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# The Cygnus Region - a prime target for cosmic ray accelerators

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Regions with prominent star formation activity are of great interest for understanding the properties of cosmic rays. The interactions of cosmic rays with the Galactic interstellar gas and radiation fields lead to the emission of very-high-energy (VHE; E>100 GeV) diffuse gamma radiation. The Cygnus region contains a large number of molecular clouds and massive stars with strong winds, and exhibits a high star-formation rate. Several potential TeV-emitting objects such as supernova remnants, pulsar wind nebulae (PWN), and X-ray binary systems are also seen in this direction. The emitted gamma rays from the Cygnus region bring information about the gas and cosmic ray content on the scale of the whole Cygnus complex. Here we will summarize the latest results on the various sources detected in the Cygnus region with the VHE $\gamma$-ray observatory VERITAS (Very Energetic Radiation Imaging Telescope Array System) located at Mt. Hopkins, AZ, USA.

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## 1. Introduction

Cosmic rays are charged particles which span a wide range of energy up to above $10^{20}$ eV. These particles travel through our Galaxy and are thought to have escaped from astrophysical accelerators which produced them. The Cygnus region is located approximately 1.7 kpc away from the Solar System in the Galactic plane. Since there are three arms of the Milky Way Galaxy in our line of sight towards the direction of the Cygnus region, it is sometimes difficult to determine counterparts to VHE gamma-ray sources. This leads to a rich region for exploration. During the past years, several experiments have undertaken observations of this region. EGRET and *Fermi*-LAT surveyed at GeV energies while HEGRA [1] observed it at TeV energies. The Milagro air shower array [2, 3] measured at multi-TeV energies. In addition, the VERITAS observatory carried out a survey of the Cygnus region from 2007 to 2008 which is discussed in more detail below.

## 2. The VERITAS Instrument

VERITAS is an Imaging Air Cherenkov Telescope experiment that consists of four telescopes, each with an optical reflector with a diameter of 12 m. The telescopes use the stereoscopic approach of imaging and direction reconstruction of extensive air showers [4]. Each camera contains 499 PMTs and spans a field-of-view of 3.5°.

Observations with the four-telescope array started in September 2007. In 2009, one of the telescopes was moved, resulting in a more symmetric array. Together with the reduced optical point spread function this led to a significant improvement in the point-source sensitivity of VERITAS. A camera upgrade with a replacement of all PMTs followed in summer 2012 which lowered the energy threshold and led to an improved sensitivity. The data presented in this proceeding were taken before summer 2012. At the time of observations of the Cygnus region the energy range was between 100 GeV and 30 TeV. From 2007 to 2009, a sensitivity of 1% of the Crab Nebula flux was achieved in approximately 47 hours [5]. Until 2012, this sensitivity could be obtained in 25 hours [6].

## 3. The VERITAS Survey of the Cygnus Region

Between April 2007 and December 2008, VERITAS carried out a survey of the Cygnus region due to its potentially high source-density and therefore probable detection of new sources. In addition, multi-wavelength (MWL) data were already accessible from previous experiments which could aid in identifying new sources in this region. The Cygnus region was studied in the area between $67^\circ < l < 82^\circ$ and $-1^\circ < b < 4^\circ$ [7, 8], where $l$ is the galactic latitude and $b$ is the galactic longitude. The survey data consist of 150 hours of observations. Further, follow-up observations of the region were conducted in the subsequent seasons. The base survey combined with the follow-up observations resulted in the detection of several sources such as an extended source near the supernova remnant SNR G78.2+2.1 ($\gamma$-cygni), an extended source corresponding to the unidentified VHE gamma-ray source TeV J2032+4130, and the extended and complex emission in the region of the Milagro source MGRO J2019+37. An exposure map of the observations of the Cygnus region from 2007 to 2012 is shown in Figure 1. This paper summarizes the observations and results of these three sources.

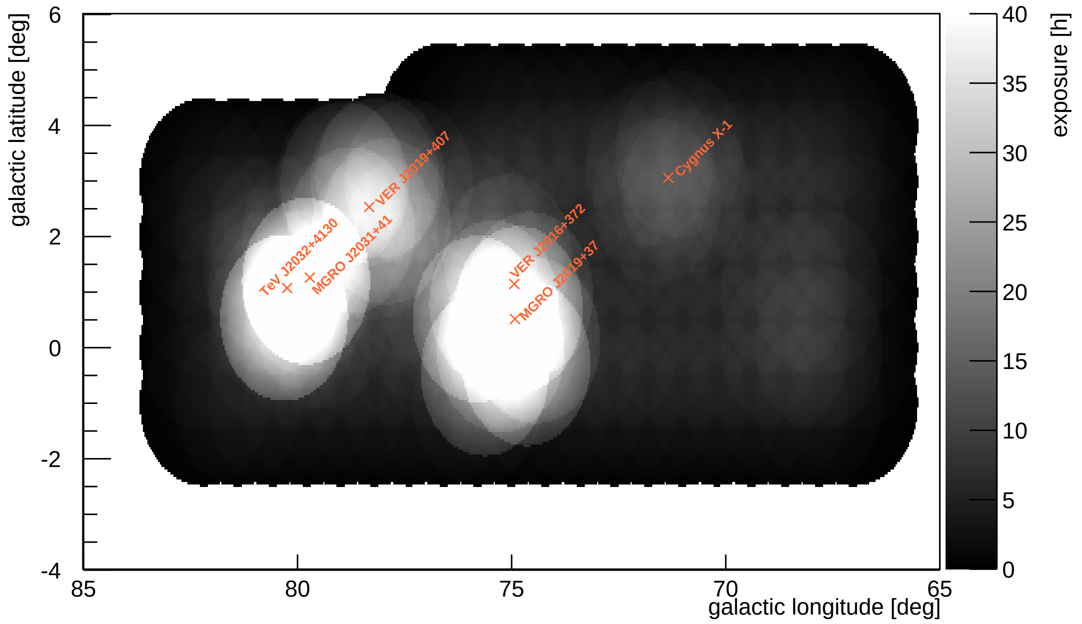


**Figure 1:** Acceptance-corrected exposure map of the base survey, follow-up observations and other additional observations in this field until summer 2012. The color bar is in units of hours with a maximum of 40 hours. The observing time on the brightest spots is around 80 hours.

## 4. VER J2019+407 ($\gamma$-Cygni)

First hints of emission in the vicinity of the supernova remnant SNR G78.2+2.1 were found during the base survey. Follow-up observations of this region were conducted and led to a total observing time of 18.6 hours. The analysis showed a clear signal in the northern rim of the supernova remnant with a post-trial-significance of 7.5 standard deviations ($\sigma$), as shown in Figure 2. This figure also shows the position of PSR J2021+4026 and the centroid emission of the remnant observed by *Fermi*-LAT above 10 GeV. The source extension is fitted to $0.23^\circ \pm 0.03^\circ_{stat}{}^{+0.04^\circ}_{-0.02^\circ sys}$ [9]. The fitted centroid position is $\alpha_{J2000} = 20^h 20^m 4.8^s$, $\delta_{J2000} = +40^\circ 45' 36''$. The spectrum of gamma-ray events within a circular region of radius $0.24^\circ$ around the center is a power law between 320 GeV and 10 TeV with a spectral index of $2.37 \pm 0.14_{stat} \pm 0.20_{sys}$. The integral flux above an energy of 320 GeV is $5.2 \pm 0.8_{stat} \pm 1.4_{sys} \times 10^{-12}$ph cm$^{-2}$s$^{-1}$ which is around 3.7% of the flux of the Crab Nebula above this energy. In addition, MWL studies in the X-ray regime by ROSAT PSPC [10, 11] and ASCA [12] showed that the gamma-ray emission overlaps a region of enhanced X-ray emission which corresponds to the bright emission in the northern rim of the SNR shell of SNR G78.2+2.1.

There are several explanations of the physics behind these observations. Mostly, the features seen in different wavelength regimes can be related to the presence of shocks interacting between the supernova ejecta and the surrounding medium. These shocks are energized by a pulsar, which produces a magnetosphere in which electrons are accelerated. Then, they produce gamma-ray emission in the TeV range via inverse-Compton scattering of electrons. However, interactions of

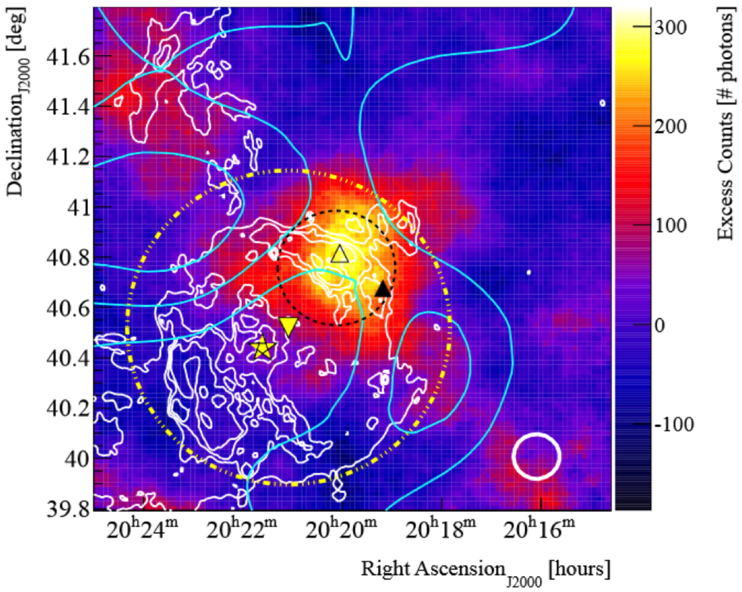


**Figure 2:** VHE $\gamma$-ray excess image of the $\gamma$-Cygni region with the bright emission of VER J2019+407 and its fitted extent (black dashed circle). The white contours show the 1420 MHz radio continuum of the supernova remnant SNR G78.2+2.1. The gamma-ray pulsar PSR J2021+4026 is indicated as a yellow star. The *Fermi*-LAT emission and its extent above 10 GeV are shown by the inverted yellow triangle and the yellow dot-dashed line. For more details and references see [9].

hadrons of accelerated nuclei are also possible. Furthermore, a PWN scenario could cause the emission as well. The PWNe in the TeV regime are typically extended sources belonging to a SNR and they are energized by electrons which are accelerated in the pulsar wind. From the MWL studies, it is more probable that the emission arises from the interaction of the shock of SNR G78.2+2.1 and its surrounding medium.

## 5. TeV J2032+4130

The source TeV J2032+4130 is the first unidentified gamma-ray source at very high energies (above 100 GeV). It was the first source with no counterpart in any other wavelength regime [1]. This source was initially observed by VERITAS during the Cygnus sky survey between 2007 and 2008 with follow-up observations until 2012; these observations resulted in a total of 48.2 hours of data (Figure 3). The analysis led to a significance of 8.7$\sigma$. The position of the centroid is $\alpha_{J2000} = 20^h31^m40^s \pm 65^s$, $\delta_{J2000} = +41^\circ 33' 53'' \pm 37''$. The VERITAS source is called VER J2031+415 [13]. The spectrum can be fitted by a simple power law with index $2.10 \pm 0.14_{stat} \pm 0.21_{sys}$ and the integral flux above 1 TeV corresponds to 4% of the flux of the Crab Nebula above this energy. The energy threshold of this analysis is found to be 520 GeV.

During a blind search, *Fermi*-LAT discovered a previously unknown pulsar PSR J 2032+4127, slightly offset from the center of VER J2031+415. In addition, MWL studies in the region around TeV J2032+4130 were performed by VERITAS, Spitzer and the Canadian Galactic Plane Survey. An image of the source and its surroundings is presented in Figure 3. VER J2031+415 is located in a void of the generally bright emission at radio and infrared wavelengths. There are several

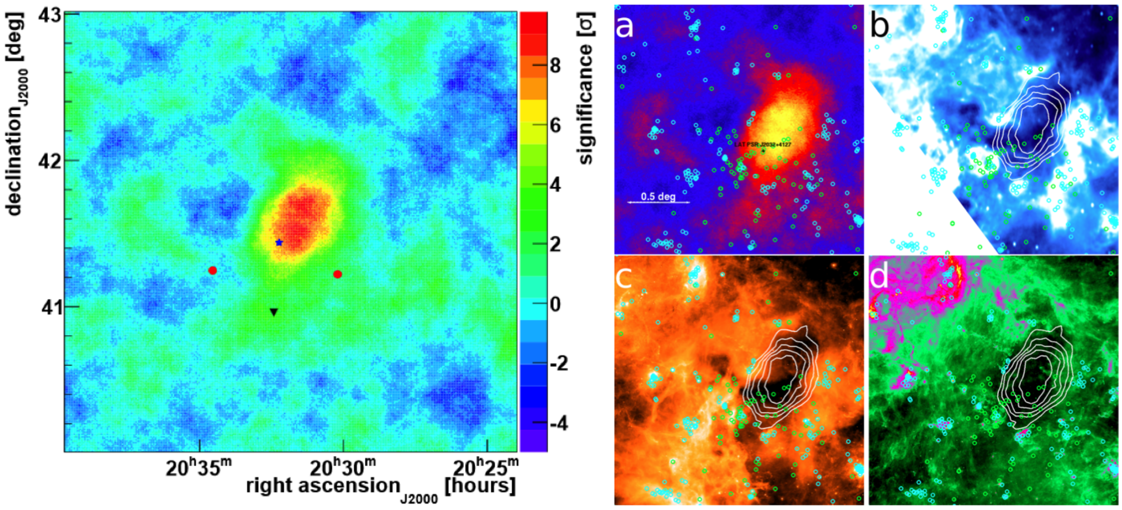


**Figure 3: Left:** Significance map of the $\gamma$-ray emission of VER J2031+415 obtained with VERITAS. The blue star indicates the position of the *Fermi*-LAT pulsar PSR J2032+4217 while the red dots show the shared wobble locations. The black inverted triangle locates Cygnus X-3. **Right:** A MWL image of VER J2031+415 and its vicinity: a) VHE $\gamma$-rays as seen by VERITAS with the marker representing the position of the *Fermi*-LAT PSR J2032+4127; b) 1.4 GHz image from Canadian Galactic Plane Survey; c) 24 $\mu$m image from *Spitzer* MIPS; d) 8 $\mu$m image from *Spitzer* GLIMPSE. The white curves in images b, c and d show the VERITAS significance contours from 4 to 8 standard deviations. The green and cyan dots indicate the star forming regions. For more details and references see [13].

explanations for the origin of this feature. It could be an explosion of a supernova and its expansion as a supernova remnant. Another reason could be the stellar winds arising from the massive star forming region of the Cygnus OB2 association. This is not very favoured as most of the OB stars and star forming regions are located outside of the void. On the other hand, the size of the remnant is comparable with the size of the void. The emission of VHE gamma-rays could result from a pulsar wind powered by PSR J2032+4127. However, the scenario of the VHE emission powered by stellar winds cannot be excluded, although there are significantly fewer massive stars within the void.

## 6. MGRO J2019+37

The extended unidentified source MGRO J2019+37 is the brightest source within the Cygnus-X region first seen by the Milagro experiment. Its flux is about 80% of the Crab Nebula flux at 20 TeV [3]. Milagro was not able to resolve this source, but due to its better angular resolution, VERITAS was able to get a sharper view. Figure 4 shows the excess map of the VHE $\gamma$-ray emission. Two separate sources can be identified. The point-like source VER J2016+371 lies at a position of $\alpha_{J2000} = 20^h16^m2^s \pm 3^s_{stat}$, $\delta_{J2000} = +37^\circ 11' 52'' \pm 42''_{stat}$. Its significance is found to be $5.8\sigma$ and the position of the new source is consistent with the radio SNR CTB 87 [14].

The other emission region is located in the center of the region. It is found to be at $\alpha_{J2000} = 20^h19^m25^s \pm 72^s_{stat}$, $\delta_{J2000} = +36^\circ 48' 14'' \pm 58''_{stat}$ and is called VER J2019+368. The significance is found to be $7.2\sigma$. The origin of VER J2019+368 is difficult to figure out as there are several

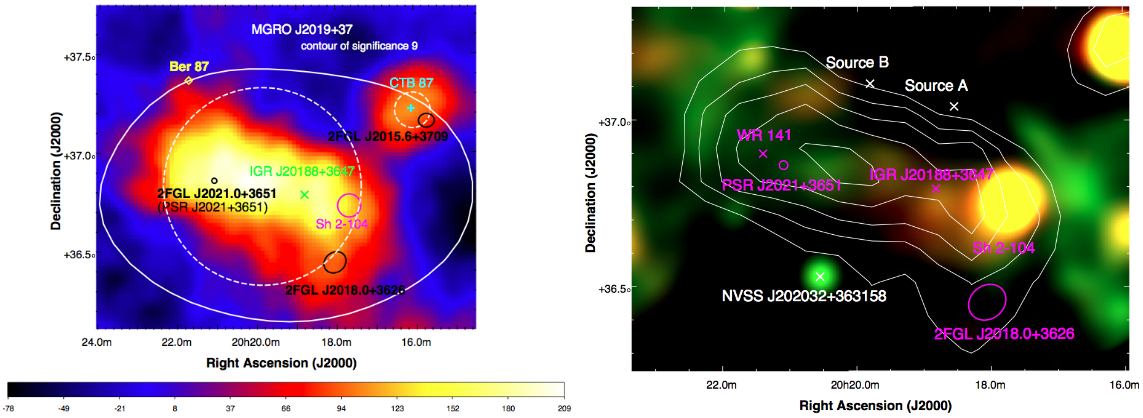


**Figure 4: Left:** Excess map of VHE $\gamma$-rays above 600 GeV of the MGRO J2019+37 region obtained with VERITAS. The color bar indicates the number of excess events. The white dashed circles represent the regions used in the spectral analysis of VER J2016+371 and VER J2019+368. The white solid line indicates the $9\sigma$ significance level of MGRO J2019+37. **Right:** Radio diffuse image of the region of VER J2019+368 obtained with the CGPS 408 GHz in green and the GB6 6 cm in red. The white curves indicate the VERITAS significance contours at 3, 4, 5, 6 and $7\sigma$. Magenta labelled sources are possible counterparts of MGRO J2019+37 if falling inside $3\sigma$ countours. White represents sources outside the $3\sigma$ contours. For more details and references see [15].

objects which may contribute to the emission, such as the pulsar PSR J2021+3651, the Wolf-Rayet star WR 141, the transient X-ray source IGR J20188+3647, the star formation region Sh 2-104 or the unassociated *Fermi*-LAT source 2FGL J2018.0+3626. The main contributor seems to be the pulsar with its PWN as shown in Figure 4. Further follow-up MWL observations will help to determine the origin of VER J2019+368.

## 7. Conclusions and Outlook

Due to the high star-forming activities and concentration of potential VHE sources in the Cygnus region, it is a very suitable region in the northern sky to study VHE gamma-ray emission. VERITAS has published several significant results such as the discovery of VER J2019+407 and significantly better views of the complex sources TeV J2032+4130 and MGRO J2019+37. Currently, there is an ongoing effort to analyze the large data set of the survey and its follow-up observations using updated analysis techniques, as well as an analysis of the *Fermi*-LAT data in this region over five years. Results will motivate additional VHE observaions in the Cygnus region. With the complete analysis of the VERITAS data, we will be able to put constraining limits on the potential TeV emitters. Furthermore, studies of the gamma-ray emission at different energy bands can yield insight into the origin of Galactic cosmic rays.

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