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The VERITAS Survey of the Cygnus Region of the Galactic Plane

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VERITAS is an array of imaging atmospheric Cherenkov telescopes, located in southern Arizona, that operates in the 100 GeV to 50 TeV energy range. With VERITAS we have conducted a survey of the Cygnus region of the Galactic plane between $67^\circ < l < 82^\circ$ and $-1^\circ < b < 4^\circ$. The Cygnus region was chosen for a blind search due to its high content of potential Very High-Energy (VHE, >100 GeV) gamma-ray sources (including Supernova Remnants, Pulsar Wind Nebulae, X-Ray Binaries and stellar OB associations) as well as several previously discovered VHE sources. There are also several high-energy gamma-ray emitters in this region as detected by the Fermi gamma-ray space telescope. The survey has accumulated more than 140 hours of observations and reaches an estimated point-source VHE sensitivity of ∼4% of the Crab Nebula flux above an energy threshold of 200 GeV. We present details of the survey, analysis, initial results and follow-up observations.

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1. Introduction

The first survey to be conducted using the current-generation of Imaging Atmospheric Cheren kov Technique (IACT) telescopes, was with the High Energy Stereoscopic System (HESS) [4]. The HESS array is well suited to survey-style observations due to its large field of view (5°) and location in the southern hemisphere (allowing much better observing conditions for searches of the inner part of the Galactic plane). The initial stage of the HESS survey was conducted between May and July 2004 between $l = \pm 30^\circ$ and $b = \pm 3^\circ$, reaching ∼2% of the Crab and revealing 14 new sources of VHE gamma-ray emission [5]. A further extension of the HESS survey carried out after 2004 has extended its limits to encompass latitudes $60^\circ < l < 275^\circ$ [6] expanding the catalogue of TeV sources detected by the HESS Galactic plane survey to ∼52. Many of these sources were serendipitous discoveries and have no known counterparts in other wavelengths, while others have the predicted associations with supernova remnants (SNRs), pulsar wind nebulae (PWNe), stellar OB associations etc.

The great success of the HESS survey showed that a dedicated, sensitive survey of the Galactic plane using the IACT can provide an excellent opportunity for an efficient increase in TeV source detections, with the potential for discovery of unexpected VHE emission and/or source classes. The first results from the HESS survey, circa 2004, were the driving force behind the VERITAS collaboration's plans for a survey of the Galactic plane at northern latitudes and as such was classified as a VERITAS "Key Science Project".

2. Survey Observations of the Cygnus Region

Between April 2007 and December 2008, the VERITAS collaboration conducted a survey of the Cygnus region of the Galactic plane between $67^0 < l < 82^0$ and $-1^0 < b < 4^0$ in a search for sources of VHE gamma-ray emission. The choice of the Cygnus region was motivated by the presence of potential TeV-emitting objects such as SNRs, PWNe, stellar OB associations, X-ray and Colliding Wind Binary systems along with the availability of multi-wavelength archival data necessary for association studies for any new regions of VHE gamma-ray emission.

The survey observations were organized as a series of 120 grid-pointings with a grid-spacing of 0.8° in Galactic longitude and 1.0° in Galactic latitude. This allowed for a reasonable efficiency in the overlapping regions, considering the off-axis response of the array to gamma rays. An exposure time of 1 hour per grid-pointing was targeted (observations were taken in 20 minute exposures, as close together in time as possible). Figure 1 illustrates the overlapping exposures in the survey grid, along with the acceptance-corrected ("effective") exposure map of the base survey (i.e. before any follow-up observations with ∼1 hour exposure at each grid-pointing). The base survey achieves a relatively uniform coverage of ∼6-7 hours.

The survey began during the commissioning phase of the VERITAS array, with data taken in Spring 2007 using the 3-telescope array (telescopes T1, T2 and T3). Data taken from Autumn 2007 up to Autumn 2008 was taken with the full 4-telescope array configuration.

3. Follow-up Observations

Motivated by statistical hot-spots within the base survey, follow-up observations using the

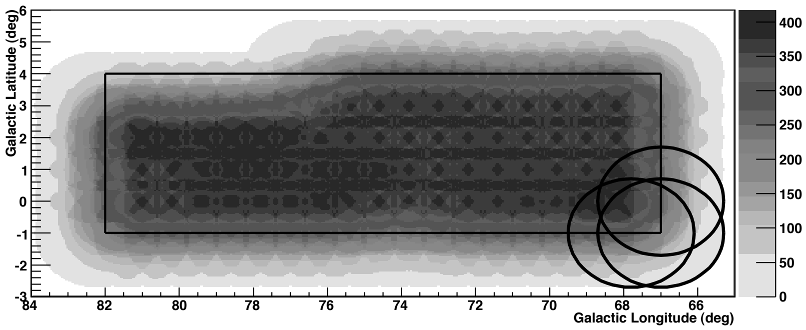


Figure 1: Acceptance-corrected exposure map of the base survey using data from Spring 2007 through to Autumn 2008. The black box indices the boundary of the survey proper; the black circles provide an illustration of the observation overlapping procedure used to tile the survey region. The color scale gives the effective exposure time in minutes.

4-telescope configuration of the array were taken in Autumn 2008. These observations were a combination of re-pointings at grid locations which overlap the region of interest, coupled with wobble observations at both 0.5° and 0.7° offsets from that same point.

Further to this, wobble observations using the current, most-sensitive configuration of the VERITAS array were taken in the Spring and Autumn of 2009. The current configuration was created with the redeployment of T1 to a new location at the array site, resulting in a sensitivity improvement of approximately 30% [7].

4. Survey Analysis

As the HESS and Milagro Cherenkov air shower array surveys showed, the majority of TeV sources in the Galactic plane are moderately extended ($\sigma_{ext} \sim 0.1 - 0.3°$), with spectral indices ranging from "soft" ($\Gamma \sim 2.4$) to "hard" ($\Gamma \sim 2.0$) [5, 8]. Using these previous results as a guide for *a priori* cuts selection to maximize the survey sensitivity and also minimize the trials factor, four different parallel analyzes cuts were agreed upon.

Firstly, VERITAS data are calibrated and cleaned as described in [9]. After calibration, several noise-reducing cuts are made. The VERITAS standard analysis consists of parameterization using a moment analysis [10] and following this, the calculation of scaled parameters are used for event selection [11, 12]. The mean scaled length (MSL) and mean scaled width (MSW) parameters summarize the differences in image shape between gamma ray events and the large majority of cosmic-ray events (these cuts are determined *a priori*). A further cut used is to cut on the square of the angular distance (θ^2) between a reconstructed shower and the sky position of a potential source.

For the relevant survey analyzes, all used the same scaled parameter cuts (optimized for 1% Crab-strength source; 0.05< MSW <1.06 and 0.05< MSL <1.24) but the four individual analyzes were also optimized for a specific source description (i.e. a soft-spectrum point source, a soft-spectrum extended source, a hard-spectrum point source and a hard-spectrum extended source). Two cuts allow for these differentiations, the minimum image *size* (which corresponds to the total integrated charge in digital counts (dc), of an image) and the θ^2 parameter. Therefore, any images in the specific analyzes which did not have an integrated size value above the minimum size cut (either 600dc or 1000dc for the soft spectrum and hard spectrum source searches respectively) were rejected from the generation of the photon sky maps. The θ^2 values of 0.013 and 0.055 were used for the point source and extended source analyzes. The contribution due to the residual cosmic-ray background was estimated using the "Ring Background Model" [13].

5. Survey Results

Figure 2 shows the significance map (pre-trials) of all positions for Galactic latitudes $l > 76^\circ$ in the Cygnus region covered by the survey. This map was generated using the soft-spectrum extended source analysis and includes all survey data taken up to Autumn 2009. This region contains two clear detections of VHE gamma-ray emission: the previously known source TeV J2032+4130 [14], and a newly detected source in the vicinity of the shell-type SNR γ-Cygni, designated VER J2019+407. Both sources are in close proximity to a Fermi pulsar, and TeV J2032+4130 is also coincident with the Milagro source MGRO J2032+41.

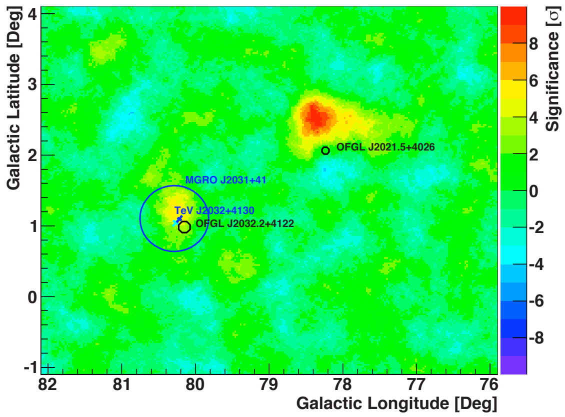


Figure 2: Significance map above 76° Galactic latitude, including all follow-up data taken through Autumn 2009. The error circles of two pulsars from the Fermi six-month bright source list [16], 0FGL J2021.5+4026 and 0FGL J2032.2+4122 are indicated by black circles, and the position and extent of MGRO J2031+41 [8] is indicated in blue. The position of TeV J2032+4130 as measured by the HEGRA and MAGIC experiments is indicated by the dark and light blue crosses respectively [14, 15].

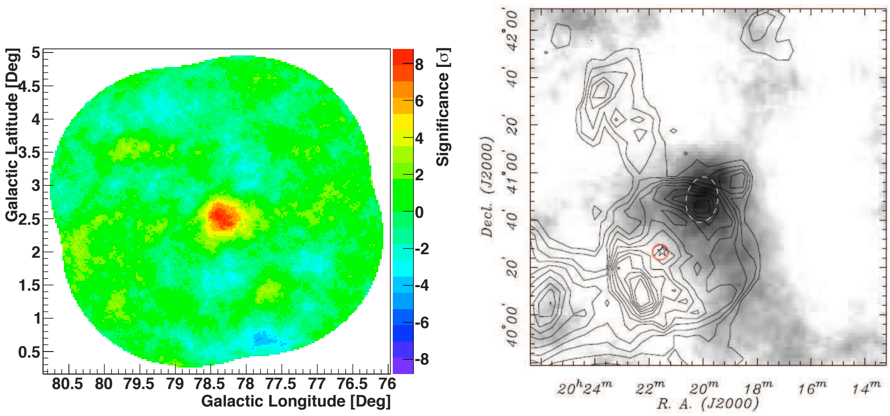
5.1 VER J2019+407

The analyzes of the base survey data set revealed a consistent extended region of gamma-ray excess (at the $\sim 4\sigma$ level) in the northwest region of the γ-Cygni SNR. Further follow-up observations in Autumn 2008, along with pointed wobble observations in Spring 2009 raised the signal to $\sim$ 5-7 σ (pre-trials) in the various survey analyzes. Furthermore, independent 0.6° wobble observations were also taken in Autumn 2009 around the location RA=$20^{\rm h}19^{\rm m}48^{\rm s}$, Dec = $40^\circ 54' 00''$.

The significance map around VER J2019+407 is shown in Figure 3(a), extended emission was detected with a maximum significance of 8.5 σ (7.5σ post-trials) within a search region of radius 0.25° around the central wobble location, using the soft-spectrum extended source analysis from the survey. The analysis and search region were chosen *a priori* based on the previous survey results.

The centroid and intrinsic extension of the source are based on the Autumn 2009 observations only, and were characterized by fitting an asymmetric two-dimensional Gaussian convolved with the point-spread function (PSF) of the instrument, to an acceptance corrected uncorrelated excess map with 0.05° bins. The PSF was derived from a fit to Crab data taken in Autumn 2009 and has a 68% containment radius of 0.1°. A preliminary centroid position of RA=$20^h19^m52.80^s$, Dec = $40°47'24''$ has been calculated along with a preliminary extension of $0.16°\pm0.028°$ and $0.11°\pm0.027°$ along the major and minor axes respectively.

The nature of VER J2019+407 is still unclear. An association with the Fermi pulsar is unlikely due to the 0.5° offset between the emission centroid and the pulsar location. One possible explanation for the TeV emission is due to the SNR shock-front interacting with local molecular clouds. The presence of structures in the hard X-ray waveband in this area of the remnant [17] were used as an argument for a shock-cloud interaction scenario. The association of the EGRET source 3EG J2020+4017 with these clumps was an important construct of the theory, but since the detection of the Fermi pulsar 1FGL J2021.5+4026 (now the likely counterpart of the EGRET source) 0.5° away, further X-ray observations must be taken in order to better understand the particle acceleration mechanisms occurring at this location.



(a) (b)

Figure 3: (a) Significance map of the region around VER J2019+407, using data from observations taken in Autumn 2009 only. (b) Acceptance-corrected excess map of the region around VER J2019+407, using all data taken through Autumn 2009. The black contours show the 1420 MHz radio emission in the region (taken from the Canadian Galactic Plane Survey [18]) and clearly show the extent of the γ-Cygni remnant. The white-dashed line shows the 1σ ellipse from the VER J2019+407 source extension fit; the circle is the error circle of the 0FGL J2021.5+4026 and the star is the position of the associated Fermi pulsar.

6. Summary

The VERITAS collaboration has completed a 140-hour survey of the Cygnus region of the Galactic plane. Follow-up observations within the survey region have also resulted in two source detections; TeV J2032+4130 (likely associated with the coincident Fermi source 0FGL J2032.2+4122) and a newly-discovered region of extended emission, VER J2019+407, which is located in a region coincident with the north-west section of the γ-Cygni SNR. This region of VHE gamma-ray excess may or may not be related to the nearby Fermi source 0FGL J2021.5+4026.

VERITAS observations are currently being undertaken on areas of interest within the surveyed area of the Cygnus region of the Galactic plane, with more work ongoing on the calculation of upper limits on sources of interest in the region using the current data set.

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