the direction of the blazar TXS 0506+056 region, and potentially associated with the blazar, led to the first detection of the blazar in TeV energies. At the time of the IceCube announcement, the blazar was flaring at GeV energies according to the *Fermi*-LAT observations. The follow-up observation by the MAGIC telescope resulted in the TeV detection of blazar TXS 0506+056 at 5σ [16], making this the first detection of TeV gamma rays from a neutrino event direction.

VERITAS conducted one-hour observation within 12 hours of the IceCube event, however, the weather conditions were not favorable at the VERITAS site during the time period. The observation under non-optimal weather did not result in detection of gamma-ray emission. However, the observations were continued over the next 5 months yielding 35 hours of data resulting in detection at 5.8σ [17]. The spectral energy distribution above 110 GeV as shown in Fig. 7 is well described by a power-law spectrum with a soft spectral index of 4.8. The total integral flux is about 1.6% of the Crab Nebula flux above 110 GeV. The GeV (measurements by *Fermi*-LAT) to TeV spectrum favors a spectral shape with a curvature. The spectral softening between the *Fermi*-LAT and VERITAS energy range indicates either a break in the parent particle population or intrinsic absorption of the potential hadronic emission at the source.

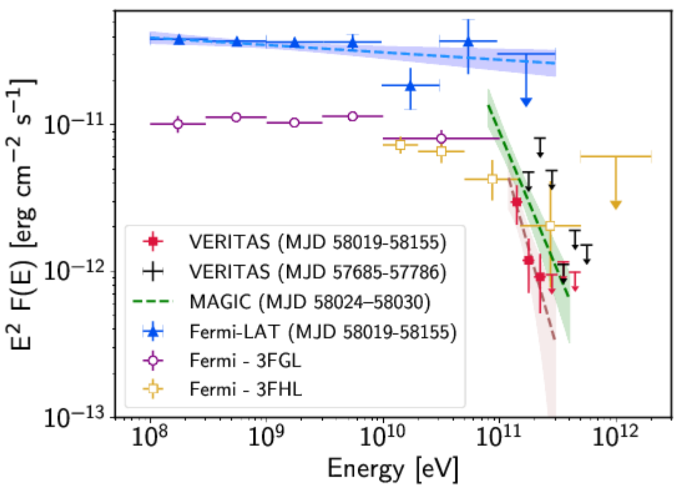


Fig. 7. (Color online) Spectral measurements of the blazar TXS 0506+056 from [17] by VERITAS (red and black), MAGIC (green) and *Fermi*-LAT (blue, purple, and yellow).

5.2. Gravitational wave follow-up

The discovery of electromagnetic signal possibly associated with the neutron star mergers by LIGO/Virgo has strengthened the need for multi-messenger campaigns to explore the most energetic events in our Universe. As an active member of the gravitational wave follow-up community, after the announcement of the gravitational wave event GW170104 via the GRB Coordinates Network 5 hours after the detection, VERITAS observed the region. However, the follow-up did not result in any detection of the gamma-ray source. Additionally, the non-optimal weather with the presence of clouds made it challenging to set upper limits.

A new method to search for very high energy counterparts of binary neutron star merger candidates in archival IACTs data was presented in [18]. Using the new method, eight hours of the archival VERITAS observations were identified to be coincident spatially and temporally with seven binary neutron star merger candidates. The search did not result in gamma-ray detection. The paper [18] presented the upper limits on the integral flux for the coincident regions. The method used in [18] to the archival data could also be extended to near real-time observation.

6. Summary

Since 2007, VERITAS has been contributing to gamma-ray and multi-messenger science and will continue its operation until the completion of the next generation IACT, the Cherenkov Telescope Array (CTA) [8] which will be ten times more sensitive than VERITAS. The prototype Schwarzschild–Couder telescope (SCT) designed for the CTA has successfully detected Crab. Till the operation of the next generation IACT, in addition to already mentioned science campaigns for very high energy regime, VERITAS will also be working on the science results with the joint pSCT and VERITAS data, follow up of new HAWC and LHAASO sources, and the advanced analysis methods to improve source sensitivity.

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