VERITAS: Status and Highlights

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Abstract: The VERITAS telescope array has been operating smoothly since 2007, and has detected gamma-ray emission above 100 GeV from 40 astrophysical sources. These include blazars, pulsar wind nebulae, supernova remnants, gamma-ray binary systems, a starburst galaxy, a radio galaxy, the Crab pulsar, and gamma-ray sources whose origin remains unidentified. In 2009, the array was reconfigured, greatly improving the sensitivity. We summarize the current status of the observatory, describe some of the scientific highlights since 2009, and outline plans for the future.

Keywords: Gamma-ray astronomy, VERITAS

1 Overview: VERITAS

VERITAS (the Very Energetic Radiation Imaging Telescope Array System) is an array of four atmospheric Cherenkov telescopes located near Tucson in southern Arizona (31°40’N 110°57’W, 1268 m a.s.l) \textsuperscript{1}. It is used to study astrophysical sources of gamma-ray emission in the 100 GeV-30 TeV range via the imaging atmospheric Cherenkov technique. The array was commissioned in 2007, and the source catalogue now contains 40 objects, including pulsar wind nebulae (PWN), supernova remnants (SNR), active galaxies, binary systems, a starburst galaxy and a pulsar, along with other objects whose nature remains unclear.

Each of the four telescopes consists of a 12 m diameter segmented reflector, at the focus of which is a 499-pixel photomultiplier tube (PMT) camera covering a field of view of 3.5° \textsuperscript{2}. A coincident Cherenkov signal in 2 out of 4 telescopes triggers a read-out of the PMT signals by custom-built 500 MSPS FADCs, at a typical rate of \sim 250 Hz. The resulting images in each camera are parameterized by their second moments, and these parameters are then used to discriminate gamma-ray initiated air showers from those initiated by cosmic ray particles. The recorded images are also used to reconstruct the energy and arrival direction of the primary photon. The angular resolution and energy resolution of the reconstruction is energy dependent, reaching \sim 0.1° and \sim 15%, respectively, for gamma-ray primaries with an energy of 1 TeV.

The sensitivity of the array can be quantified by the observing time required to detect a typical weak source. The sensitivity of VERITAS has steadily improved over the lifetime of the array, due to improvements in data analysis techniques, optical alignment, calibration and, most significantly, following the relocation of the original prototype telescope to a more favourable location in 2009. Currently,
a source with a flux of 1% of the Crab Nebula flux and a spectrum similar to the Crab Nebula can be detected in approximately 25 hours of observations: roughly half of the time required when the array was originally commissioned. Figure 1 shows the array in both its initial (top) and current (bottom) configurations. Typically, around 1000 hours of data are collected every year, ~20% of which are taken when the moon is visible.

2 Extragalactic TeV Gamma-ray Astronomy

Approximately two-thirds of the VERITAS program of observations is dedicated to the study of extragalactic gamma-ray sources and source candidates. This focus has resulted in the detection by VERITAS of 21 blazars, one radio galaxy (M 87) and one starburst galaxy (M 82). The extragalactic program is described in more detail elsewhere in these proceedings [3, 4]. Here, we highlight some of the recent results and ongoing studies.

Table 1 lists all of the extragalactic sources detected, roughly half of which were first identified as > 100 GeV gamma-ray sources by VERITAS.

2.1 Blazars

The most common extragalactic TeV sources are the blazars: Active Galactic Nuclei (AGN) in which a relativistic jet is directed along the line-of-sight to the observer. The first few TeV blazars to be identified were all high-frequency-peaked BL Lac objects. The combined

| Source Name    | Class | z      |
|----------------|-------|--------|
| Mrk 421        | HBL   | 0.030  |
| Mrk 501        | HBL   | 0.034  |
| 1ES 2344+514   | HBL   | 0.044  |
| 1ES 1959+650   | HBL   | 0.047  |
| BL Lac         | LBL   | 0.069  |
| W Comae        | IBL   | 0.102  |
| RGB J0710+591  | HBL   | 0.125  |
| H 1426+428     | HBL   | 0.129  |
| 1ES 0806+524   | HBL   | 0.138  |
| 1ES 0229+200   | HBL   | 0.139  |
| 1ES 1440+122   | IBL   | 0.162  |
| RX J0648.7+1516| HBL   | 0.179  |
| 1ES 1218+304   | HBL   | 0.182  |
| RBS 0413       | HBL   | 0.190  |
| 1ES 0414+009   | HBL   | 0.287  |
| PG 1553+113    | HBL   | 0.43 < z < 0.50 |
| 1ES0502+675    | HBL   | ?      |
| 3C 66A         | IBL   | ?      |
| B2 1215+30     | LBL   | ?      |
| PKS 1424+240   | I/HBL | ?      |
| VER J0521+211  | HBL   | ?      |
| M 87           | FR I  | 16.7 Mpc |
| M 82           | Starburst | 3.9 Mpc |

Table 1: Extragalactic sources of TeV gamma-ray emission detected by VERITAS.
results of H.E.S.S., MAGIC and VERITAS have dramatically expanded the TeV blazar catalogue over the past few years, allowing population studies to be carried out and adding new classes of object. Originally, due mainly to limited sensitivity and biases in target selection, only high-frequency peaked BL Lac objects were detected at TeV energies. More recently, intermediate- and low-frequency-peaked BL Lacs have been observed [5], as well as flat-spectrum radio quasars. The population is also growing as the catalogue extends to ever larger distances. An illustration of these developments is provided by Figure 3 which shows VERITAS observations of three blazars, one high-frequency and two intermediate-frequency BL Lac objects, all contained within the 3.5° field-of-view of the array.

VERITAS observations of blazars have, in many cases, been guided and enhanced by the results of observations at other wavelengths. In particular, the *Fermi*-LAT instrument provides a daily view of the entire sky in the energy range just below that covered by VERITAS, and the VERITAS blazar discovery program now focuses on objects detected by *Fermi*-LAT. Objects are typically selected from the LAT catalog based either upon a power-law extrapolation of their energy spectra, or upon the detection of clusters of high energy (> 10 GeV) photons by the LAT. We have also implemented analysis pipelines that automatically process and analyze *Fermi*-LAT data on a daily basis, in order to identify flaring objects [6].

The Whipple 10m telescope has played an important role in the blazar program, providing regular monitoring of bright, known, variable blazars such as Mkn 421 and Mkn 501 [7]. Summer 2011 marks the end of operations for the Whipple 10m, which holds a remarkable record as the longest operating atmospheric Cherenkov telescope (since 1968), and as the instrument on which the Whipple Collaboration developed the imaging technique used to detect the first TeV source, the Crab Nebula [8].

Highlights from the VERITAS blazar program presented at this conference include the measurement of an extremely bright flare from Mkn 421 in February 2010 [9]. During 5 hours of VERITAS observations on February 17, gamma-ray emission from the source reached a flux level
Figure 4: **Top** Nightly lightcurve of Markarian 421 during the VERITAS 2009-2010 observing campaign, with a zoom of the flare on the night of February 17, 2010 [9]. **Bottom** Nightly lightcurve of BL Lacertae during the VERITAS 2010-2011 observing campaign, with a zoom of the flare on the night of June 28, 2011 [12].

of 8 times the steady flux from the Crab Nebula, allowing precise measurement of the light curve with a time resolution of two minutes (Figure 4). We also summarize observations of PG 1553+113 between May 2010 and May 2011 [10]. This source is one of the most distant TeV blazars known, making it an important tool for studies of the extragalactic background light. The VERITAS spectral measurements presented here are used to place an upper limit on the source redshift of $z < 0.5$ at 95% confidence. The identification of a new high-frequency-peaked blazar, RBS 0413, with VERITAS and Fermi-LAT was also presented [11], providing a good example of the impact of the LAT upon TeV target selection. Finally, observations of BL Lac (the eponymous BL Lacertae object) were shown. BL Lac is the first blazar classified as ‘low-frequency-peaked’ from which VERITAS has detected gamma-ray emission. Following reports of activity from several observatories at other wavelengths in May 2011, VERITAS commenced monitoring the source and, on June 28, 2011, observed the tail-end of a flare during 40 minutes of observations, with further observations curtailed by the rising sun. The flux decreased rapidly from a maximum of $\sim 50\%$ of the steady Crab Nebula flux, demonstrating variability on a timescale of $\sim 4$ minutes [5](Figure 4).

2.2 Other Extragalactic Sources

In addition to blazars, VERITAS has been used to observe various other extragalactic gamma-ray source candidates, including radio galaxies, galaxy clusters, starburst galaxies and globular clusters [4]. Highlights from this program include the study of gamma-ray emission from M 87 and M 82, which we summarize here.

2.2.1 M 87

M 87 is the central giant radio galaxy of the Virgo cluster, located at a distance of $16.7 \text{ Mpc}$ [13]. Its proximity, and the fact that its jet is not aligned along the line-of-sight, allows detailed study of the jet structure in radio, optical and X-ray wavelengths. This provides the possibility of
identifying which structures in the jet are responsible for the TeV emission, and so M 87 has been a prime target for gamma-ray observatories since the initial report of gamma-ray emission by the HEGRA array in 2003 [14]. A concerted multiwavelength monitoring campaign involving all of the TeV observatories, as well as Chandra, VLBA and a number of optical observatories, has been ongoing for several years (e.g. [15]). Initial multiwavelength results indicated that the gamma-ray emission may originate from a region close to the core of the galaxy. In April 2010, the brightest flaring event to date was observed, with a peak flux exceeding 10% of the steady Crab Nebula flux. The VERITAS lightcurve for 2010 is shown in Figure 5, revealing flux variability during the flare on the timescale of $\sim 1$ day.

2.2.2 M 82

M 82 is a bright galaxy located at a distance of approximately 3.9 Mpc, with an active starburst region at its centre. The star formation rate in this region is approximately 10 times that of the Milky Way, with an estimated supernova rate of 0.1 to 0.3 per year. High cosmic-ray and gas densities in the starburst region make it a promising target for gamma-ray observations, with gamma-ray emission expected to result from the interactions of hadronic cosmic rays in the dense gas. A deep VERITAS exposure (137 hours) in 2008-2009 resulted in a detection of gamma-ray emission from M 82 with a flux of $(3.7 \pm 0.8_{\text{stat}} \pm 0.7_{\text{syst}}) \times 10^{-13}$ cm$^{-2}$ s$^{-1}$ above the 700 GeV energy threshold of the analysis, consistent with the predictions of models based on the acceleration and propagation of cosmic rays in the starburst core [16].

2.2.3 Gamma-ray Bursts

VERITAS has maintained a continuous program to search for very high-energy emission associated with gamma-ray bursts (GRBs). The motivation for such searches has been given added impetus in recent years, due to the detection high energy emission from GRBs by Fermi-LAT with a delay of hundreds of seconds from the start of the burst. VERITAS results at this conference focused on bursts which were detected by both the Fermi and Swift satellites [17]. Since VERITAS is a pointed instrument, with a field of view of 3.5°, the telescopes must move into position when a burst alert is received. The average time delay for this re-point is $240$ s, and in many cases significantly shorter. Predictions based on the brightest bursts observed by the LAT indicate that the potential for detecting TeV emission associated with a GRB with VERITAS is promising, assuming no intrinsic spectral cut-off of the high energy emission.

2.2.4 Dark Matter Searches

Objects outside of our own galaxy provide some of the best locations in which to search for the annihilation signatures of dark matter particles. Dwarf spheroidal galaxies of the local group are among the most promising of these, due to their proximity, their large dark matter content and the absence of astrophysical background sources (supernova remnants, pulsar wind nebulae, etc.). Studies of the stellar kinematics of the dwarf spheroidal galaxy Segue I indicate that is is the most dark matter dominated dwarf spheroidal galaxy known. The results of a 48 hour VERITAS exposure on Segue I were presented at this conference [18], along with upper limits on the annihilation cross-section for vari-
ous annihilation channels, illustrated in Figure 6. The limits lie in the range $10^{-22} - 10^{-24} \text{cm}^3 \text{s}^{-1}$, depending on the annihilation channel and dark matter particle mass.

3 Galactic TeV Gamma-ray Sources

The VERITAS Galactic catalogue contains 17 sources, listed in Table 2. VERITAS is located in the northern hemisphere, and can therefore only view the outer Galaxy at high elevation angles ($l < -30^\circ$ and $l > 150^\circ$). The relative scarcity of Galactic TeV sources in this region, compared to the inner Galaxy, is balanced in part by the variety of source classes which have been identified and studied. These include pulsars and their nebulae, supernova remnants, gamma-ray binary systems, and a number of sources whose identification remains unclear. Some of the recent highlights from the Galactic program are summarized here. Additional VERITAS results are presented elsewhere in these proceedings, including observations of CTA 1 [19], LS I+61°303 and 1A 0535+262 [20], and VER J2019+407 [21].

3.1 HESS J0632+057

HESS J0632+057 was first identified as an unresolved point source of TeV gamma rays in HESS observations of the Monoceros Loop SNR [22]. The possibility that this source might be a new TeV binary system, comprised of a massive star and a compact companion, was noted in the original detection paper, based on the fact that the gamma-ray emission was centered on the location of a massive emission-line star (MWC148). Further support for this idea came from the detection of variable radio [23] and X-ray emission...
source at the same location, and with the discovery of gamma-ray flux variability by VERITAS [25].

Recently, a long-term monitoring campaign with Swift has been used to identify a 321-day period in the X-ray emission, presumably associated with the binary orbit [26]. The X-ray emission is characterized by a bright flare lasting for ~20 days, which may be associated with a periastron passage. VERITAS and H.E.S.S. observations are presented at this conference [27] which total 150 hours over the past seven years, including a deep VERITAS exposure around the X-ray flare in February 2011. A bright gamma-ray flare is also observed, with the peak slightly offset from the X-ray flare, suggesting that the gamma-ray emission fades away at the onset of the X-ray high state. Figure 7 shows the VERITAS/H.E.S.S. lightcurve, folded by the X-ray period.

3.2 The Crab Pulsar

Steady emission from the Crab Nebula has provided a standard candle for ground-based gamma-ray observatories since its detection in 1989 [8]. The Crab pulsar, which powers the Nebula, is among the most energetic pulsars in our galaxy, with a spin-down power of $4.6 \times 10^{38}$ erg s$^{-1}$. Existing measurements of the pulsar spectrum can be fitted by a power-law with an exponential cut-off, consistent with theoretical predictions based on curvature radiation as the dominant gamma-ray production mechanism [28, 29].

Figure 7: The Swift (Top) and VERITAS/ H.E.S.S. (Bottom) light curves for HESS J0632+057, folded by the 321-day X-ray period [27].
A deep, 107 hour, VERITAS exposure of the Crab pulsar region now reveals that the pulsar spectrum extends to much higher energies than previously expected [30, 31]. The emission is fit by a power-law spectrum between 100 and 400 GeV with an index of $\alpha = -3.8 \pm 0.5_{\text{stat}} \pm 0.2_{\text{sys}}$. The pulse profile (Figure 8) exhibits two peaks, 2-3 times narrower than those measured at 100 MeV. The dominant pulse is observed at phase 0.4 and a smaller pulse at phase 0.1, again, in contrast to the measured profile at 100 MeV. These results likely require a substantial revision of our understanding of the high energy emission from pulsars, both in terms of the location of the emission region, and the mechanisms responsible.

3.3 The Galactic Centre

The Galactic Centre is a complex region at TeV energies, comprised of a bright source in the direction of SgrA*, and extended diffuse emission along the Galactic ridge [32, 33, 34]. For VERITAS, the source culminates at an elevation angle of below 30°. The path length to the Cherenkov emission from the air shower is therefore larger than for observations at high elevation angles, resulting in an increase in the energy threshold above which gamma-ray initiated showers can be detected. This is compensated by a corresponding increase in the collection area for high energy primaries, due to the larger light pool on the ground. Using an analysis specifically tailored to such observations,
a 25 hour VERITAS exposure has been used to clearly detect the Galactic Centre gamma-ray source, and to measure its spectrum above 2 TeV \[35\] (Figure 9). Future observations using this method offer the possibility of improving measurements of the high energy cut-off of the emission spectrum.

Figure 9: A significance map of the Galactic Center region, measured with VERITAS

### 3.4 The Cygnus OB1 Region

The Cygnus region hosts some of the closest and most active areas of massive star formation and destruction in the Galaxy, providing numerous potential sources for TeV gamma-ray production. The brightest and most extended source in the Milagro Galactic Plane survey, MGRO J2019+37 overlaps with the Cyg OB1 association, with a total flux of \( \sim 80\% \) of the steady Crab Nebula flux above 12 TeV, spread over an area of \( 0.6^\circ \times 1.0^\circ \) \[36\]. At this conference we present 75 hours of VERITAS observations centered on this region \[19\], revealing two distinct areas of gamma-ray excess. One of these, VER J2016+372, is point-like, within the angular resolution of the instrument, and consistent with the location of a pulsar wind nebula, CTB 87, which is the likely counterpart. The other gamma-ray excess is extended over a region which encompasses multiple possible counterparts, including the powerful pulsar PSR J2021+3651 and its nebula. Figure 10 shows the VERITAS skymap of this region above 650 GeV.

![Figure 10](image)

**Figure 10:** The VERITAS skymap of the Cygnus OB1 region above 650 GeV.

### 3.5 Tycho’s SNR

Tycho’s SNR is the remnant of a historical type Ia supernova, recorded by Tycho Brahe in 1572. The SNR environment and morphology are relatively simple, making Tycho’s SNR a favored system for theorists seeking to model particle acceleration processes in SNR blast waves (e.g. \[37\]). Evidence for nuclear particle acceleration has already been claimed, based on detailed studies of the shock front and contact discontinuity locations \[38\]. VERITAS observations of Tycho’s SNR comprise a 68 hour exposure, taken between 2008 and 2010, and reveal a faint, unresolved gamma-ray source \( \sim 0.9\% \) Crab, significant at the level of 5.0 standard deviations \[39\]. Figure 11 shows the gamma-ray excess map, along with X-ray and \(^{12}\)CO emission. Dense molecular cloud/ SNR interactions provide both the high energy particle population and interaction target material ideal for the production of a high energy gamma-ray signal (e.g. \[40\]). However, no direct evidence of such an interaction exists, and the molecular emission may simply be a chance association.

The VERITAS result alone is consistent with both leptons and hadrons as the dominant particle population responsible for the gamma-ray emission, although in both cases the models provide evidence for magnetic field amplification, and hence nuclear particle acceleration. Recent results from Fermi-LAT provide further constraints and, combined with the VERITAS results, have been used to argue strongly for a hadronic origin \[41, 42\].

![Figure 11](image)

**Figure 11:** A map of excess gamma-ray events for VERITAS observations of Tycho’s SNR. Black contours show the Chandra X-ray emission, magenta contours are \(^{12}\)CO. The instrumental PSF is also indicated. See \[39\] for details.

### 4 The VERITAS Upgrade

As described in the introduction, the sensitivity of VERITAS has steadily increased since the array was commissioned. Ongoing analysis developments promise incremental improvements in the future, but a significant further step requires new hardware. VERITAS is currently in the process of implementing a series of fully-funded upgrades to the instrument \[43\]. These consist of:

- Replacing all of the existing photomultiplier tubes in the telescope cameras with more sensitive, super-bialkali devices.
• Replacing the telescope-level trigger system with a higher speed, FGPA-based device.

• Upgrading inter-telescope networking and communications.

• Adding instrumentation to the central pixels of each camera to allow high-speed optical monitoring and stellar intensity interferometry.

The first of these, the photomultiplier replacement, is expected to have the most significant impact on the array performance. The new photomultipliers (Hamamatsu R10560-100-20) are currently being fabricated and tested. Initial results, both in the laboratory and in the telescope cameras, indicate at least a 35% improvement in Cherenkov photon collection efficiency \[44\]. The Hamamatsu PMTs are also significantly faster: Figure 12 shows the measured pulse shape, in comparison with the existing Photonis tubes. Installation of the new PMT pixels will take place during the regular summer shutdown in 2012. All four of the upgraded trigger systems have also been constructed and tested, and will be installed in Fall 2011. No loss of observing time is foreseen for any of the upgrade tasks. Figure 12 illustrates the expected increase in the differential gamma-ray event rate at the trigger level for a source with a spectrum similar to that of the Crab Nebula. The predicted energy threshold at the hardware level is defined as the energy giving the peak rate in this figure, corresponding to 75 GeV.

5 Summary
The results presented here constitute a brief summary of the status the VERITAS project after ~ 4 years of operation. Observations are expected to continue for at least the next ~ 5 years, which will allow us to fully exploit the VERITAS upgrade, and to complement the Fermi-LAT effectively until the next generation of ground-based instruments come online.
Figure 13: Monte Carlo predictions of the differential event rate for gamma-ray events from a Crab-Nebula-like source at the trigger level, both before and after the upgrade.

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