

Highlight Talk: Recent Results from VERITAS

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Abstract. VERITAS is a state-of-the-art ground-based gamma-ray observatory that operates in the very high-energy (VHE) region of 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 efficiency and with excellent performance. This talk summarizes the recent results from VERITAS, including the discovery of eight new VHE gamma-ray sources.

Keywords: gamma rays, galactic observations, extragalactic observations

I. INTRODUCTION

Construction on the VERITAS (Very Energetic Radiation Imaging Telescope Array System) experiment, located at the basecamp of the F.L. Whipple Observatory (FLWO) in southern Arizona, USA, started in 2003 and was completed in June 2007. As shown in Figure 1, the array consists of four 12m-diameter imaging atmospheric Cherenkov telescopes, with a typical baseline between telescopes of ~ 100 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 constant fraction discriminators on each pixel, Level 2 is a pattern trigger for each telescope, and Level 3 is the array trigger. More details on VERITAS can be found in [1].

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 at least 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.

With two years of data in hand, the performance attributes of VERITAS are now well understood. These attributes are 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%. The gamma-ray point source sensitivity of VERITAS in its original configuration corresponds to the detection of a 1% Crab Nebula source at the five standard deviation (σ) level in less than 50 h. In Summer 2009, Telescope 1 was relocated to improve the array geometry (see Figure 1). This change had a significant impact on the performance of VERITAS; a point source at the 1% Crab Nebula flux level can now be detected in under 30 h of observation.

The observing time of VERITAS during its first two years was divided into *Key Science Projects*, the *Bulk Program*, and *Director's Discretionary Time*, corresponding to 50%, 40%, and 10% of the observation time, respectively. The Key Science Projects were a sky survey of the Galactic plane in the Cygnus region, a blazar program, a study of supernova remnants and pulsar wind nebulae, and a search for dark matter. The bulk program was determined by individual observing proposals submitted to a time allocation committee (TAC). The Director's Discretionary Time was set aside for GRB's, ToO's, and occasional high-risk sources.

In this paper, we summarize the scientific highlights of VERITAS, concentrating on recent results obtained in the last year and presented at the 31st International Cosmic Ray Conference (Lodz, Poland, July 2009). For additional details, see the individual contributions to the conference [2].

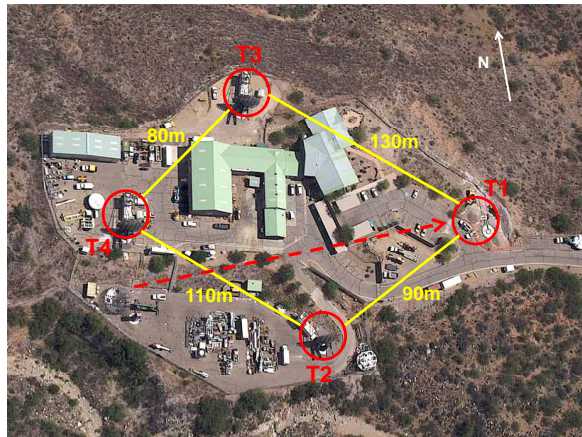


Fig. 1: Aerial view of VERITAS at the Whipple Observatory basecamp in Arizona, USA. The number of the telescopes specifies the order in which they were constructed; the yellow lines connecting telescopes indicate the inter-telescope baselines; the dashed red line indicates the relocation of Telescope 1 that was carried out in Summer 2009.

II. HIGHLIGHT: DETECTION OF STARBURST GALAXY M 82

Starting with the discovery of Markarian 421 in 1992 [3], atmospheric Cherenkov telescopes have been remarkably successful in the detection of VHE gamma-radiation from extragalactic sources. Indeed, the VHE catalog presently includes approximately 25 extragalactic entries [4]. To date, however, all of these sources are active galactic nuclei (AGN), mostly of the blazar type. The observational data support the general picture in which the VHE emission results from acceleration processes that are ultimately powered by accretion onto a supermassive black hole. However, the vast majority of galaxies are not active at the present time, and an important question is whether there is detectable VHE emission from galaxies not associated with black hole activity.

The importance of finding new types of extragalactic VHE emitters motivated the VERITAS observations of the M 82 starburst galaxy. M 82 is a prototype starburst galaxy where the interaction of a group of galaxies produces a very active starburst region. In this region, a high cosmic ray density, as inferred from radio synchrotron emission [5], is believed to result from the high star formation and supernova (SNR) rate. M 82 also contains a high mean gas density of ~ 150 particles/cm² [6]. A natural mechanism to produce gamma rays involves the interaction of cosmic rays (both hadrons and electrons) with the dense gas and photon fields. This is the very mechanism that produces the Galactic diffuse gamma-ray emission in the Milky Way. Previous limits on the flux of VHE gamma rays from M 82 $< 10\%$ Crab Nebula flux have come from Whipple [7] and HEGRA [8].

The VERITAS M 82 data set, taken in dark time

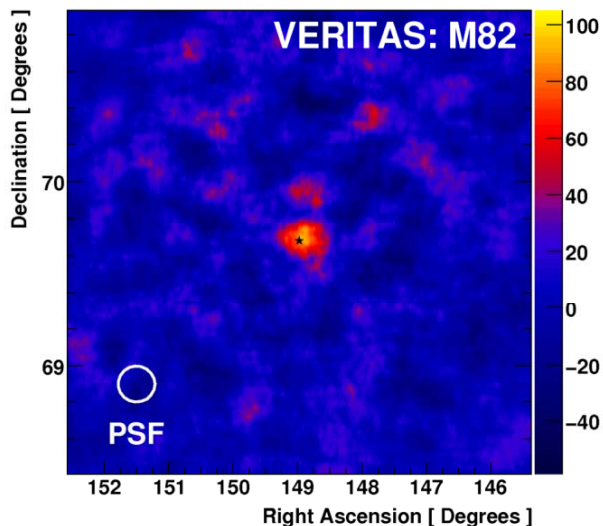


Fig. 2: VHE gamma-ray image of M 82 by VERITAS. The image shows the measured excess of gamma-ray like events above the estimated background in a region centered on M 82. The white circle represents the point-spread function (68% containment) of VERITAS and the black star indicates the location of the core of M 82.

between 2007 and 2009, constitute a very deep exposure of 137 h. Selection criteria to increase the sensitivity of the instrument at high energies (so called “hard cuts”) were developed from an *a priori* study of the Crab Nebula at similar zenith angles as M 82. These cuts yield a post-trials significance of 4.8σ . The excess counts map (see Figure 2) is consistent with a point source at the position of M 82. The detected gamma-ray flux of $\sim 0.9\%$ Crab Nebula ($E > 700$ GeV) is among the weakest VHE sources yet detected. Numerous systematic checks were made to provide confidence that the gamma-ray signal is genuine. Complete details on the VERITAS detection of M 82 can be found in a recent publication [9].

The discovery of VHE gamma-ray emission from M 82 by VERITAS represents the first detection of gamma rays from a starburst galaxy and the first extragalactic VHE source not clearly associated with AGN activity. The detected flux level is consistent with theoretical predictions [10], [11] that are based on standard mechanism of cosmic-ray interactions. At this meeting, we learned about the detection by HESS of VHE emission from the starburst galaxy NGC 253 by HESS [12] and, subsequently, about the detection by Fermi-LAT of high-energy gamma-ray emission from M 82 [13].

III. HIGHLIGHT: GALACTIC PLANE SURVEY

The Sky Survey of the Galactic plane in the region of Cygnus was a VERITAS key science project, carried out over two observing seasons between 2007 and 2009 [14]. The Cygnus region is a natural target for a survey, containing a variety of potential VHE sources, including supernova remnants, pulsar wind neb-

ulae, X-ray binaries, and massive star clusters. The first unidentified TeV gamma-ray source, TeV J2032+4130, was reported by HEGRA from a survey of Cygnus [15], [16]. At GeV energies, Fermi-LAT has detected at least four distinct sources, all associated with pulsars [17]. At >10 TeV, Milagro reported two unidentified sources (MGRO J2031+41 and MGRO J2019+37) [18]. MGRO J2031+41 appears to be associated with TeV J2032+4130.

The VERITAS sky survey covers the region of Galactic longitude $67^\circ < l < 82^\circ$ and Galactic latitude $-1^\circ < b < 4^\circ$. The observations consisted of a base survey of 112 h and follow-up observations of 32 h. The base survey was carried out by a set of grid pointings where grid points had separations of 0.8° in Galactic longitude and 1.0° in Galactic latitude. Figure 3 shows an exposure-weighted map of the base survey. Observations were carried out using three and four VERITAS telescopes and at zenith angles less than 35° . The exposure across the survey region is relatively uniform with an effective (acceptance-corrected) exposure of ~ 6 h for all points within the survey boundaries.

The analysis of the survey data was made using a set of pre-defined selection criteria (cuts) designed to maximize the sensitivity of the survey to sources with varying spectral shape and extension. In particular, cuts were made on the integrated charge (size) and on the distance between the reconstructed direction and direction of a potential source (θ^2). The cuts resulted in a total of four parallel analyses (*i.e.* a trials factor of four); see [14] for details.

The preliminary result from the base survey is that no sources are detected at a significance level greater than 5σ (post-trials). The survey sensitivity is estimated using a technique in which simulated gamma rays are injected into background survey fields taken from actual data. The estimated sensitivity leads to preliminary 99% C.L. limits on the flux of VHE gamma rays of $< 3\%$ Crab Nebula (point source) and $< 8.5\%$ Crab Nebula (extended source of diameter 0.5°) at a median energy of 200 GeV. These limits are 3-4 times more stringent than those achieved in the previous work of HEGRA [15]. They also indicate that the population density of VHE sources in the northern hemisphere is markedly different than in the southern hemisphere, where HESS found 12 sources above a flux level of 5% Crab Nebula [19]. Follow-up observations are continuing in specific regions of the survey.

IV. EXTRAGALACTIC SOURCES

A. Blazars

Until the detection of starburst galaxies, the extragalactic sources detected at very high energies were all active galactic nuclei (AGN), of which blazars represented the dominant source class. The general picture for blazars involves the accretion of matter onto a supermassive black hole that powers relativistic jets of plasma flow that are pointed in the direction of Earth. VHE

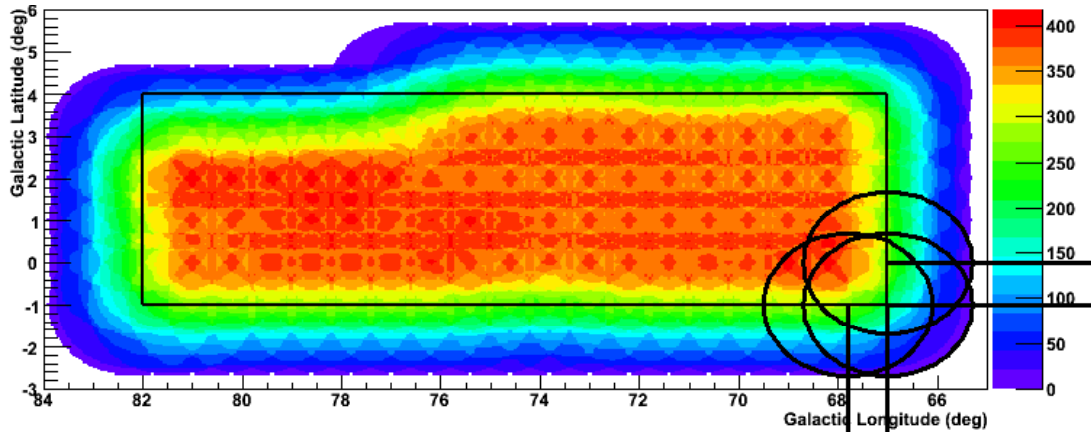


Fig. 3: Exposure-weighted map of the VERITAS Sky Survey of the Cygnus region. The color scale indicates the effective exposure in minutes. The black circles indicate the field-of-view of VERITAS at survey grid pointings separated by 1.0° in Galactic longitude and 0.8° in Galactic latitude.

particle acceleration takes place in the jets, resulting in GeV and TeV gamma-ray emission.

The main science goal of studying blazars at gamma-ray energies is to gain an understanding of the physics taking place in jets and to ultimately connect that physics to the black hole accretion. Another goal is to use the gamma-ray emission from blazars as a probe of intergalactic radiation fields, both the extragalactic background light (EBL, through the absorption process $\gamma + \gamma \rightarrow e^+e^-$) and the intergalactic magnetic field.

Most high-energy blazars exhibit “double-peaked” spectral energy distributions in which the low-energy peak can be attributed to synchrotron emission and the high-energy peak to inverse-Compton scattering. However, as yet, we cannot conclusively pinpoint whether the parent particles accelerated in the jet are electrons or protons. In this context, multiwavelength observations can be particularly effective in constraining model parameters. To date almost all of the blazars detected at TeV energies are high-frequency peaked BL Lacertae (HBL) objects in which the synchrotron peak lies in the X-ray band. This is contrasted with low-frequency peaked BL Lac (LBL) objects, predominantly detected at GeV energies, where the synchrotron peak is in the radio band.

The VERITAS blazar key science project uses a multi-faceted approach to improve our knowledge of the acceleration and emission mechanisms taking place in blazars. The project is divided approximately equally into discovering new sources, multiwavelength campaigns, and targets of opportunity [20]. Fifty blazars have been observed so far, resulting in eleven detections and five discoveries of VHE emission. The first source discovered by VERITAS was 1ES 0806+524, where a 40 hour exposure in the 2007/2008 observing season led to a detection of this relatively weak HBL at a flux level of $\sim 2\%$ Crab Nebula [21].

A recent blazar discovery by VERITAS is RGB

0710+591, an HBL at a redshift of $z = 0.125$ [22], [23]. This source was detected by VERITAS at significance of $\sim 6\sigma$ from 20 h of observations in 2009. The relatively hard energy spectrum (preliminary differential spectral index $\Gamma = 2.8 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$) should provide significant constraints on the density of the EBL.

An important result from the VERITAS blazar program has been the establishment of intermediate-frequency peaked BL Lacertae (IBL) objects as emitters in the VHE band. IBL objects are thought of as an intermediate class between LBLs and HBLs, although in reality it is likely there is a continuum of objects. The first IBL to be established at very high energies was W Comae, a known EGRET source at a redshift of $z = 0.102$, detected by VERITAS during 40 h of observation in Spring 2008 [24]. This source exhibited strong variability and a very steep energy spectrum, with differential spectral index of $\Gamma = 3.81 \pm 0.35_{\text{stat}} \pm 0.34_{\text{sys}}$. A second VHE flare from W Comae was detected in June 2008 at a significantly higher flux level than the first [25].

The second IBL to be discovered by VERITAS was 3C 66A [26]. This is a rather famous source that has long been considered a likely candidate for VHE emission. 33 h of observation in 2008 by VERITAS resulted in a strong detection ($\sim 21\sigma$) of 3C 66A with variability seen on day time scales. The measured energy spectrum is very steep, $\Gamma = 4.11 \pm 0.4_{\text{stat}} \pm 0.6_{\text{sys}}$, which may be entirely due to the absorption by the EBL; 3C 66A has an uncertain redshift of $z = 0.44$. 3C 66A lies 0.12° away from the radio galaxy 3C 66B. MAGIC reported the detection of VHE emission from the region that is consistent (at 85% C.L.) with 3C 66B. However, as shown in Figure 4, the VERITAS data exclude the position of 3C 66B at the 4.3σ level. Fermi LAT has detected bright emission from 3C 66A; the results from a joint Fermi-VERITAS study of the source are discussed elsewhere at this conference [27].

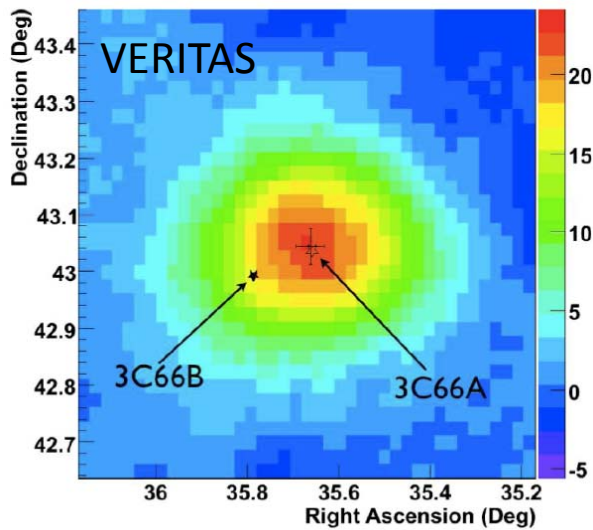


Fig. 4: Smoothed significance map derived from VERITAS observations of 3C 66A. The cross shows the VERITAS localization of the VHE emission. The open star indicates the position of 3C 66A and the closed star indicates the position of 3C 66B.

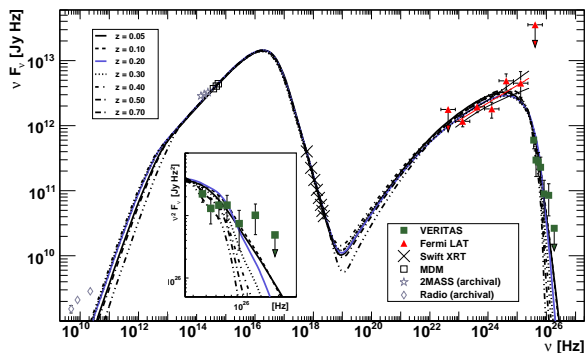


Fig. 5: Spectral energy distribution of PKS 1424+240, from [29]. The lines show SSC= model fits assuming different redshifts. The inset shows a zoom of the VERITAS data. The Fermi data are presented with their corresponding power-law fit and one standard deviation uncertainty.

The third IBL, and the latest blazar, to be discovered at very high energies by VERITAS is PKS 1424+240. This source, with an unknown redshift, was first detected in gamma rays by Fermi [17]. The VERITAS detection came from 14 h of data taken in Spring 2009 [28]. The source was relatively weak at VHE energies, at a flux level $\sim 2\%$ Crab Nebula above 200 GeV. PKS 1424+240 is the first VHE discovery motivated by Fermi observations. As shown in Figure 5, joint analysis of the VERITAS and Fermi data provides constraints on both the redshift of the source as well as the inverse-Compton model parameters [29].

Additional blazar papers presented at this conference by VERITAS describe variability of the VHE emission

from 1ES 1218+304 [30] and multiwavelength studies of Mrk 421, Mrk 501 and 1ES 2344+514 [31]. Results from the Whipple 10m blazar monitoring program of five key sources were also presented [32].

B. Radio Galaxies and Gamma-Ray Bursts

Almost all of the AGN detected in the VHE gamma-ray band are blazars, but there are also two radio galaxies seen: M 87 and Centaurus A. The fact that these objects are much closer to us than the blazars allows better resolution of their structure. M 87 is a giant radio galaxy in the Virgo cluster, Misalignment of its jet relative to the line-of-sight to Earth permits imaging of the jet in the radio, optical and X-ray bands. After its first detection by HEGRA [33], M 87 has now been extensively studied by VHE gamma-ray telescopes.

M 87 was first detected by VERITAS in 2007, at flux level of $\sim 2\%$ Crab Nebula [34]. In this epoch the source exhibited relatively little variability. In February 2008, however, strong flaring in gamma rays was detected during a joint observation campaign involving the VLBA and the VHE instruments VERITAS, MAGIC, and HESS [35], [36]. During this flaring, Chandra revealed the nucleus of M 87 to be active in the X-ray band, providing evidence that the TeV photons are emitted from the core of M 87. In 2009, M 87 is apparently in a relatively low state; ~ 20 h of observation by VERITAS yielded only a marginal detection [37]. Further multiwavelength efforts are likely needed to provide clear insight into the acceleration and emission mechanisms of this fascinating source.

Gamma-ray bursts (GRBs) are the most powerful cosmic explosions known, with complex acceleration mechanisms that likely involve shocks in a highly relativistic jet. To date, no convincing evidence of VHE emission from GRBs has been presented, although GeV photons have been detected by both EGRET and now Fermi-LAT. The targeting of GRBs is very high priority for VERITAS. Since 2006, 31 GRBs have been observed. The response time of VERITAS to GRB alerts is excellent, with typical delays of two to four minutes from the beginning of the burst and 92 s as the best case [38] So far, no detections have been made, but the future looks promising for an upgraded VERITAS with improved sensitivity and lower energy threshold [39].

VERITAS also reported results from observations of the radio galaxies NCG 1275 and 3C 111 and the Coma cluster of galaxies [40].

V. GALACTIC SOURCES

The Galaxy is a rich source of high-energy gamma-ray emission, with 90% of the astrophysical photons seen at GeV energies corresponding to diffuse emission in the Galactic plane. To date, we have four types of Galactic objects at TeV energies: pulsar wind nebulae (PWN), supernova remnants (SNRs), binary systems, and unidentified sources. In these objects we study the acceleration of electrons and protons in shock fronts,

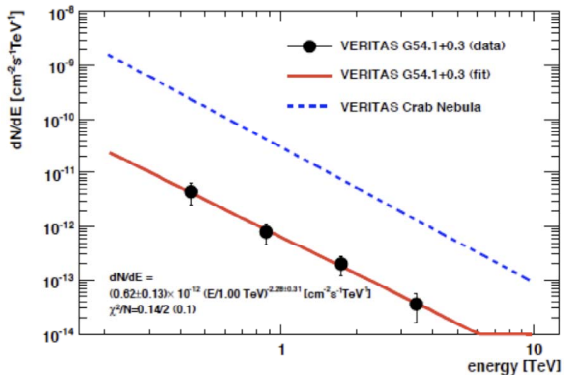


Fig. 6: Preliminary differential energy spectrum as measured by VERITAS for the VHE gamma-ray emission from SNR G54.1+0.3. The spectrum is well-fit by a power-law form with spectral index $\Gamma = 2.3 \pm 0.3(\text{stat}) \pm 0.3(\text{sys})$.

colliding winds, superbubbles, etc., with a primary goal of pinning down the origin of cosmic rays.

The observation of Galactic sources is a high priority for VERITAS. In addition to the Sky Survey discussed earlier, there is a second key science project focused on PWN and SNRs [41]. Here we report on new detections by VERITAS of four Galactic sources.

A. G54.1+0.3 and G106.3+2.7 (Boomerang)

The supernova remnant G54.1+0.3 has many similarities to the Crab Nebula, with an X-ray jet and torus being observed around the pulsar PSR J1930+1852. With an age of $\sim 2,900$ years and a spin-down luminosity of $\dot{E} \sim 1.2 \times 10^{37}$ erg/s, this remnant/PWN is a likely candidate for VHE gamma-ray emission. The presence of a nearby molecular cloud as a possible target material for VHE cosmic rays provides further observational motivation.

Following a hint of a signal from moonlight data taken in 2007, G54.1+0.3 was observed by VERITAS for 31 h in 2008, yielding a solid detection at the 7.0σ level. The VHE emission is consistent with a point source at the pulsar location. The preliminary flux level is $\sim 3\%$ Crab Nebula above 1 TeV. As shown in Figure 6, the preliminary differential spectral index is $\Gamma = 2.3 \pm 0.3_{\text{stat}} \pm 0.3_{\text{sys}}$.

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 [42]. 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 [17]. Milagro reported >10 TeV emission from the general region [43] with a large error box $\sim 1^\circ$ in diameter.

The VERITAS detection of VHE emission came from

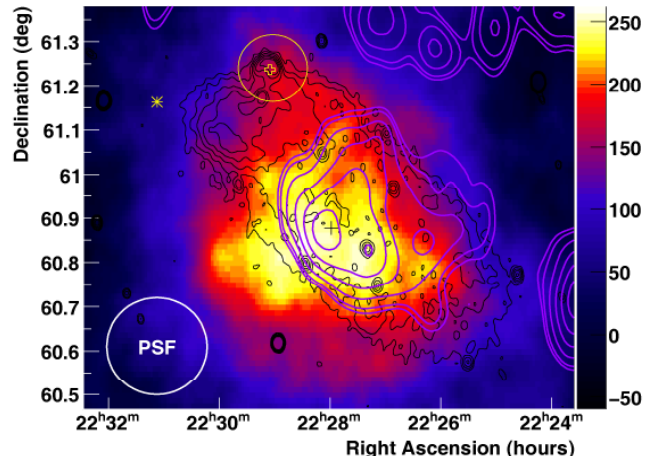


Fig. 7: Sky map of VHE gamma-ray emission from G106.3+2.7 as measured by VERITAS. The color scale indicates the excess gamma-ray events from the region; the centroid of the VHE emission is indicated by the black cross. The yellow circle indicates the 95% error contour for the Fermi source OFGL J2229.0+6114 and the white circle represents the gamma-ray point spread function (68% containment) of VERITAS. Radio contours and CO emission contours are indicated by the black and magenta lines, respectively.

33 h of observations carried out in 2008 that resulted in a post-trials significance of 6.0σ and an integral gamma-ray flux level of $\sim 5\%$ Crab Nebula above 1 TeV [44]. As shown in Figure 7, the VHE emission is clearly extended, spanning a region approximately 0.4° by 0.6° in size. However, the peak of the emission is clearly 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 the Milagro energy of 35 TeV. The spectrum and the observed morphology of the source support a possible hadronic origin for the VHE emission.

B. Other Supernova Remnants

The SNRs Cassiopeia A (Cas-A) and IC 443 are now well established VHE gamma-ray sources. Observations of Cas-A by VERITAS in 2007 totalled 22 h and yielded a clear detection at the 8.3σ statistical level [45]. The integral gamma-ray flux is $\sim 3.5\%$ Crab Nebula above 1 TeV. The VERITAS energy spectrum is well fit by a power-law form 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. There is also no evidence for any source extension [46].

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. In their subsequent paper, MAGIC reported a 5.7σ detection of the source, corresponding to an integral flux of $\sim 2.8\%$ Crab Nebula above 300 GeV [47]. The initial VERITAS

data set on IC 443, of ~ 16 h taken in 2007 with three telescopes, was augmented in 2008 by ~ 21 h taken with four telescopes. The overall data set yields a post-trials statistical significance of 7.5σ and an integral flux of $\sim 3.2\%$ Crab Nebula, consistent with the MAGIC result. However, the VERITAS data show for the first time that the gamma-ray emission is extended, with a characteristic fitted two-dimensional Gaussian radius of 0.16° [48]. The VHE emission also overlaps with a dense CO molecular cloud. Further observations at both GeV and TeV energies are needed to unambiguously determine whether the primary particles accelerated in IC 443 are protons or electrons (or some combination).

C. Unidentifieds and Other Galactic Sources

The W44 SNR has long been a candidate source of TeV gamma-ray emission. HESS detected two unidentified sources, HESS J1857+026 and HESS J1858+020, in the region, but not W44 itself [49]. Based on 13 h of observations taken in 2008, VERITAS confirms the HESS results. HESS J1857+026 is detected at the 5.6σ significance level, with the VERITAS data showing a comparable spectrum and position to HESS. HESS J1858+20 is marginally detected at the 3.4σ level. W44 is not detected in the VERITAS data and an integral flux upper limit of $< 2.0\%$ Crab Nebula is obtained.

HESS J0632+057 was discovered during HESS observations of the Monoceros Loop in 2004 and 2005 [50]. At that time, the source was at a flux level of $\sim 3\%$ of the Crab Nebula. As one of only two unidentified sources in the Galactic plane consistent with being point-like, HESS J0632+057 was logically postulated to be a binary system [51]. VERITAS observed the source over a three year period for a total of ~ 30 h, with no strong evidence for VHE gamma-ray emission [52], [53]. From these data, an integral flux upper limit from the source of $< 1.1\%$ Crab Nebula above 1 TeV is obtained. The VERITAS observations exclude the possibility of steady VHE emission from HESS J0632+057 at $> 99.99\%$ C.L.. This strongly supports the source being variable, and it could well be a binary.

Other VERITAS Galactic source results reported at this conference include long-term studies of the TeV binary LS I +61 303 [54], observations of globular clusters [55], Geminga [56], X-ray binaries [57], magnetars [58], and a forbidden velocity wing [59], and a search for bursts of gamma rays from the Crab Pulsar [60].

VI. DARK MATTER SEARCHES

The nature of dark matter is one of the most compelling mysteries in physics and astronomy today. Particle dark matter candidates, *e.g.* the weakly interacting massive particle (WIMP), predict unique high energy gamma-ray signatures. For example, the WIMP self-annihilation signal is expected to yield a continuum gamma-ray spectrum that terminates at the WIMP mass. Depending on the particle physics, there may also be gamma-ray line emission.

The search for dark matter is a key science project of VERITAS, encompassing $\sim 6\%$ of the observing time. To carry out a comprehensive search of astrophysical systems that are likely to contain a preponderance of dark matter, we targeted a variety of objects, including nearby dwarf galaxies (*e.g.* Draco, Ursa Minor), local galaxies (*e.g.* M32, M33), globular clusters (*e.g.* M5), and galaxy clusters (*e.g.* Coma). So far, no clear gamma-ray signals are detected from any of the dark-matter candidate sources and strong limits are placed on the gamma-ray emission from seven targets [61].

VII. ICECUBE HOTSPOT

The large IceCube neutrino telescope is currently under construction at the South Pole, and the partially-completed detector is already carrying out searches for astrophysical sources of VHE neutrinos. The all-sky neutrino map from the 22-string IceCube detector revealed a hotspot (excess of 7.7 events) at the sky position $(\alpha, \delta) = (10\text{h}13\text{m}30\text{s}, +11\text{d}22\text{m}30\text{s})$ [62]. Information about this hotspot was conveyed to VERITAS and Director's Discretionary Time was used to carry out observations of it. VERITAS observed the IceCube hotspot for 2.5 h in April 2009 in moonlight conditions. No signal was detected and an upper limit on the integral flux of gamma rays of $< 4.0\%$ Crab Nebula above 1 TeV was obtained.

VIII. FUTURE

Given the excitement of the field of gamma-ray astronomy, it is natural to consider ways to improve the performance of VERITAS. This goal is especially true in light of the unique capabilities of Fermi, currently planned to operate through 2013, at least, and very likely beyond that. Given this timetable, it makes sense to consider upgrade options that can be carried out on a time scale of two to three years.

The VERITAS upgrade program has three stages. The first stage, already accomplished, involved improving the optical point spread function through better mirror alignment [63] and the relocation of Telescope 1. As shown in Figure 1, the first VERITAS telescope was moved in Summer 2009 to increase the baseline distances between it and the other telescopes. As discussed in Section 1, this change in the layout of VERITAS has had a significant impact on its performance. A point source with a flux of 1% Crab Nebula can now be detected in under 30 h.

The second stage of the upgrade program is aimed at further improving the sensitivity and extending the reach of VERITAS to lower energies [39]. We are proposing to upgrade each VERITAS camera by replacing the existing PMTs with ones having higher quantum efficiency. A new topological telescope trigger system is also envisioned [64]. Possibilities for a future third upgrade stage include an automatic mirror alignments system and an additional telescope (T5).

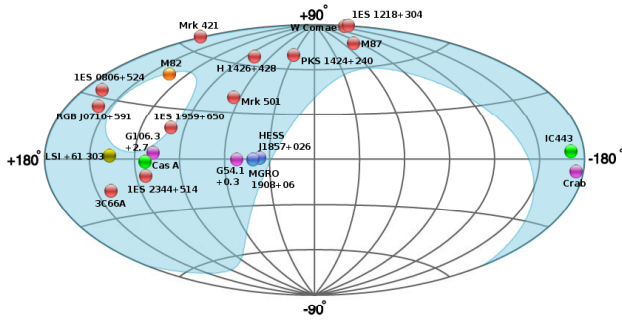


Fig. 8: Sky map of VERITAS VHE gamma-ray source detections, as of July 2009. The various source classes are: AGN (red), binary systems (yellow), pulsar wind nebulae (purple), starburst galaxies (orange), supernova remnants (green), and unidentified sources (blue).

IX. SUMMARY

The four-telescope VERITAS array is operating extremely well ($> 95\%$ uptime) and with excellent sensitivity. Based on two years of quality data, VERITAS presented many new results at this meeting, including:

- the discovery of gamma-ray emission from the starburst galaxy M 82,
- stringent limits on source fluxes from the Galactic plane sky survey,
- the detection of five new blazars (1ES 0806+524, W Comae, 3C 66A, RGB 0710+541, and PKS 1424+240),
- correlated multiwavelength emission from the radio galaxy M 87 (with MAGIC and HESS),
- the detection of two new SNRs/PWN (G106.3+2.7 and G54.1+0.3),
- detailed studies of the supernova remnants IC 443 and Cas-A, and
- limits on the annihilation of dark matter to VHE gamma rays in seven astrophysical targets.

The current VERITAS sky map is shown in Figure 8. VERITAS has detected 21 VHE gamma-ray sources, eight 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.

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REFERENCES

- [1] J. Holder *et al.*, *Status of the VERITAS Observatory*, AIP Conf. Proc. **1085**, 657 (2008).
- [2] VERITAS Collaboration *Contributions to the 31st International Cosmic Ray Conference*, arXiv:0908.0150v2 (2009).
- [3] M. Punch *et al.*, *Detection of TeV Photons from the Active Galaxy Markarian 421*, Nature **358**, 477 (1992).
- [4] See, for example, <http://tevcat.uchicago.edu>.
- [5] G.H. Rieke *et al.*, *The Nature of the Nuclear Sources in M 82 and NGC 253*, Astrophys. J. **238**, 24 (1980).
- [6] A. Weiss *et al.*, *The Effect of Violent Star Formation on the State of the Molecular Gas in M 82*, Astron. & Astrophys. **365**, 571 (2001).
- [7] T. Nagai, *Search for TeV Gamma-Ray Emission from Nearby Starburst Galaxies*, Ph.D. Thesis, University of Utah (2005).
- [8] N. Gotting, *Nachweis von TeV-Gamma-Strahlung aus der Richtung der Blazare H1426+428 und 1ES1939+650 sowie der Radiogalaxie M87 mit den HEGRA-Cherenkov-Teleskopen*, Ph.D. Thesis, University of Hamburg (2007).
- [9] V.A. Acciari *et al.*, *A Connection Between Star Formation Activity and Cosmic Rays in the Starburst Galaxy M82*, Nature, Nov. 1, 2009, published online at <http://www.nature.com/nature/journal/vaop/ncurrent/full/nature08557.html>.
- [10] M. Persic, Y. Rephaeli, and Y. Arieli, *Very-High-Energy Emission from M82*, Astron. & Astrophys. **486**, 143 (2008).
- [11] E. de Cea del Pozo, D.F. Torres, and A.Y.R. Marrero, *Multimessenger Model for the Starburst Galaxy M82*, Astrophys. J. **698**, 1054 (2009).
- [12] F. Acero *et al.*, *Detection of Gamma Rays from a Starburst Galaxy*, Science, Sept. 24, 2009, published online at <http://www.sciencemag.org/cgi/content/abstract/1178826>.
- [13] A.A. Abdo *et al.*, *Detection of Gamma-Ray Emission from the Starburst Galaxies M82 and NGC 253 with the Large Area Telescope on Fermi*, submitted to Science (2009).
- [14] A. Weinstein *et al.*, *The VERITAS Survey of the Cygnus Region of the Galactic Plane*, arXiv:0907.5435v1 (2009).
- [15] F. Aharonian *et al.*, *an unidentified TeV Source in the Vicinity of Cygnus OB2*, Astron. & Astrophys. **393**, L37 (2002).
- [16] F. Aharonian *et al.*, *The Unidentified TeV source (TeV J2032+4130) and Surrounding Field: Final HEGRA IACT-System Results*, Astron. & Astrophys. **431**, 197 (2005).
- [17] A.A. Abdo *et al.*, *Fermi Large Area Telescope Bright Gamma-ray Source List*, Astrophys. J. Suppl. **183**, 46 (2009).
- [18] A.A. Abdo *et al.*, *TeV Gamma-Ray Sources from a Survey of the Galactic Plane with Milagro*, Astrophys. J. **664**, L91 (2007).
- [19] F. Aharonian *et al.*, *The H.E.S.S. Survey of the Inner Galaxy in Very High Energy Gamma Rays*, Astrophys. J. **636**, 777 (2006).
- [20] W. Benbow *et al.*, *The VERITAS Blazar Key Science Project*, arXiv:0908.1412v1 (2009).
- [21] V. Acciari *et al.*, *Discovery of Very High Energy Gamma-Ray Radiation from the BL Lac 1ES 0806+524*, Astrophys. J. **690**, L126 (2009).
- [22] R.A. Ong (for the VERITAS Collaboration), *VERITAS Discovery of VHE Gamma-Ray Emission from BL Lac Object RGB J0710+591*, The Astronomer's Telegram #1941 (2009).
- [23] J.S. Perkins *et al.*, *Blazar Discoveries with VERITAS*, arXiv:0907.4978v1 (2009).
- [24] V. Acciari *et al.*, *VERITAS Discovery of >200 GeV Gamma-ray Emission from the Intermediate-frequency Peaked BL Lac Object W Comae*, Astrophys. J. **684**, L73 (2008).
- [25] G. Maier *et al.*, *Multiwavelength Observations of a TeV Flare from W Com*, arXiv:0907.4048v1 (2009).
- [26] V. Acciari *et al.*, *VERITAS Observations of a Very-High-Energy Gamma-Ray Flare from the Blazar 3C66A*, Astrophys. J. **693**, L104 (2009).
- [27] L.C. Reyes *et al.*, *Simultaneous Observations of Flaring Gamma-ray Blazar 3C 66A with Fermi-LAT and VERITAS*, arXiv:0907.5175v1 (2009).
- [28] R.A. Ong (for the VERITAS Collaboration), *Discovery of VHE Gamma-Ray Emission from the Fermi-LAT Source PKS 1424+240*, Astronomer's Telegram #2098 (2009).
- [29] V.A. Acciari *et al.*, *Discovery of Very High Energy Gamma Rays from PKS 1424+240 and Multiwavelength Constraints on its Redshift*, submitted to Astrophys. J. (2009).
- [30] A. Imran *et al.*, *VERITAS Discovery of Variability in the VHE Gamma-Ray Emission of 1ES 1218+304*, arXiv:0908.0142v1 (2009).
- [31] J. Grube *et al.*, *Highlights of Recent Multiwavelength Observations of VHE Blazars with VERITAS*, arXiv:0907.4862v1 (2009).

- [32] A. Pichel *et al.*, *Highlights from the Whipple 10m Blazar Monitoring Program*, arXiv:0908.0010v1 (2009).
- [33] F. Aharonian *et al.*, *Is the Giant Radio Galaxy M 87 a TeV Gamma-Ray Emitter?*, *Astron. & Astrophys.* **403**, L1 (2003).
- [34] V.A. Acciari *et al.*, *Observation of Gamma-Ray Emission from the Galaxy M87 above 250 GeV with VERITAS*, *Astrophys. J.* **679**, 397 (2008).
- [35] R.M. Wagner *et al.*, *A First Joint M87 Campaign in 2008 from Radio to TeV Gamma Rays*, arXiv:0907.1465v1 (2009).
- [36] V.A. Acciari *et al.*, *Radio Imaging of the Very-High Energy Gamma-Ray Emission Region in the Central Engine of a Radio Galaxy*, *Science* **325**, 444 (2009).
- [37] C.M. Hui *et al.*, *VERITAS Observations of M87 from 2007 to Present*, arXiv:0907.4792v1 (2009).
- [38] N. Galante *et al.*, *VERITAS Observation of Gamma-Ray Bursts*, arXiv:0907.4997v1 (2009).
- [39] A.N. Otte *et al.*, *Upgrade of the VERITAS Cherenkov Telescope Array*, arXiv:0907.4826v1 (2009).
- [40] N. Galante *et al.*, *Observation of Radio Galaxies and Clusters of Galaxies with VERITAS*, arXiv:0907.5000v1 (2009).
- [41] B. Humensky *et al.*, *Observations of Supernova Remnants and Pulsar Wind Nebulae: A VERITAS Key Science Project*, arXiv:0907.5020v1 (2009).
- [42] R. Kothes, B. Uyaniker, and S. Pineault, *The SNR G106.3+2.7 and its Pulsar Wind Nebula: Relics of Trigger Star Formation in a Complex Environment*, *Astrophys. J.* **560**, 236 (2001).
- [43] A.A. Abdo *et al.*, *Milagro Observations of Multi-TeV Emission from Galactic Sources in the Fermi Bright Source List*, *Astrophys. J.* **700**, L127 (2009).
- [44] V.A. Acciari *et al.*, *Detection of Extended VHE Gamma-Ray Emission from G106.3+2.7 with VERITAS*, *Astrophys. J.* **703**, L6 (2009).
- [45] B. Humensky *et al.*, *Observations of Supernova Remnants with VERITAS*, arXiv:0907.5018v1 (2009).
- [46] V.A. Acciari *et al.*, *Observations of the Shell-Type SNR Casiopeia A at TeV Energies with VERITAS*, submitted to *Astrophys. J.* (2009).
- [47] J. Albert *et al.*, *Discovery of VHE Gamma Radiation from IC 443 with the MAGIC Telescope*, *Astrophys. J.* **664**, L64 (2007).
- [48] V.A. Acciari *et al.*, *Observation of Extended Very High Energy Emission from the Supernova Remnants IC 443 with VERITAS*, *Astrophys. J.* **698**, L133 (2009).
- [49] F. Aharonian *et al.*, *HESS Very-High-Energy Gamma-ray Sources Without Identified Counterparts*, *Astron. & Astrophys.* **477**, 353 (2008).
- [50] F. Aharonian *et al.*, *Discovery of a Point-Like Very-High-Energy Gamma-ray Source in Monoceros*, *Astron. & Astrophys.* **469**, L1 (2007).
- [51] J. Hinton *et al.*, *HESS J0632+057: A New Gamma-Ray Binary?*, *Astrophys. J.* **690**, L101 (2009).
- [52] G. Maier *et al.*, *VERITAS Observations of HESS J0632+057*, arXiv:0907.3958v1 (2009).
- [53] V.A. Acciari *et al.*, *Evidence for Long-Term Gamma-Ray and X-Ray Variability from the Unidentified TeV Source HESS J0532+057*, *Astrophys. J.* **698**, L94 (2009).
- [54] J. Holder *et al.*, *VERITAS Observations of LS I +61 303 in the Fermi Era*, arXiv:0907.3921v1 (2009).
- [55] M. McCutcheon *et al.*, *VERITAS Observations of Globular Clusters*, arXiv:0907.4974v1 (2009).
- [56] G. Finnegan *et al.*, *Search for TeV Emission from Geminga by VERITAS*, arXiv:0907.5237v2 (2009).
- [57] R. Guenette *et al.*, *VERITAS Observations of X-ray Binaries*, arXiv:0908.0714v2 (2009).
- [58] R. Guenette *et al.*, *VERITAS Observations of Magnetars*, arXiv:0908.0717v1 (2009).
- [59] J. Holder *et al.*, *VERITAS Observations of a "Forbidden Velocity Wing"*, arXiv:0907.3918v1 (2009).
- [60] M. Schroedter *et al.*, *Search for Short Bursts of Gamma Rays above 100 MeV from the Crab using VERITAS and SGARFACE*, arXiv:0908.0182v1 (2009).
- [61] R.G. Wagner *et al.*, *Indirect Dark Matter Searches with VERITAS*, arXiv:0910.4563 (2009).
- [62] T. Montaruli (private communication).
- [63] A. McCann, D. Hanna, and M. McCutcheon, *An Alignment System of Imaging Atmospheric Cherenkov Telescopes*, arXiv:0907.4975v1 (2009).
- [64] M. Schroedter *et al.*, *A Topological Trigger System for Imaging Atmospheric Cherenkov Telescopes*, arXiv:0908.0179v1 (2009).