VER J2019+407 and the Cygnus Cocoon

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Abstract: Current gamma-ray observatories have made substantial advances in the study of potential cosmic ray accelerators such as supernova remnants (SNRs), but the study of cosmic rays in flight from their parent accelerators remains a topic of great interest. The Fermi Gamma-ray Space Telescope (FGST) discovered a four square degree region of gamma-ray emission between 3 GeV and 100 GeV. This structure lies between the Cygnus OB2 association and the \( \gamma \)-Cygni SNR, which is bright in gamma rays above 10 GeV. The atmospheric Cherenkov observatory VERITAS also sees VHE (\( > 100 \) GeV) gamma-ray emission from the direction \( \gamma \)-Cygni (VER J2019+407). We discuss the relationship of VER J2019+407 to both the \( \gamma \)-Cygni SNR and the cocoon. Toy model simulations are used to evaluate prospects for detecting the cocoon at very high energies with VERITAS, as well as ways in which cocoon emission at these energies could impact measurements of the morphology and spectrum of VER J2019+407.

Keywords: Cygnus cocoon, Cygnus OB2, gamma-Cygni, VERITAS, VER J2019+407.

1 Introduction

The cosmic rays that pervade our galaxy are thought to have escaped from astrophysical accelerators that accelerate them, such as supernova remnants (SNRs). Direct observations of cosmic rays provide little information as to their origin, since the paths of cosmic rays are distorted by interstellar magnetic fields. However, cosmic-ray accelerators may be mapped and studied indirectly through high energy (300 MeV - 100 GeV) and very high energy (100 GeV - 30 TeV) gamma-ray observations. Particles still trapped within these accelerators are expected to produce gamma-ray emission through a number of mechanisms. Accelerated electrons may produce gamma-ray emission through synchrotron radiation and inverse Compton (IC), while interactions of accelerated protons and heavier nuclei with the interstellar medium may produce gamma rays through neutral pion decay. Cosmic rays recently escaped from their parent accelerators may also produce recognizable signatures of diffuse gamma-ray emission.

2 Fermi-LAT Observations of the Cygnus Region

Recent observations with the Large Area Telescope (LAT) on the Fermi Gamma-ray Space Telescope have revealed a region of highly extended gamma-ray emission \( \Omega \), best characterized by a Gaussian with \( \sigma=2.0 \pm 0.2 \) and an energy (300 MeV - 100 GeV) and very high energy (100 GeV - 30 TeV) gamma-ray characteristics. The fitted source spectrum follows a differential power law

\[
\frac{dN}{dE} = N_0 \times \left( \frac{E}{\text{TeV}} \right)^{-\Gamma}.
\]

with flux normalization \( N_0 = 1.5 \pm 0.2_{\text{stat}} \pm 0.4_{\text{sys}} \times 10^{-12} \) TeV\(^{-1}\)cm\(^{-2}\)s\(^{-1}\) and photon index \( \Gamma = 2.37 \pm 0.14_{\text{stat}} \pm 0.2_{\text{sys}} \).

Alui et al. (2013) consider the possibility that the gamma-ray emission from VER J2019+407 is produced by either
hadronic interactions of accelerated nuclei with ambient gas or inverse Compton (IC) scattering of ambient light by accelerated electrons. They calculate that a density of 1.0-5.5 cm\(^{-3}\) is required to produce the gamma-ray flux above 320 GeV if the emission is hadronic in nature and note this is consistent with estimates of nearby densities obtained from optical observations. Due to the lack of non-thermal X-ray emission near VER J2019+407, Aliu et al. (2013) do not favor an IC origin to the source, but cannot rule out leptonic emission at this time.

VERITAS has not detected evidence of the cocoon itself. This does not necessarily imply that gamma-ray emission above 100 GeV is not present since the methods of background estimation used up to this point are not suited to detection of such largely extended sources.

To demonstrate this we can consider one method for background estimation known as the Ring Background method where the background is measured by integrating the number of counts within an annulus centered at the test location. The normalization of the integrated background is corrected for the radial acceptance of the camera. Consider two observations of the cocoon, one centered on the source, and one offset. In the former scenario it is easy to see that for most choices of annulus size, the estimated background counts will be nearly identical to the counts in the source region near the center of the field of view, since the background region still overlaps the expected emission region.

The later scenario would result in a less gamma-ray-contaminated field of view allowing for the choice of more sensible background regions, but the overall exposure to the cocoon is subsequently reduced. This is similar to the above observations of VER J2019+407 by Aliu et al. (2013) which overlap with the cocoon region. Since they do not include the cocoon when modeling this region it is possible that gamma-ray leakage from the cocoon could impact the background estimation for its detection and spectrum.

5 VERITAS Prospects in the Cocoon Region

We propose an alternative method for analyzing VERITAS data in the cocoon region, a maximum likelihood method similar to that used for Fermi source detection. However, in addition to modeling contributions of compact and diffuse gamma-ray sources, a VERITAS likelihood would also require modeling of the irreducible isotropic cosmic ray background. The fit is unbinned in three dimensions—two spatial coordinates and a gamma-hadron discrimination parameter known as mean-scaled-width (MSW) — and is performed simultaneously in three coarse bins in energy (100 - 500 GeV, 500 GeV - 1 TeV, and >1 TeV). These specific energy bins were chosen to accommodate differences in the telescope response at threshold, moderate, and high energies.

Maximum likelihood estimation would then be used to evaluate the significance of a source at a grid of reasonably chosen locations in the field of view to produce a significance map. This is done by calculating a likelihood value for a purely cosmic ray background model (\(L_{\text{null}}\)) and for a model which includes our gamma-ray source model as well as a purely background model (\(L_{\text{test}}\)). These two likelihood values represent the likelihood our data originates from the associated model. A test statistic (TS) can then be computed via

\[
TS = -2 \cdot \log \left( \frac{L_{\text{null}}}{L_{\text{test}}} \right),
\]

We also generate toy Monte Carlo simulations representing real data which can be used to evaluate how this TS value relates to true source significance. This is covered more in section 5.3.

In the case of point sources or slightly extended gamma-ray sources the spatial models for gamma-ray and cosmic ray emission are quite distinct from each other (since cosmic rays are distributed across the whole field of view, only modulated by variations in sensitivity over the camera). In this case the spatial dimensions are sufficient to allow for a good source detection. For highly extended sources (\(\sigma > 1.0^{\circ}\)) the spatial model for gamma-rays differs only slightly from the cosmic ray spatial model. A maximum likelihood analysis based only on spatial information will therefore be insensitive to sources on this scale. In order to increase the sensitivity to highly extended gamma-ray sources we also fit in mean-scaled-width (MSW).

The models used in the fit can also be used to produce toy Monte Carlo simulations of VERITAS observations in order to test the ability of VERITAS to detect emission from the cocoon region. As mentioned above, the actual fit is performed simultaneously in three bins in energy. This allows us to accommodate the fact that key parameters of these models, such as gamma-ray PSF and cosmic ray background distributions, in both space and MSW, are energy-dependent.

Unless otherwise stated, standard cuts have been applied to all data used in the following discussion (mean-scaled-length <1.3, size >4000dc, image centroid distance <1.43, number of telescopes used in position reconstruction \(\geq 3\)).
5.1 Spatial Models

The VERITAS field of view is sufficiently small at 3.5° that any intrinsic fluctuations in the cosmic ray background is neglected for an individual pointing. However, the response of the instrument is not uniform across the field of view showing a higher acceptance near the center of the camera while dropping off towards the edge. To model this radial acceptance curve we make use of data containing no detectable gamma-ray component and sum the number of observed events within multiple annuli around the camera center. Each bin is then corrected for the area of the annulus, the histogram fit with a polynomial, and the resulting curve extrapolated into two dimensions (assuming azimuthal symmetry) to produce a spatial cosmic ray model.

In order to model the instrument response to gamma-rays an uncontaminated sample of gamma-rays was needed. Use was made of simulations assuming a point source observed by the VERITAS detector and processed in the same way as VERITAS data. The resulting distribution was then fit with a Gaussian obtaining a sigma between 0.05-0.09 depending on the energy range of the fit. It should be noted that a more rigorous treatment of the gamma-ray distribution will consider certain detector specific properties such as energy resolution and effective area as outlined by Mattox et al. [11]. A Gaussian is, however, a good approximation for our proof of principle study. For an extended source this gamma-ray point source model is then convolved with the expected source extension model, which for the Cygnus cocoon is a Gaussian with σ=r.2.0°.

To remove edge effects in these models, events with a reconstructed position greater than 1.7° from the camera center are not used in the fits. As a result, both cosmic ray and gamma-ray spatial distributions are modeled to an angular distance of 1.7° from the center of the field of view.

5.2 Mean-Scaled-Width Models

MSW is a parameter which relates the average image width of an event as observed by each VERITAS telescope to the expected image width from simulations [8]. The distribution of MSW is narrowly peaked around 1 for gamma-ray events.

The distribution for cosmic ray events is much broader and peaks between 1.5-2.0. The cosmic ray distribution is dependent on parameters such as radial offset from the camera center and energy, however for MSW ≤ 1.5 the shape is sufficiently uncorrelated that we can neglect these effects. As a result we confine our MSW models to the range 0.05-1.5 (see figure [2]). It is important to note that while the spatial models and MSW models are correlated at large values of MSW, for the cuts outlined the correlations are small and may be neglected. As a result, we may simply multiply the spatial and MSW pdfs and our full input model in spatial (x,y) and MSW (w) is

\[ F(x,y,w) = N \cdot [ f \cdot S_{\text{src}}(x,y) \cdot MSW_{\text{src}}(w) + (1-f) \cdot S_{\text{bkgd}}(x,y) \cdot MSW_{\text{bkgd}}(w) ] \]

where \( S_{\text{src,bkgd}} \) represents the spatial models for the source (gamma-rays) or background (cosmic rays) respectively, and \( MSW_{\text{src,bkgd}} \) represents the associated MSW models. \( N \) is the total number of observed events, and \( f \) is the fraction of the total number of events accounted for by the signal component. These two parameters are determined in our likelihood fits for each energy bin, however in the above expression and the example to follow we only consider the energy range 500 GeV - 1 TeV. This is a simplification relative to the full fit where these two parameters would be replace by spectral parameters such as flux normalization and spectral index and fit across the full energy range of the instrument.

5.3 Toy Monte Carlo Data Generation

The resulting cosmic ray and gamma-ray models are combined to form the expected emission model in the cocoon region. Using a Monte Carlo technique and these idealized models, a toy Monte Carlo simulation of an actual VERITAS observation is produced. These simulated observations can then be processed normally through standard or new techniques to investigate the ability of VERITAS to observe the Cygnus cocoon and surrounding region.

As a test of our models, toy Monte Carlo simulating approximately 20 hrs of VERITAS observations of a 2° extended emission region similar to the cocoon were generated and fit in a single bin of energy (0.5 - 1 TeV). An estimate on the expected excess signal events was obtained by integrating the cocoon spectrum obtained by Ackermann et al. [6] in this energy range. The result was then compared to the Crab nebula flux in this energy range and the ratio of the two fluxes multiplied by the best fit \( f_{0.5-1\text{ TeV}} \) to real Crab Nebula observations. Using the above MSW and spatial cuts on the toy simulations resulted in an estimated gamma-ray excess of 1.8 min⁻¹ across the entire field of view (within a typical RBM source integration window of radius 0.13° this would correspond to an excess of 0.011 min⁻¹). Fitting only the spatial model (without MSW) to the generated data results in no significant detection. Including the MSW dimension in our fits results in a significance of 27.2σ. Both models use the same 2° Gaussian model that was used for the generation of the data and calculate the significance by taking the square root of the TS value from eqn. 2. The resulting excess map integrated over the full 20 hour simulated observation can be viewed in figure [4].

6 Conclusions

The Cygnus cocoon observed by Fermi presents a rare opportunity to study the origin of Galactic cosmic rays. An intense study of this region could reveal insight as to the nature of cosmic rays still within their parent accelerators, including their composition and energy distributions relative to those still trapped. Understanding the spectrum and
morphology of the cocoon at energies above 100 GeV could prove essential to understanding both the population of cosmic rays within the cocoon and the relationship of the cocoon to nearby potential cosmic ray accelerators such as VER J2019+407. While the toy Monte Carlo study discussed here is both idealized and highly preliminary, it indicates that a three-dimensional maximum likelihood method shows promise for detecting sources such as the cocoon that have previously been thought inaccessible (or nearly inaccessible) to small field-of-view gamma-ray observatories.

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References
[1] Abdo, A. A., Ackermann, M., Ajello, M., et al. 2009, ApJS, 183, 46
[2] Abdo, A. A., et al. 2010, ApJS, 188, 405
[3] Aharonian, F. et al., A&A 393 pL37-L40 (2002)
[4] Aharonian, F., Akhperjanian, A. G., Aye, K.-M., et al. 2005, A&A, 430, 865
[5] Aliu, E., Archambault, S., et al. 2013, ApJ, 770, 93
[6] Ackermann, M., Ajello, M., Allafort, A., et al. 2011, Sci, 334, 1103
[7] Gosachinskij, I. V. 2001, AstL, 27, 233
[8] Hillas, A. 1985, Proc. of the 19th ICRC (La Jolla), 3, 445
[9] Holder, J., Acciari, V.A., Aliu, E., et al. 2008, in AIP Conf. Proc. 1085, Proc. 4th Int. Meeting on High Energy Gamma-Ray Astronomy, ed. F.A. Aharonian, W. Hofmann, & F. Rieger (Melvill, NY: AIP), 657
[10] Lande, J., Ackermann, M., Allafort, A., et al. 2012, ApJ, 756, 5
[11] Mattox, J. R., et al. 1996, ApJ, 461, 396
[12] Trepl, L., et al. 2010, MNRAS, 405, 1339-1348