VERITAS: STATUS c. 2009

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VERITAS is a ground-based gamma-ray observatory that uses the imaging atmospheric
Cherenkov technique and operates in the very high-energy (VHE) region of the gamma-ray
spectrum from 100 GeV to 50 TeV. The observatory consists of an array of four
12m-diameter imaging atmospheric Cherenkov telescopes located in southern Arizona,
USA. The four-telescope array has been fully operational since September 2007, and over
the last two years, VERITAS has been operating with high reliability and sensitivity.
It is currently one of the most sensitive VHE observatories. This paper summarizes the
status of VERITAS as of October, 2009, and describes the detection of several new VHE
gamma-ray sources.

Keywords: gamma ray; atmospheric Cherenkov telescopes; active galactic nuclei.

1. Overview

The presence of very high energy particles in the relativistic outflows from gamma-ray
bursters, from microquasars and from active galactic nuclei (AGN) can only be
unambiguously established by the observation of gamma rays or neutrinos. Unfor-
tunately neutrino astronomy still lacks the required sensitivity and satellite-based
gamma-ray telescopes lose sensitivity above 100 GeV. Hence the best channel for
the investigation of the TeV content of relativistic outflows come from the use of ground-based gamma-ray telescopes. Here the imaging atmospheric Cherenkov technique is particularly useful. The technique was originally developed to probe the origin of the cosmic radiation which is generally assumed to be tied to shock acceleration in supernova remnants.

The observation of TeV gamma rays from AGN has been particularly successful and emission from more than two dozen blazars is now well established. Recently emission has also been detected from radio and starburst galaxies but it is the highly variable and beamed emission from blazars that is of most interest to this community.

There is also some evidence for TeV emission from microquasars although the sample is small. The evidence is strong for the presence of high energy particle acceleration in the relativistic outflows. From the small sample observed it is clear that the Galactic analog to blazars (microblazars) is rare and not a dominant feature of the Galactic relativistic sky.

To date, there has been no definite detection of TeV gamma rays in gamma-ray bursts. However at cosmological distances the emitted flux of TeV gamma rays would be strongly attenuated by photon-photon pair production in extragalactic space. Also, if the emission only occurs during the few seconds of prompt gamma-ray activity, then it is only with serendipity that an imaging telescope would have the burst within its limited field of view. All-sky ground-based telescopes have relatively poor sensitivity for the detection of such transients.

2. Operational Status of VERITAS

The VERITAS (Very Energetic Radiation Imaging Telescope Array System) observatory, located at the basecamp of the Fred Lawrence Whipple Observatory in southern Arizona, USA, was completed in June 2007.

The observatory (Figure 1) consists of four 12m-diameter imaging atmospheric Cherenkov telescopes, with a typical baseline between telescopes of \( \sim 100 \text{m} \). Each telescope has a 499-photomultiplier tube (PMT) camera, spanning a field of view of 3.5°. The signal from each camera pixel is amplified and recorded by a separate 500 MS/s Flash-ADC channel. VERITAS employs a three-level trigger system; Level 1 corresponds to the discriminators on each pixel, Level 2 is a pattern trigger for each telescope, and Level 3 is the array trigger.

Regular observations with the full four-telescope array started in September 2007, with approximately 1000 h per year of observations taken. The array has operated extremely well during the last two years; more than 95% of the observations have all four telescopes operational. The ability to take scientifically useful data under partial moonlight was an important development – it adds approximately 30% to the annual data yield. At the recent ICRC a comprehensive review of the status of VERITAS was given by R. Ong; this brief report is an abbreviated summary of the same material but is slightly updated.
VERITAS has an angular resolution (68% containment) of $< 0.1^\circ$, a pointing accuracy of $< 50$ arc-secs, an energy range of 100 GeV–50 TeV, and an energy resolution (above 200 GeV) of 15–20%.

In the summer of 2009, two important upgrades were made to VERITAS. Firstly, Telescope 1 was moved to give a better array configuration. Secondly, the facet alignment on individual telescopes was refined to give better image definition. With the combined effect of these upgrades, the integral flux sensitivity is as shown in Figure 2. The measured gamma-ray point source sensitivity of VERITAS in its new configuration corresponds to the detection of a 1% Crab Nebula source at the five standard deviation level in less than 25 h.

3. Extragalactic Sources

3.1. M82

A significant addition to the VHE zoo was the detection of the prototypical starburst galaxy, M82. Although the conventional picture of cosmic ray origins is diffusive shock acceleration in isolated supernova remnants (SNR)\textsuperscript{9}, it has been argued\textsuperscript{10} that acceleration in superbubbles, regions of high cosmic ray density, formed by multiple supernovae explosions, is another viable source. There is already some evidence for such emission from star-forming regions of the Galaxy. The active regions of starburst galaxies (which contain an unusually large number of SNR) are also likely sources of cosmic ray acceleration and are prime targets for the possible emission of VHE gamma rays. The large size and activity level of starburst galaxies compensates for their distance and permits a calorimetric measurement of the expected high cosmic ray density. Because of its relative proximity the brightest such starburst galaxy is expected to be M82; it is considered the prototype of such galaxies.

M82 was observed with VERITAS for a total of 137 hours of good quality data.
between January, 2008 and April, 2009. Using the standard analysis for low flux, hard spectrum, sources a signal at the 4.8 sigma level (Figure 3) was detected. The flux level is 0.9% that of the Crab Nebula and, as such, is the weakest source detected by VERITAS thus far. The observed differential gamma-ray flux is best fitted with a power law with index $\Gamma = 2.5 \pm 0.6_{\text{stat}} \pm 0.2_{\text{sys}}$. The gamma-ray luminosity above 700 GeV is $2 \times 10^{32}$ W or $2 \times 10^6$ times smaller than the infrared luminosity\footnote{11}.

There is a correlation between the far infrared emission (thermal radiation from warm dust) and radio emission (from synchrotron radiation from cosmic-ray electrons) in starburst galaxies. The gamma-ray flux from M82 provides an estimate of the cosmic ray density which is directly associated with both radiation mechanisms.

### 3.2. M87

A summary of observations by VERITAS and other VHE observatories is given elsewhere by M. Belicke in these proceedings. It is of interest that the three objects: M1, M82 and M87, that were the prime targets of observations with the atmospheric Cherenkov technique some four decades ago\footnote{12} have now all been detected.

### 3.3. Blazars

According to the canonical model, gamma rays are produced in relativistic jets which are powered by accretion unto the supermassive black holes in the centers of AGN. When the jet is pointed in the direction of the observer it is defined as a blazar. The spectral energy distribution (SED) of these objects is characterized by a double-humped structure, the first (low energy) peak is due to synchrotron
radiation from high energy electrons in the jet, the second (high energy) peak more likely from the inverse-Compton scattering of these same electrons. If the low energy peak is at optical-infrared frequencies, then the source is designated a low frequency BL Lac (LBL) and if, at X-rays frequencies, it is called a high frequency BL Lac (HBL). Generally the bulk of the AGN detected at MeV-GeV energies are LBLs and those at GeV-TeV energies are HBLs. There is however a continuous distribution of properties and VERITAS has recently detected several intermediate frequency BL Lacs (IBLs).

3.3.1. W Comae

This was the first IBL detected and appears to be highly variable. It was first apparent as a flare over four nights in March, 2008 (9% Crab at peak) but is also seen as a weak steady source. It flared again three months later. The spectrum is very soft with index $3.8 \pm 0.4$. The SED is shown in Figure 4.

3.3.2. 3C66a

VERITAS detected 3C66a when it was flaring in 2008. It is the second IBL detected by VERITAS. An earlier report by the Crimean group in 2002 suggested it was at a very high level of emission. A signal from this region was also reported by the MAGIC group but they suggested an identification of the source with

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**Fig. 3.** Sky map in TeV gamma rays as seen by VERITAS in the vicinity of M82. The star symbol represents the position of the galaxy. The PSF (69%) has the dimension shown in bottom left corner; clearly the source is not resolved.
3C66b, a nearby radio galaxy. The VERITAS sky map (Figure 5) shows the peak of the TeV emission is very close to the nominal position of 3C66a (but not consistent with 3C66b at the 4.8 sigma level). The spectral index is very soft and is consistent with absorption by extragalactic photons if the distance is that indicated by the published redshift of 0.444. However, as with most BL Lac, there is some uncertainty about this value.

3.3.3. PKS 1424+240

PKS 1424+240 is a BL Lac object of unknown redshift. It was detected by VERITAS in the spring of 2009 (ATEL #2084). No variations were seen. Similarly Fermi showed no variability was detected. The VERITAS signal is about 5% of the Crab and it detected at the ~7.5 sigma level. The spectral index of the VERITAS measurements above 140 GeV is $\Gamma = 3.8 \pm 0.5_{\text{stat}} \pm 0.3_{\text{sys}}$. The SED is well described by a one-zone synchrotron self-Compton model [18].

3.3.4. VER J0521+211

VERITAS detected this source in October, 2009 (ATEL #2260). The observations were motivated by the detection of a > 30 GeV source by Fermi at this position which is consistent, within errors, with the radio-loud active galaxy RGB J0521.8+2112 of unknown redshift. At discovery the flux was ~5% of the Crab flux but rose to 3-4 times this value the following month (ATEL #2309).

Fig. 4. SED of W Comae during its high state. Data comes from VERITAS, Swift and radio and optical observatories. Synchrotron self Compton and external synchrotron model fits are shown.
3.3.5. **1ES 0502+675**

The detection of TeV gamma rays from the HBL BL Lac object, 1ES 0502+675, is particularly important because of the apparent large red-shift \( z = 0.341 \) of the object (ATEL #2301). It was seen by VERITAS in 13 hours of data taken in September-November, 2009. The observations were motivated by the flux and spectrum reported by Fermi. The VERITAS flux was about 4% of the Crab.

4. **Galactic Sources**

Here we report on new detections by VERITAS of several Galactic sources. A summary of VERITAS observations of microquasars is reported by A. Smith elsewhere in these proceedings.

4.1. **G54.1+0.3**

The supernova remnant, G54.1+0.3, was observed by VERITAS for 31 h in 2008, yielding a solid detection at the 6.8\( \sigma \) level. The VHE emission is consistent with a point source at the pulsar location and there is no evidence for variability. The flux level is \( \sim 2.5\% \) Crab Nebula above 1 TeV. The differential spectral index is \( \Gamma = 2.4 \pm 0.2_{\text{stat}} \pm 0.3_{\text{sys}} \). The source is most likely associated with the Pulsar Wind Nebula in G54.1+0.3.
Figure 6. Sky map of TeV gamma rays from G106.3+2.7 as seen by VERITAS. The circle at top indicates the error contour for the source seen by Fermi. The radio and CO contours are shown as continuous lines. The peak of the gamma-ray emission is displaced from the pulsar and instead overlaps with a region of high CO density. The measured VHE spectrum, with differential spectral index $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$, is relatively hard and is consistent with a power-law form up to the Milagro energy of 35 TeV. The spectrum and the observed morphology of the source support a possible hadronic origin for the VHE emission.

4.2. G106.3+2.7 (Boomerang)

The supernova remnant G106.3+2.7 is part of a complex system that may have been created by a supernova explosion occurring in a previously existing HI bubble. The energetic pulsar associated with this system, PSR J2229+6114, has an estimated age of $\sim$10,000 years and a spin-down luminosity of $\dot{E} \sim 2.2 \times 10^{37}$ erg/s. The SNR is within the error box of the EGRET source 3EG J2227+6112, and the pulsar appears on the Fermi Bright Source List. Milagro reported $>10$ TeV emission from the general region with a large error box $\sim 1^\circ$ in diameter.

The VERITAS detection of VHE emission came from 33 h of observations in 2008 resulting in a post-trials significance of 6.0 sigma and an integral gamma-ray flux level of $\sim$5% Crab Nebula above 1 TeV. As shown in Figure 6, the VHE emission is clearly extended spanning a region approximately 0.4$^\circ$ by 0.6$^\circ$ in size.

4.3. Cassiopeia A

Cassiopeia A (Cas-A) is now a well established VHE gamma-ray source. Observations of Cas-A by VERITAS in 2007 yielded a clear detection at the 8.3$\sigma$ statistical level. The integral gamma-ray flux is $\sim$3.5% of the Crab Nebula above 1 TeV. The VERITAS energy spectrum is well fit by a power-law with differential spectral index $\Gamma = 2.6 \pm 0.3_{\text{stat}} \pm 0.2_{\text{sys}}$ and there is no indication of a cut-off at high energy.
Fig. 7. Sky map of gamma rays as seen by VERITAS in the vicinity of IC443. The VERITAS data show that the gamma-ray emission is extended, with a characteristic fitted two-dimensional Gaussian radius of $0.16^\circ$. The VHE emission also overlaps with a dense CO molecular cloud whose contours are shown as continuous lines.

There is also no evidence for any source extension.$^{23}$

4.4. IC443

The emission of VHE gamma rays from IC 443 was first reported by MAGIC and VERITAS in April 2007 at the VERITAS First Light Celebration. MAGIC reported a $5.7\sigma$ detection of the source, corresponding to an integral flux of $\sim2.8\%$ Crab Nebula above 300 GeV$^{24}$. The VERITAS observations yield a statistical significance of $7.5\sigma$,$^{25}$ and an integral flux of $\sim3.2\%$ Crab Nebula, consistent with the MAGIC result.

5. Outlook

The four-telescope VERITAS array is operating extremely well (> 95% uptime) and with excellent sensitivity. VERITAS has detected 27 VHE gamma-ray sources, ten previously not seen by other instruments. An upcoming upgrade program will further improve the performance of VERITAS, ensuring that it remain a premier gamma-ray observatory well into the next decade. The upgrade is aimed at further improving the sensitivity and extending the reach of VERITAS to lower energies.
The existing PMTs in each VERITAS camera will be replaced with ones having higher quantum efficiency. A new topological telescope trigger system is also envisioned.

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