Recent VERITAS Results

D. Staszak, for the VERITAS Collaboration
McGill University, 3600 rue University, Montreal, Quebec, H3A2T8, Canada

Abstract

VERITAS is an array of four imaging atmospheric Cherenkov telescopes near Tucson, Arizona and is one of the world’s most sensitive detectors of very high energy (VHE: >100 GeV) gamma rays. The scientific reach of VERITAS covers the study of both extragalactic and Galactic objects as well as the search for astrophysical dark matter. In these proceedings we will discuss the status of VERITAS operations and upgrades and present a selection of recent results.

Keywords:

1. Introduction and Array Status

VERITAS is an array of four imaging atmospheric Cherenkov telescopes near Tucson, Arizona and is one of the world’s most sensitive detectors of very high energy (VHE: >100 GeV) gamma rays. The array has been fully operational since 2007 and now has a catalog of more than 40 detected extragalactic and Galactic sources. VERITAS science covers a wide range of topics. In these proceedings we will highlight a few recent results from both extragalactic and Galactic areas of study as well as briefly describe the status of the dark matter science program.

The VERITAS array can currently measure astrophysical gamma rays over the energy range of ∼85 GeV to 30 TeV with an energy resolution of ∼15-25%, an angular resolution of <0.1° at 1 TeV, and a pointing accuracy error <50′′. VERITAS can detect a 1% Crab flux source in ∼25 hours and the Crab Nebula itself in ∼70 seconds (the Crab Nebula flux is taken as 2.1 × 10^{-10} γ s cm^{-2} s^{-1}). Two major upgrade efforts have been performed since 2007. The first in 2009 developed an improved optical alignment tool[1] and relocated one of the telescopes to better symmetrize the array[2]. The second in 2011-2012 replaced the L2 trigger system[3] and installed new PMTs in each of the four cameras[4]. The new PMTs are high quantum efficiency models (with photon detection efficiencies reaching 35%) and were installed during the summer monsoon shutdown, resulting in no observing downtime. These PMTs collect significantly more light and extend our effective detection area, especially at lower energies. Fig. 1 shows our sensitivity before and after this upgrade[5].

Since the latter part of the 2011-2012 observing season, VERITAS has aggressively extended observations to cover a larger fraction of the monthly moon cycle. During bright moonlight phases we now observe in two separate non-standard modes designed to limit the effect of background light introduced by the moon: reducing the PMT high-voltages, and covering each of the four PMT cameras with UV-filters. These operation modes increased our effective live time over the season by ∼20%. However, since these observations require dedicated simulations and analysis care, the main use of this time so far is to monitor known or potential sources to catch interesting flaring events. Fig. 2 shows one of these filters that is designed to pass the peak of the Cherenkov spectrum (∼250-400 nm) while blocking the majority of the moon’s reflected solar spectrum.

2. Extragalactic Results

All VERITAS extragalactic source detections are blazars with two exceptions: M82, a starburst galaxy, and M87, a radio galaxy[1]. The VERITAS extragalactic science program emphasizes the detection and characterization of as many blazars and AGN as possible since there are many scientific topics that benefit from a sizeable population to study. VERITAS currently has exposures on roughly 100 different AGN and has a monitoring program to catch interesting events (flares) from a large number of VHE detected or candidate AGN.

At the 2013 ICRC, VERITAS announced the detection of a second radio galaxy, NGC 1275.
VERITAS blazar source detections range from the relatively close, Mrk 421 with a redshift of 0.030, to the most distant blazar yet detected, PKS 1424+240 with a newly measured lower limit redshift of 0.6035. This newly-published limit makes PKS 1424+240 one of the most intriguing VHE blazar detections thus far and challenges the existing models of the extragalactic background light (EBL). A combined spectral analysis of Fermi-LAT and VERITAS data shows a clear spectral break at \( \sim 100 \text{ GeV} \). Whereas VHE photons are believed to be absorbed by \( \gamma_{\text{VHE}} + \gamma_{\text{EBL}} \rightarrow e^+ + e^- \) processes, GeV photons are expected to be unaffacted by these interactions. A deabsorped VHE spectrum of PKS 1424+240 using several existing EBL models does not adequately correct the majority of the VHE points to an extrapolated LAT spectrum. While the remaining difference could arise from unaccounted-for effects at the VHE source, it could also indicate the possibility that the gamma-ray opacity of the Universe has been overestimated.

This past observing season was witness to a historic flaring event from Mrk 421. In March of 2013 a MWL campaign began to look at the nearby blazar with MAGIC, VERITAS, and the newly commissioned NuSTAR satellite. Flaring activity was seen by all three, as well as with Fermi-LAT and Swift. Fig. 3 shows VERITAS preliminary flux levels that reach up to \( \sim 14 \) Crab units. Note that many of the holes in VERITAS coverage are filled by MAGIC (not shown here). This is a rich dataset containing up to 11 hours of VHE/GeV/X-ray overlap data (X-rays from both NuSTAR and Swift) that has only begun to be explored.

In addition to the excitement from the two blazars described above, we can report two new VERITAS blazar detections, 1ES 1011+496 and 1ES 0647+250. Both of these blazars were originally discovered in the VHE band by MAGIC but not detected by VERITAS prior to this season. Both were also initially observed during partial moonlight observations, emphasizing the usefulness of extending observation into moonlight conditions. 1ES 1011+496 was detected in 10.4 hours at 8.5\( \sigma \) significance with an observed flux of 6.3\% Crab units \( > 150 \) GeV. 1ES 0647+250 was detected in 10.9 hours at 6.2\( \sigma \) significance with an observed flux of 7\% Crab units \( > 200 \) GeV.

3. Galactic Results

VERITAS is a northern hemisphere observatory and so primarily views the outer galaxy. Galactic sources detected by VERITAS include SNRs, PWN, binary systems, unidentified sources, and the first detected pulsar above 100 GeV.

One of the main focuses of the VERITAS Galactic science program is to understand the origin of TeV cosmic rays in the Galaxy. Gamma rays are unique probes of energized regions since they are neutral and thus not deflected by the intervening magnetic fields. SNRs have long been believed to be the main source up to energies around the knee. However, the gamma-ray production mechanism isn’t necessarily understood and can vary from source to source (from shock acceleration at the shell to pulsar emission to PWN emission).

CTA 1 is a composite shell-type SNR that is X-ray filled and has a radio shell of diameter 1.8\( ^\circ \). Fermi-LAT performed a blind search for pulsations and discovered a \( \gamma \)-ray pulsar in the center region with a period of 315 ms and an age comparable to that of the SNR. This was the first direct evidence that this SNR could possibly be a PWN. VERITAS observed CTA 1 for 41 hours and detected extended emission (with angular extent \( \sim 0.25^\circ \)) from the object at 6.3\( \sigma \) post-trials significance (see Fig. 4). The measured flux is \( \leq 4\% \) Crab flux units \( > 1 \) TeV and the fitted centroid of the VERITAS significance is within 5 arcmin of the Fermi pulsar. The source name of this object is VERJ0006+729. A PWN explanation is strongly favored by the physical proximity of the VHE source to the Fermi pulsar as well as the extended yet compact emission region. CTA 1 fits well with the emerging picture of relatively young, high E-dot pulsars being good candidates for TeV PWN emission.

There are four gamma-ray binary systems detected at VHE energies: LSI +61\(^°\) 303, HESS J0632+057, PSR B1259-63, and LS5039. These are complicated systems where the VHE emission may arise from either colliding winds or be powered by accretion. VERITAS has detected two of the four, LSI +61\(^°\) 303, HESS J0632+057, the latter being unique of the four in that it isn’t detected by the Fermi-LAT.

LSI +61\(^°\) 303 is a high mass X-ray binary system that contains a compact object (neutron star or black hole) orbiting a large main sequence star with a 26.5 day elliptical orbit. It exhibits X-ray emission throughout the orbit, radio emission that peaks at periastron and apastron, MeV/GeV emission throughout the orbit, and VHE activity typically detected at apastron (seen by MAGIC and VERITAS). The history of VHE emission of this system is intriguing. Strong detections by
The search for particle dark matter is a major effort within VERITAS. Many of the leading candidates for dark matter, including WIMPs, axions, and Kaluza-Klein particles, predict annihilation and/or decay channels with photon final states. These photons can arise from either direct annihilation (for example, $\chi\chi\rightarrow\gamma\gamma$, in the case of the supersymmetric neutralino) or from hadronic or leptonic decay chains (leptonic channels with final state radiation). Direct annihilation would provide the cleanest evidence of DM but is suppressed relative to hadronic channels by higher order loops. VERITAS and other IACTs are an important part of the search for DM since they are sensitive to photon energies that are relatively unconstrained by direct nuclear recoil experiments and collider experiments. Further, any hint of a DM particle seen on Earth would need to be confirmed as the actual astrophysical DM.

VERITAS has targeted several different DM over-densities, including galaxy clusters, dwarf spheroidal galaxies (DSphs), the Galactic Center (GC), and candidate unidentified Fermi-LAT sources. Each source class has advantages and disadvantages based on predicted $\gamma$-ray flux, distance from Earth, astrophysical background levels, and DM density. For brevity in these proceedings, we’ll discuss results and projections from two of the most promising observations, the GC and DSphs.

The GC is a challenging region to analyze because of the dominant astrophysical backgrounds. Additionally, the GC is only visible at large zenith angles ($\text{LZA}>50^\circ$) since VERITAS is a northern hemisphere observatory. VERITAS uses an ON and OFF observation technique to better characterize the background, whereby observations are split between directly targeting the GC and targeting a field in the vicinity of GC without a known VHE emitter. VERITAS detects the astrophysical object at the GC (Sgr A*) and finds a spectrum that is in agreement with prior measurements of this source from other experiments\cite{17,18}. The DM search strategy in this region is motivated by line-of-sight integrals of the DM density that suggest overdensities extending off the Galactic Plane (GP). Signal and background regions are selected within the field of view that avoid the known emitters and the GP while optimizing to different DM over-densities, (see \cite{19} for further details). Fig. 6 shows DM sensitivity projections with VERITAS data including the current 2012-2013 observing season\cite{19}. Note that LZA observations of this region increase the array collection area at high energies. This could benefit VERITAS since the LHC has seen no new physics in their 7-8 TeV Run and the relatively high mass Higgs they measure may have the effect of increasing the SUSY production energy scale, leading to higher mass neutralinos.

DSphs are very promising observation targets because they are DM dominated objects that are nearby with little astrophysical background. VERITAS has observed several DSphs and previously published upper limits on DM flux from Draco, Ursa Minor, Willman 1, and Boötes \cite{20} and more recently from a deeper exposure of Segue 1\cite{21}. Current limits from these studies are two orders of magnitude away from constraining the canonical models of DM. However, Segue I limits do con-
VERITAS flux levels of this flare reached 14 Crab units and a good fraction of the data has X-ray, GeV, and TeV overlapping coverage. VERITAS reports the detection of extended emission from the central region of CTA 1 and finds the emission likely to arise from a PWN. Utilizing 2011-2012 MWL data we show a contemporaneous GeV-TeV spectrum of the high mass X-ray binary object LSI +61° 303. Results show a spectral break at a few GeV and seem to indicate two populations of emitters. However, further investigation will be needed to form a definitive understanding of this object’s nature. Finally, we report that the recent series of upgrades resulted in no loss of observing time and have successfully lowered the energy threshold of the VERITAS array. Additionally, new bright moonlight observation modes are increasing the amount of observing data per season by ~20%.

As a final note we can say that for the first time an IACT experiment has opened up a fraction of its observing time to the larger community. A VERITAS/Fermi pilot program was initiated for Cycle-6 of the Fermi Guest Investigator program (2012-2013)\footnote{For more information see http://fermi.gsfc.nasa.gov/ssc/proposals/}. Roughly 4% of the accepted GI proposals were joint Fermi/VERITAS proposals. VERITAS observations for these proposals will take place during the next observing season.

Acknowledgment

This research is supported by grants from the U.S. Department of Energy Office of Science, the U.S. National Science Foundation and the Smithsonian Institution, by NSERC in Canada, by Science Foundation Ireland (SFI 10/RFP/AST2748) and by STFC in the U.K. We acknowledge the excellent work of the technical support staff at the Fred Lawrence Whipple Observatory and at the collaborating institutions in the construction and operation of the instrument.

References

[1] McCann, A. et al., Astropart.Phys. 32 (2010) 325-329.
[2] Perkins, J. et al. 2009 Fermi proceedings. (arXiv: 0912.3841).
[3] Zitzer, B. et al. 2013 ICRC proceedings. (arXiv:1307.8360).
[4] Otte, N. et al. 2011 ICRC proceedings. (arXiv:1110.4702).
[5] Kieda, D. et al. 2013 ICRC proceedings.
[6] Furniss, A., et al. ApJ 768, L31 (2013).
[7] ATel #4974, Balokovic, M. et al. ATel #4976, Cortina, J. et al. ATel #4977, Paneque, D. et al.
[8] Dumm, J. et al. 2013 ICRC proceedings. (arXiv:1308:0287).
[9] Abdo, A. A., et al. Science 322, 1218 (2008).
[10] Alu, E., et al. ApJ 764, 38 (2013).
[11] Kargaltsev, O. and Pavlov, G. 2009 X-ray Astronomy proceedings. (arXiv:1002.0885).
[12] Smith, A. W., et al. 2013 ICRC Proceedings. (arXiv:1308.0050).
[13] Maier, G. et al. 2011 ICRC Proceedings. (arXiv:1111.2155).
[14] Albert, J. et al. Science 213, 1771 (2006).
[15] Aliu, E., et al. accepted by ApJ. (arXiv:1310.7913).
[16] Beilicke, M., et al. 2011 Fermi proceedings. (arXiv:1109.6836).
[17] Kostyuk, K., et al. ApJ 688, 97 (2004).
[18] Aharonian, F. A., et al. A&A 425, L13 (2004).
[19] Smith, A. W., et al. 2013 ICRC proceedings. (arXiv:1304.6367).
[20] Acero, F. et al. ApJ 720, L174 (2010).
[21] Alu, E., et al. Phys. Rev. D 85, 062001 (2012).
[22] Geringer-Sameth, A. and Koushiappas, S. M. PRL 107, 241303 (2011).
[23] Lattanzi, M., et al. Phys. Rev. D79, 083523 (2009).
[24] Arkani-Hamad, N., et al. Phys. Rev. D79, 015014 (2009).