PROCEEDINGS OF SCIENCE

Recent Results from VERITAS

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VERITAS (Very Energetic Radiation Imaging Telescope Array System) is an array of four 12-m atmospheric Cherenkov telescopes located near Tucson, Arizona, USA. It is sensitive to astrophysical gamma rays at energies above 100 GeV. Since becoming fully operational in September 2007, VERITAS has detected a variety of sources, including active galactic nuclei, pulsar wind nebulae, and supernova remnants. Gamma rays have also been observed from a starburst galaxy, a radio galaxy and an X-ray binary system. Searches for dark-matter annihilation and black-hole evaporation are a continuing part of the science program. This presentation will highlight recent results from VERITAS and outline plans for future upgrades and further observations.

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1. Introduction and Experimental Details

TeV gamma-ray astronomy has strong connections to particle physics, the central theme of the ICHEP conference series, and VERITAS [1] is one of the new generation of TeV instruments pursuing an active program in this area. In this contribution I will highlight some recent results which are connected to the astronomy side of particle astrophysics, namely recent discoveries of new sources of TeV gamma rays. For more details please visit the VERITAS public web-site (http://veritas.sao.arizona.edu).

The VERITAS detector comprises an array of four imaging atmospheric Cherenkov telescopes (IACTs) located at an altitude of 1.3 km on Mount Hopkins in southern Arizona. Each telescope consists of a 12-metre reflector which collects Cherenkov light from extensive air showers and directs it onto a ‘camera’ made from 499 photomultiplier tubes read out by 500 MS/s FADCs. Each camera has a field of view 3.5° in diameter. The array was built in stages between 2003 and 2007 with four-telescope observations beginning in September, 2007.

VERITAS covers the energy range from approximately 100 GeV to beyond 30 TeV with a resolution of between 15 and 20% and single-event angular resolution (68% containment) of 0.1°. It can make a five-sigma detection of a source with a flux of 1% of that of the Crab Nebula in less than 30 hours. More details can be found in [2]. As of the summer of 2010, VERITAS had made 32 detections, of which 15 were discoveries; the rest were already known to be VHE emitters. Eighteen of the detected sources are extragalactic, seven are galactic and seven have not yet been identified with objects known at other wavelengths.

Figure 1: The VERITAS array on Mount Hopkins in southern Arizona.

2. Extragalactic Sources

Most of the extragalactic sources studied by VERITAS are blazars, active galactic nuclei (AGN) with one jet pointed along our line of sight. The aim of these studies is to understand jet production by supermassive black holes and the physics behind gamma-ray production therein. Here multiwavelength studies can be useful in determining whether accelerated protons or electrons are ultimately the source of the gamma rays. Another goal is to measure the level of extragalactic background light (EBL) via its energy-dependent attenuation effects on VHE gamma rays.

PKS 1424+240: One the most recent AGNs to be detected by VERITAS is PKS 1424+240[3]. This object is the first TeV source to be detected as the result of a trigger from the *Fermi* satellite[4], which has all-sky sensitivity at GeV energies. It became the subject of a multiwavelength campaign involving VERITAS, *Fermi*, *Swift*[5] and the MDM observatory. The energy spectrum derived from

VERITAS data acquired between February 19 and June 21, 2009 is plotted in figure 2. The data can be fit with a steep (index = $3.8 \pm 0.5 \pm 0.3$) power law above 140 GeV. Contemporaneous *Fermi* observations in the range $0.1 < E < 300\ GeV$ yield a power-law spectrum with an index of $1.73 \pm 0.07 \pm 0.05$, indicating that there is spectral break between the two ranges. This is expected for distant emitters since high energy gamma rays are attenuated by pair-production reactions with infra-red photons (the EBL) along the way. Unfortunately, the redshift of PKS 1424+240 is unknown; this is a common feature of BL Lacs, the class of AGN to which this source belongs, since a defining characteristic is their lack of spectral lines. Assuming the increase in power-law index is due to EBL effect and making use of recent EBL models, one can derive a redshift of $z = 0.5 \pm 0.1 \pm 0.1$ making this one of the most distant sources to be detected in TeV gamma rays. However spectral modeling can explain the break as intrinsic to the source and can accommodate more modest z values. It is clear that progress here requires independent distance estimators.

1ES 1218+304: In contrast to the previous source, the AGN 1ES 1218+304 has a known redshift: $z = 0.182$. It was previously detected by MAGIC[6] and VERITAS[7] with a steady flux at $\sim 6\%$ of the Crab Nebula and no evidence for time variability. The power-law-spectrum index (approximately 3) from these observations presents a challenge; a source at such a redshift should have had its spectrum steepened considerably by the effects of the EBL. Unfolding the attenuation effects using models of the EBL results in hard intrinsic spectra (indices less than 1.3) [8] which are difficult to explain with the simplest models of blazar gamma-ray production. A model [9] that posits production over kiloparsec distance scales far out in the jet is able to accommodate the data however. VERITAS acquired new data [10] on this source between December, 2008 and May, 2009. During this time a flare was detected, as shown in the light curve displayed in figure 3. This rapid time variation is evidence in favour of a much smaller emission region ($< 10^{-3} pc$, assuming a Doppler factor of 20) and thus challenges theorists to come up with other mechanisms for producing hard blazar spectra.

M82: A final highlight of the VERITAS extragalactic program is the detection of TeV emission from the starburst galaxy M82, also known as the Cigar Galaxy. This is a spiral galaxy with a dense core where stars are being formed at a rate ten times that of the Milky Way. This leads to many supernova explosions as well as collisions of intense stellar winds, both thought to be responsible for producing most of the charged cosmic rays in a galaxy. Concomitant gamma-ray production is expected from π^0s produced by cosmic ray collisions. VERITAS observed M82 for 140 hours over a two-year time period and detected gamma rays at energies greater than 700 GeV [11] and a flux level of 0.9% of the Crab. This five-sigma post-trials detection is the first evidence for gamma-ray production in a starburst galaxy and provides support for the cosmic-ray origin paradigm.

3. Galactic Sources

VERITAS Galactic observations target supernova remnants and pulsar wind nebulae as well as binary systems. Candidates are selected by their similarity to known TeV sources and by their activity at other energies such as X-rays. A survey of the Cygnus region is also part of the program.

Cassiopeia A: This source is a young (330 years old) shell-type supernova remnant expanding into vaccuum; the uncomplicated surroundings make it relatively easy to model. VERITAS detected

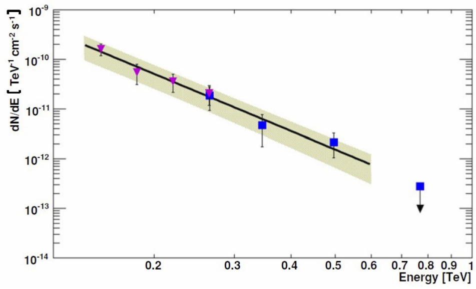

Figure 2: Time-averaged differential photon spectrum of PKS 1424+240. The triangles and squares correspond to analyses with different cut values and the line is a power-law fit explained in the text. The shaded region shows the systematic uncertainty of the fit, dominated by a 20% uncertainty on the energy scale.

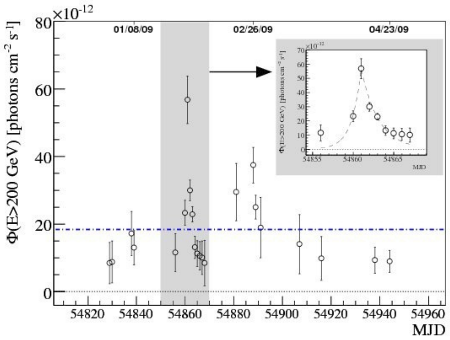

Figure 3: Light curve for 1ES 1218+304 between 2008 December 29 and 2009 April 23. Data points represent integral flux above 200 GeV assuming a power-law spectrum with index 3.07. The flare portion (inset) is fit with two exponentials ($e^{\lambda t}$) yielding $\lambda_{rise} = 0.86$ day and $\lambda_{fall} = -0.47$ day.

Cas-A using data from 22 hours of observations carried out in October and November 2007[12]. The sky map is shown in figure 4 where it can be seen that the signal extent is approximately the same as the gamma-ray point-spread-function so with the data in hand we can only say that the source is consistent with being point-like. A power law with index of $2.6 \pm 0.2 \pm 0.2$ describes the data well over the range from 0.4 to 4 TeV. The integral flux above 1 TeV is approximately 3.5% that of the Crab. Modeling of the production mechanism for gamma rays by the *Fermi*-LAT team[13] using *Fermi* and VERITAS measurements slightly favours a hadronic origin over leptonic but either can be made to work.

Tycho's SNR: The remnant of the supernova observed by Tycho Brahe in 1572 was observed by VERITAS for 67 hours in 2008 and 2010 resulting in a five-sigma (post trials) detection of this source, the first time it has been detected in TeV gamma rays. Although X-ray data from this object imply the existence of electrons accelerated to energies above 10 TeV, it has never been detected in gamma rays, even at GeV energies with EGRET and *Fermi*. The flux level is approximately 0.9% of the Crab about 1 TeV. Its spectrum between 1 and 10 TeV can be described by a power law with index $2.0 \pm 0.5 \pm 0.3$. More details will be available in an imminent publication.

4. VERITAS Upgrade

VERITAS is undergoing an upgrade. During the summer of 2009 one of the telescopes was moved in order to make a more symmetric array with increased baselines, resulting in significantly improved sensitivity. Building on this, we plan to replace all phototubes with new ones having 50% higher quantum efficiency, thereby increasing the effective area of the mirrors by the same factor. An improved array trigger is also foreseen and analysis strategies to reduce the energy threshold of VERITAS are under development. The enhanced instrument will allow deeper, more sensitive observations and help VERITAS to remain a key player in this exciting field.

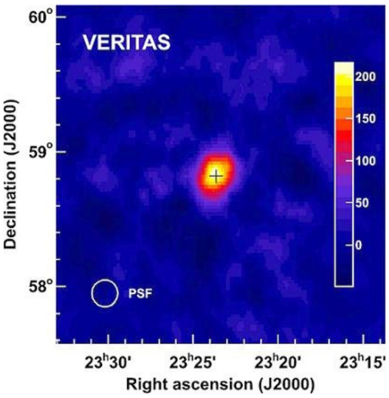

Figure 4: Smoothed sky map of excess counts for the Cas-A data set. The black cross indicates the measured position of the TeV emitter and the white circle the VERITAS point-spread-function.

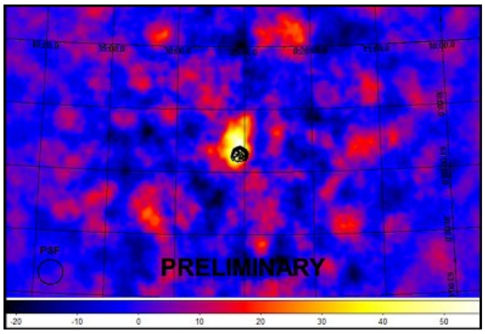

Figure 5: Preliminary sky map of excess counts from the Tycho data set. The black contours on the gamma-ray signal region are from Chandra ACIS measurements[14].

5. Acknowledgements

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