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Recent Results on Galactic Sources in Cygnus by VERITAS

RENE A. ONG[1], FOR THE VERITAS COLLABORATION.

[1] *Department of Physics and Astronomy, University of California, Los Angeles, CA 90095, USA*

rene@astro.ucla.edu

Abstract: The Cygnus region of the Galactic plane is a promising target for high-energy and very high energy (VHE) gamma-ray telescopes as it is home to many potential sources, such as supernova remnants, pulsar wind nebulae, X-ray binaries and massive star clusters. The VHE gamma-ray observatory VERITAS (Very Energetic Radiation Imaging Telescope Array System) is an array of four 12 m diameter imaging atmospheric Cherenkov telescopes located at Mt. Hopkins, AZ, USA. Over the period of 2007 to 2012, VERITAS has carried out extensive observations in the direction of Cygnus. These observations were initiated by a sky survey that covered Galactic longitudes between 67 and 82 degrees and Galactic latitudes between -1 and 4 degrees. Additional deep observations have been made near specific sources, including TeV J2032+4130, Cygnus X-3, VER J2019+407 (SNR G78.2+2.1/γ-Cygni), CTB 87, and MGRO J2019+37. This contribution will summarize the latest VERITAS results on the various source detections in Cygnus and will discuss a comparison of the sky maps for the region as detected by VERITAS and Fermi-LAT.

Keywords: VERITAS, Galactic sources, Cygnus, atmospheric Cherenkov telescopes, VHE gamma-ray astronomy

1 Introduction

Cosmic ray particles span an enormous energy range, from below 1 GeV to above 10^{20} eV, and they pervade our Galaxy with an energy density comparable to that in the Galactic magnetic field or starlight. In spite of many years of research, the origin of the very high energy (VHE, E $>$ 100 GeV) cosmic rays remains a significant mystery today. Neutral messengers, such as gamma rays and neutrinos can provide critical information about cosmic ray origins as they directly trace the energetic processes taking place at acceleration sites throughout our Galaxy.

In recent years, VHE gamma-ray telescopes have been very successful at detecting sources in our Galaxy that can help to shed light on the origin of cosmic rays. At the present time, there are $\sim$100 firmly established objects within a few degrees of the Galactic plane [1]. Identified sources include: 1) supernova remnants (SNRs), that are generally believed to produce the dominant portion of the cosmic rays up to the knee in the spectrum (i.e. up to E $\sim$1 PeV), 2) binary systems, in which the acceleration may involve colliding winds or accretion-powered jets, 3) pulsar wind nebulae, in which the acceleration results from the interaction of a pulsar-driven wind with ambient radiation fields, and 4) star forming regions, in which the gamma rays trace interactions taking place in molecular clouds or near OB associations. In addition to these sources, there are a significant number of VHE detections that are not yet firmly associated with any known astronomical object. Understanding the nature of the unidentified VHE detections is thus an important goal in piecing together the overall high-energy Galactic source population.

The Cygnus region of the Galactic plane is a prime target for high-energy and VHE gamma-ray telescopes. It is a region that is rich in star formation activity and it contains a substantial catalog of possible accelerators of VHE cosmic rays. The direction towards Cygnus contains three arms of the Milky Way galaxy in our line of sight, making it difficult to determine counterparts to VHE gamma-ray sources in some cases, but leading to a fertile region for exploration. The region has been surveyed at GeV energies by EGRET and Fermi-LAT, at TeV energies by HEGRA [2], and at multi-TeV energies by the Milagro air shower array [3, 4]. Cygnus was also targeted by the VERITAS telescope which carried out a survey of the region between 2007 and 2009. The VERITAS Sky Survey is discussed in more detail below.

2 VERITAS

VERITAS (the Very Energetic Radiation Imaging Telescope Array System) is a state-of-the-art ground-based VHE gamma-ray telescope. Located at the F. L. Whipple Observatory in southern Arizona, USA, VERITAS uses the imaging atmospheric Cherenkov technique to detect gamma rays at energies from 85 GeV to 30 TeV. The observatory consists of an array of four large telescopes, each comprising a 12 m diameter optical reflector and an associated camera spanning a field-of-view of 3.5°.

Standard observations with the full four-telescope VERITAS array started in September 2007 and the instrument has been upgraded successively since then. In 2009, one of the telescopes was moved to give a more symmetrical array geometry. The new geometry, combined with a reduced optical point spread function, led to a significant improvement in the point-source sensitivity of VERITAS. The VERITAS upgrade, carried out between 2009 and 2012, led to a lowering of the energy threshold and a further improvement in the sensitivity.

3 VERITAS Sky Survey

The Cygnus region was targeted by the VERITAS Sky Survey, a flagship project that was carried out by VERITAS between 2007 and 2009. The base survey covered a region of 15° × 5° in Galactic longitude and latitude, respectively. The survey encompassed 150 hours of observations at a uniform point-source sensitivity (99% CL) of < 4% of the Crab nebula flux. This sensitivity is a factor of five better than previously done [2].

Follow-up observations were carried out in subsequent seasons. The combination of the base survey and the follow-up data led to the detection of a number of sources plus interesting hints of sources (hotspots), including: 1) an extended source near the shell-type SNR G78.2+2.1 (γ-Cygni), 2) an extended source coinciding with the unidentified VHE gamma-ray source TeV J2032+4130, and 3) extended, and complex, emission in the region of the unidentified Milagro source MGRO J2019+37. The first object represented a new VHE source, named VER J2019+407, that is associated with the γ-Cygni SNR. The second and third objects were known TeV gamma-ray emitters, originally detected by HEGRA [5] and Milagro, respectively. For these two objects, the VERITAS observations represent the most sensitive exposures taken at these energies, and they have led to sharper views and better understanding of the sources. Preliminary results from the VERITAS Sky Survey have been reported previously [6, 7]. This paper summarizes the updated results from these three source regions.

4 VER J2019+407

After the evidence from the VERITAS Sky Survey for a possible new source near the SNR G78.2+2.1 (γ-Cygni), VERITAS took follow-up data in the region in 2009. Based on 21.4 hr of new data, a clear detection of a source was made at a post-trials significance of 7.5 standard deviations (σ) [8]. As shown in Figure 1, the VERITAS source (named VER J2019+407) has moderate extension and is displaced from the location of the gamma-ray pulsar PSR J2021+4026. The source does lie, however, on the northwest rim of the SNR, in a region of enhanced radio emission. GeV gamma-ray emission from the region has been detected by Fermi-LAT; the center of this emission is displaced from the VERITAS source, but its large extent fully encompasses the VHE gamma-ray source. A maximum-likelihood fit to the VERITAS binned counts map yields a fitted extension of $0.23 \pm 0.03(stat)^{+0.04}_{-0.02}(sys)$ degrees and a fitted centroid position for the VHE source of R.A. 20h 20m 04.8s, decl. +40° 45' 36" (J2000).

The differential gamma-ray energy spectrum for VER J2019+407 is determined from a fit to those events within 0.24° of the source centroid. Between 320 GeV and 10 TeV, the spectrum is well fit by a single power law in energy with a differential spectral index of $2.37 \pm 0.14_{stat} \pm 0.20_{sys}$ and a flux normalization at 1 TeV of $1.5 \pm 0.2_{stat} \pm 0.4_{sys} \times 10^{-12}$ photons $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. The integral flux above 320 GeV corresponds to $\sim 3.7\%$ of the Crab nebula flux above that energy. Analysis of data from both ROSAT and ASCA show that the VHE gamma-ray source is coincident with enhanced X-ray emission with the X-ray spectrum fit by a Raymond-Smith thermal plasma model [8]. No evidence was found for significant non-thermal X-ray emission from the region near VER J2019+407.

A variety of scenarios are possible when trying to explain the origin of the VHE gamma-ray emission in the γ-Cygni region. Many pulsar wind nebulae (PWNe) have been detected at very high energies, but in the case of VER J2019+407, the VHE emission is significantly offset from

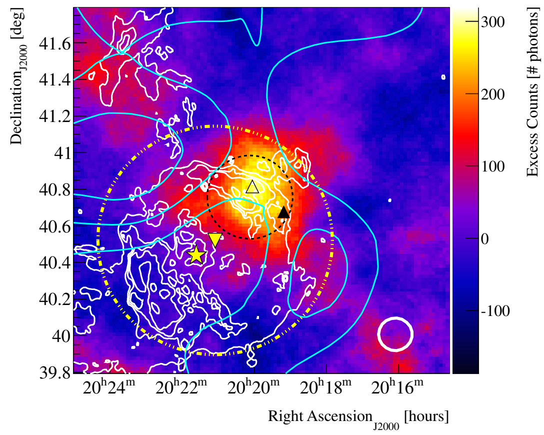

Figure 1: VHE gamma-ray image of VER J2019+407 (color, indicating excess counts) at energies above 320 GeV, overlaid with the 1420 MHz radio contours of the SNR G78.2+2.1. The fitted extent of the VHE source is shown by the black dashed circle. The yellow star gives the position of the pulsar PSR J2021+4026 and the inverted triangle and dashed yellow circle show the fitted centroid and extent of the emission detected by Fermi-LAT above 10 GeV. See [8] for details and references.

the pulsar PSR J2021+4026; the pulsar is not contained within the 99% confidence contour of the VHE source. Conversely, from the morphology of the radio, X-ray and VHE gamma-ray emission, it is more plausible that the VHE emission arises from shock interactions between the ejecta of SNR G78.2+2.1 and the surrounding medium (in particular, a dense H I shell that appears to surround the SNR). For shocks that accelerate electrons to relativistic energies, the VHE gamma rays can result from inverse-Compton scattering of the electrons off ambient radiation fields. Non-thermal X-ray emission is expected from synchrotron radiation of the same electrons, but the limit on this emission from our analysis is not low enough to constrain the possibility of an inverse-Compton origin for the VHE gamma rays.

The VHE gamma-ray emission can also arise from the shock acceleration of hadrons (particularly protons) that interact with target material to produce neutral pions that then decay to gamma rays. A straightforward calculation in the hadronic scenario determines that an average target density of 1.0-5.5 cm^{-3} is required to produce the observed VHE gamma-ray flux; this density is consistent with what we know about the region from other wavebands [8]. In this calculation, estimates are made for the age and distance of the supernova and a correction is made for the fraction of the remnant shell that appears to be producing VHE gamma rays.

5 TeV J2032+4130

As the first unidentified source discovered at VHE gamma-ray energies, as well as the first confirmed extended source, TeV J2032+4130 holds a unique place in the field. Detected first by HEGRA [5], it has also been studied at TeV energies by Whipple [10] and MAGIC [11]. Within errors, the measurements made by the atmospheric Cherenkov telescopes agree on the position of the source and the HEGRA [9] and MAGIC data indicate a source extension of ∼6 arc-minutes. The source was also observed by the Milagro [3] and ARGO-YBJ [12] air shower arrays, with Milagro detecting bright emission from the region that is much larger in extent than seen for TeV J2032+4130. The Milagro source was given the name MGRO J2031+41. In addition to these observations, there has been extensive multiwavelength work to identify the counterpart of the source, but, in spite of all of these efforts, no clear picture of its nature has emerged.

As discussed earlier, VERITAS saw evidence for TeV J2032+4130 from data taken in the VERITAS Sky Survey between 2007 and 2009. Here we discuss new results on the source from a deep exposure of the region using data taken between 2009 and 2012 [13]. This exposure, totalling 48.2 hr, represents the most sensitive study of TeV 2032+4130 yet done at these energies. With these data, the source is clearly detected at a significance level of 8.7σ. A fit to the excess counts map yields a centroid position of R.A. 20h 31m 39.8s, decl. +41° 33' 53" (J2000) and an asymmetric extension with a major axis of 0.16 ± 0.02 degrees, oriented to the north east, and a minor axis of 0.066 ± 0.009 degrees. The VERITAS source is named VER J2032+415. Its position is consistent with previous measurements but VERITAS sees an extension that is asymmetric and is somewhat larger than earlier results. The energy spectrum is well fit by a single power law in energy with a differential spectral index of $2.05 \pm 0.16_{stat} \pm 0.21_{sys}$ and a flux normalization at 1 TeV of $9.3 \pm 1.6_{stat} \pm 2.2_{sys} \times 10^{-13}$ photons TeV^{-1} cm^{-2} s^{-1}. The integral flux above 1 TeV corresponds to $\sim 4.3\%$ of the Crab nebula flux above that energy. There is no evidence for flux variability for the data taken over this three-year period. A careful study was made of the VHE gamma-ray image in three energy ranges, but no evidence was seen of an energy-dependent morphology.

A blind search of the Fermi-LAT data revealed a previously unknown gamma-ray pulsar, PSR J2032+4127, having a pulse period of 142 ms and located approximately 0.2 degrees from the center of VER J2032+415 [14]. To look for unpulsed GeV emission from the region, we carried out an analysis of the four-year data set of Fermi-LAT. Selecting only those photons in an off-pulse window and contained within 0.5° of the pulsar position, we used a binned likelihood analysis to search for nebular emission. No such emission was detected, allowing us to place flux upper limits in three energy bands [13].

The Cygnus X complex, where VER J2032+415 is located, is one of the most active star formation regions in the Galaxy. In Figure 2, images of the source and its surrounding region are shown in different wavebands. The striking feature of this figure is that VER J2032+415 appears to be located in a void in the generally bright diffuse emission at longer wavelengths. The origin of this void is not clear; it could be due to a supernova explosion and subsequent expansion as a supernova remnant or possibly due to stellar winds arising from the Cygnus OB2 association. A remnant shell comensurate with the size of the void has not been identified, but it might be very faint for a relatively old SNR. In this case, the VHE gamma-ray emission could arise from a pulsar wind powered by the Fermi-LAT pulsar PSR J2032+4127 and filling the interior of the SNR. In this scenario, the corresponding X-ray and GeV

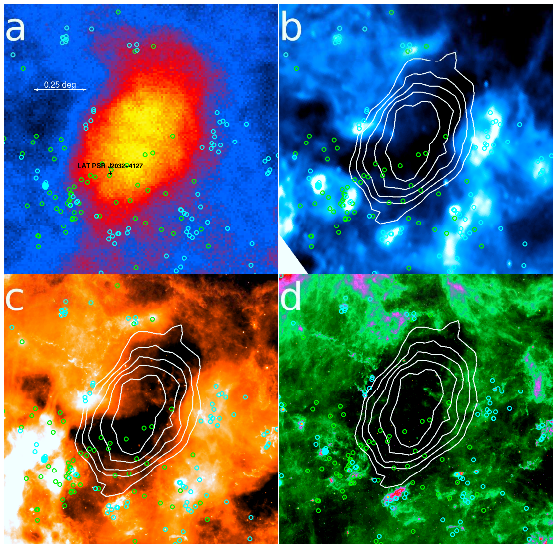

Figure 2: Images of the region around VER J2032+415 in different wavelengths: a) VHE gamma rays; VERITAS significance map showing position of the Fermi-LAT pulsar and Cyg OB2 #5, b) 1.4 GHz from Canadian Galactic Plane Survey, c) 24 μm from Spitzer MIPS, and d) 8 μm from Spitzer GLIMPSE. In images b, c, and d, the contours indicate VERITAS significance from 4 to 8 standard deviations. Green (cyan) circles indicate OB stars (star forming regions). The angular size is shown in image a. See [13] for details and references.

gamma-ray pulsar nebulae must be too faint to be detected. Compared to other known TeV pulsar wind nebula (PWN) sources, the characteristics of VER J2032+415 are not exceptional [13]. Similarly, PSR J2032+4127 is one of the oldest and weakest pulsars seen in association with a VHE gamma-ray PWN, but is still within the population of pulsars from which TeV PWN are detected.

The VERITAS observations of the region are joined by those of the air shower arrays Milagro [15] and ARGO [12]. Their observations resulted a significantly softer spectral index of 3.1 ± 0.2 and 2.8 ± 0.4, respectively, both with increased flux levels, while integrating over larger areas of the sky. ARGO operates at energies similar to those of the imaging Cherenkov telescopes and sees an extension which is roughly similar. However, MILAGRO begins its measurements at 20 TeV and observes a 3.0 ± 0.9 deg spatial extension. At GeV gamma-ray energies the *Fermi*-LAT has reported the existence of a *Cocoon* located in the Cygnus region between the locations of TeV J2032+4130 and the γ-Cygni SNR. In their paper [16], they suggest that this excess is due to a population of freshly accelerated cosmic rays. Reconciling these differing sets of observations may well be the key to understanding this complex and interesting region.

6 MGRO J2019+37 Region

In their survey of the northern hemisphere sky at multi-TeV energies, Milagro discovered three relatively bright sources (i.e. at a significant fraction of the Crab nebula flux): MGRO J1908+06, MGRO J2031+41 (discussed earlier in the context of TeV J2032+4130), and MGRO

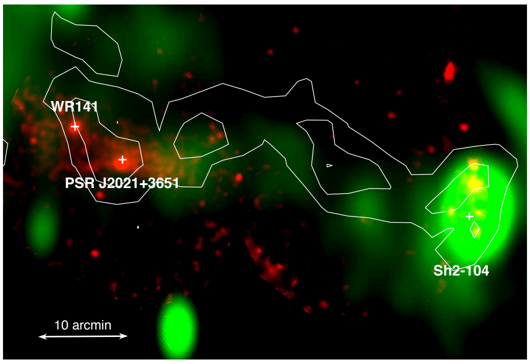

Figure 3: The inner region of MGRO J2019+37 as seen in radio (green) and X-ray (red). The VERITAS emission associated with the source VER J2019+368 is shown as the white contours with significance levels of 5 and 4σ. The positions of the pulsar PSR J2021+3651, the Wolf-Rayet star WR141, and the HII region Sh2-104 are also indicated. See [18] for more details.

J2019+37 in the Cisne region [4]. This third detection yielded a relatively broad ($1.2^\circ \times 0.7^\circ$) feature that was not spatially resolved. The excellent angular resolution of VERITAS enables a sharper view of this VHE bright region of the sky.

Dedicated VERITAS observations of the region took place in Fall 2010, totalling 71 hr. These observations yield a complex sky map in which multiple VHE gamma-ray sources are clearly evident [17]. VERITAS detects broad and extended emission from a region that is largely contained by the error circle of MGRO J2019+37 and separate and fainter emission that is consistent spatially with a point source. These two sources are given the names VER J2019+368 and VER J2016+371 [18].

The statistical significance of VER J2016+371 is 5.7σ (post-trials) and the fitted source centroid is positionally consistent with the SNR CTB 87. The energy spectrum is well fit between 650 GeV and 20 TeV by a single power law in energy with a differential spectral index of $2.3 \pm 0.3_{stat} \pm 0.3_{sys}$ and a flux normalization at 1 TeV of $3.1 \pm 0.9_{stat} \pm 0.6_{sys} \times 10^{-13}$ photons $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. A multiwavelength study [18] of CTB 87 indicates that it is most likely a PWN that is seen in both X-rays and VHE gamma rays. The properties (age, high-energy luminosity, etc.) of CTB 87 place it in line with other PWN detected at TeV gamma-ray energies.

The region encompassing VER J2019+368 is more complex and it is likely that this object is made up of multiple sources that extend approximately one degree across the sky. The VHE energy spectrum is estimated from a circular region of radius 0.5 degs centered on the best fit position of VER J2019+368. The resulting spectrum is well fit between 1 TeV and 30 TeV by a single power law in energy with a hard differential spectral index of $1.75 \pm 0.08_{stat} \pm 0.3_{sys}$ and a flux normalization at 1 TeV of $1.4 \pm 0.1_{stat} \pm 0.3_{sys} \times 10^{-12}$ photons $\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$.

Understanding the origin of the VHE emission in VER J2019+358 is challenging and there are a number of objects in the region that may be connected to this emission, including the energetic pulsar PSR J2021+3651, the Wolf-Rayet star WR141, a transient Integral source IGR J20188+3647, and the HII region Sh2-104. An extensive multiwavelength study of the region has been carried out [18]. Although no unambiguous counterparts to the VHE gamma-ray emission have been identified, the emission tends to follow a ridge of diffuse radio emission going east from SH2-104 to PSR J2021+3651, as shown in Figure 3. It is plausible that a substantial fraction of the VHE emission derives from a PWN powered by PSR J2021+3651, leaving the remaining fraction as yet unexplained.

7 Conclusions

Because of its high star-forming activity and concentration of potential sources, the Cygnus region is perhaps the best location in the northern hemisphere to study processes leading to VHE gamma-ray emission with the goal of understanding the origin of Galactic cosmic rays. VERITAS has made extensive observations in the region, starting with a sky survey between 2007 and 2009 and continuing with dedicated follow-up observations in the following years. The observations have so far yielded a number of significant results, including the discovery of a new source VER J2019+407, more precise measurements of the first unidentified source TeV J2032+4130, and a significantly sharper view of the complex region near MGRO J2019+37. Future work will focus on a comparison of the VHE gamma-ray map from the VERITAS Sky Survey with the associated maps made by the Fermi-LAT (GeV) and Milagro (multi-TeV) instruments.

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