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A VERITAS Search for VHE γ-Ray Point Sources Near Selected MILAGRO Target Regions

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Abstract: We use the VERITAS telescopes to perform follow-up observations of potential new sources of TeV γ-rays identified by the MILAGRO (MGRO) particle detector array. Three potential MGRO sources were observed by VERITAS during fall 2006 and early 2007. Initial analysis of these observations does not reveal the presence of any strong point source of VHE γ-rays associated with these observation regions. We discuss the extrapolation of the higher energy (Eγ >20 TeV), spatially extended (∅ ~ 1-3°) MGRO source fluxes to the 2-D VERITAS point source analysis.

Introduction

Recent northern-sky surveys in TeV γ-rays by the MILAGRO (MGRO) observatory have identified several new potential VHE γ-ray source regions in the Cygnus Arm region[1] as well as at several other locations along the Galactic plane [2]. In the latest analysis [2], these potential VHE sources are observed with γ-ray energies Eγ > 20 TeV. The majority of these potential sources appear to be spatially extended, with typical angular extent ∅~1-3°. It is interesting to note that several of the MGRO sources are positionally coincident with potential source regions identified by the Tibet AS-γ Observatory[3], including MGRO J2031+41[4] and MGRO J1908+06[4,5].

We report here on observations made by VERITAS[6,7,8] during the 2006-2007 observing season on selected sky regions near the potential MGRO source regions. While our analysis procedures for detecting extended sources are still under development, we feel it is of immediate interest to report here on our search for point-like sources of VHE γ-rays which may contribute to the TeV γ-ray fluxes reported by MILAGRO.

Source Selection

Potential sources from the MGRO Galactic plane survey [2] were selected for follow-up observation by VERITAS based upon their visibility and proximity to other known objects. In this paper, we describe observations on three candidate sources: MGRO J2019+37, C3 and C4. Observation on other MGRO candidate sources, scheduled for Spring/Summer 2007, will not be presented here.

MGRO J2019+37 is described in the MGRO survey paper as the strongest of the unidentified MGRO survey sources, it has a flux of nearly 800 mCrab (Eγ > 20 TeV). The MGRO source has a quoted angular extent of 1.1°±0.5°, implying a slightly extended emission region. The source region is positionally coincident with the EGRET source 3E J2016+3657, the young pulsar PSR J2021+3657, and the pulsar wind nebula (PWN) G75.2+0.1[1]. Assuming a source spectral index of -2.2, MGRO J2019+37 should have a flux at ~400 GeV energies of about 150 mCrab. If MGRO 2019 +37 is a constant point source VHE emitter, at this flux level it should be easily detected by VERITAS within a few hours of exposure.

MGRO source C3 has a quoted flux of 630 mCrab (Eγ > 20 TeV) with an angular extent of

2.8°±0.8°. C3 is positionally coincident with Geminga, the brightest northern sky source in the 3EG catalog. The observed presence of a PWN [9] related to Geminga makes this an interesting potential VHE γ-ray source.

MGRO source C4 has a quoted flux of 360 mCrab ($E\gamma > 20$ TeV) with an angular extent of 3.4°±1.7°, giving it the lowest surface brightness in the MGRO catalog. C4 is positionally coincident with the extended (1.1°× 0.8°), hard spectrum (α=-2.24) EGRET source 3EG J2227 +6112,. C4 is also nearby the 51.5 msec radio pulsar PSR J2229+6114, which is thought to be the energy source of SNR G106.6+2.9 and the Boomerang PWN[10]. The Crab, G75.2+0.1, and Boomerang have been predicted to be the three brightest PWN in the Northern sky [11], making C4 an interesting target for VERITAS observations. It should be noted that both C3 and C4 have < 3σ post trail significance.

VERITAS Observations

Observations of the selected MGRO source regions were carried out by the VERITAS γ-ray observatory. VERITAS is an array of four 12-m diameter imaging atmospheric Cherenkov telescopes located at the F.L Whipple Observatory near Amado, AZ. Each telescope uses a 499-pixel camera with 3.5° field of view to record images of Cherenkov light emitted by γ-ray and cosmic-ray extensive air showers with energies above ~100 GeV. γ- rays are selected on the basis of an imaging analysis using Hillas parameters[12]. Details regarding telescope status and performance can be found in several accompanying papers[7,8].

Exposures and Pointing

VERITAS observed the three potential MGRO source regions using a combination of two-telescope and three-telescope observations. In general, the VERITAS exposures were serendipitous observations: the MGRO source coordinates were in the same field of view of a potential point source of interest (i.e. PSR J2229+6114 or PSR J2021+3651), but the VERITAS exposures were not centered upon the MGRO source coordinates. This type of approach is considered reasonable, given the large error radius associated with the MGRO source coordinates (typically 0.25°-0.5°).

Source Observations

During fall 2006 observations, the full VERITAS array was still under construction. The observations of MGRO2019+37 and C4 were therefore made using only two VERITAS telescopes. Early in 2007, an additional VERITAS telescope became operational. Observations of C3 were therefore able to be made using three VERITAS telescopes.

The VERITAS observations were all taken in `Wobble mode', tracking a main target direction with a 0.5° offset (in the East, West, North, or South direction) from the camera pointing center. The background cosmic-ray flux in the observation region was estimated by using averaged data from the offset regions which are symmetrically distributed about the camera pointing center, distributed away from the potential source region. Table 1 summarizes the source observations. The offset of the MGRO source position from the VERITAS target pointing, the observation dates, the number of observation hours, and number of telescopes involved in the observations are listed.

Data Analysis

Table 1: Summary of VERITAS Observations of selected MGRO sources.

Target Name	Dates mm/dd/yy	Exposure (hrs)	Offset (deg)	# of Telescopes
MGRO J2019+37	11/11/06-11/23/06	9.9	0.24°	2
C3	02/16/07-03/12/07	2.0	0.59°	3
C4	11/10/06-12/13/06	12.8	1.27°	2

The data from the three VERITAS source observations were analyzed using independent analysis packages [13,14] and the different analyses yielded consistent results. The background rejection cuts were optimized for detection of a point-like source with luminosity 10% of the Crab nebula. The source region is defined as a circle with a radius R_0 about a potential source direction, and the background cosmic ray flux in the source region is estimated using three `mirror' regions. These regions have the same area and angular distance from the camera center as the source region, but are rotationally distributed about the camera center from the potential source region (the 'reflected background method'). The statistical significance is estimated using the method of Li and Ma [15].

This analysis was applied to 2 telescope data from the Crab Nebula during September and November 2006 using R_0 =0.15° . For 2 telescope data one also requires a minimum opening angle of 8.5° between the major axes of the shower measured by the two independent telescopes. The analysis resulted in an excess of 2.8γ/min toward the Crab Nebula. When applied to 3 telescope data on the Crab Nebula taken during Feb 2007 (with no minimum opening angle cuts), this analysis resulted in an excess of 5.9γ/min with a background rate of 0.75 event/min . In this preliminary paper, we estimate the flux upper limit with respect to the Crab Nebula using the method of Helene [16].

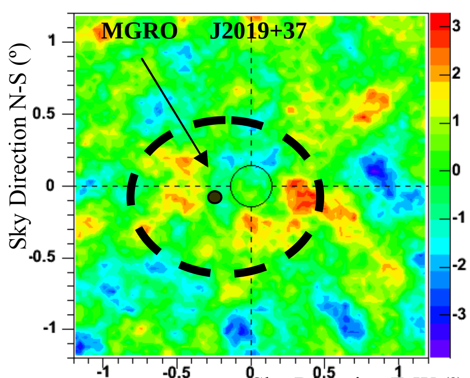

Figure 1: 2-D sky-plot of statistical significance of excess for MGRO J2019+37 region. The color scale is the excess of count rate over background in σ. The extent of MGRO J2021+37 is enclosed by the dashed line

Results

Figure 1 shows the 2-D sky plot of significance for the VERITAS observation of the MGRO J2019+37 region. The plot also shows the reported location and extent of the MGRO emission region. Within the MGRO J2019+37 source extent we find no statistically compelling point source candidate. The flux limit for a point source at the center of this field of view is approximant source $F_\gamma <$ 30 mCrab (99% c.l.).

Figure 2 shows the 2-D significance sky-plot for the VERITAS observation of the MGRO C3 region. The plot also shows the reported location and extent of the C3 emission region. The extent of the C3 emission region is large compared to the angular extent of this analysis; within this emission region we find no statistically compelling point source candidate. The flux limit for a point source at the center of this field of view is $F_\gamma <$ 41 mCrab (99% c.l.).

Figure 3 shows the 2-D significance sky-plot for the VERITAS observation of the MGRO C4 region. We find no statistically compelling evidence (point-source significance > 3 σ) for a point source of VHE γ-rays in this observation. The flux limit for a point source at the center of this field of view is $F_\gamma <$ 30 mCrab (99% c.l.).

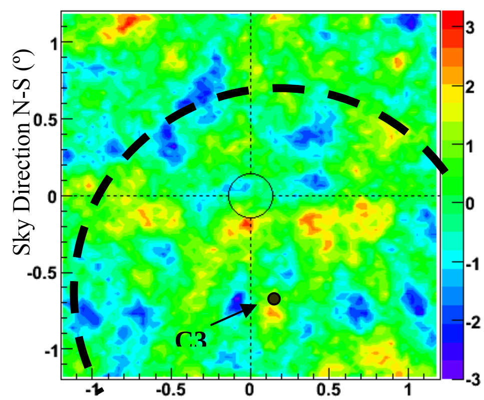

Figure 2: 2-D sky-plot of statistical significance of excess for C3 region. The color scale is the excess in count rate over background in σ. The extent of C3 is enclosed by the dashed line.

Discussion and Conclusions

If the three MGRO sources were due to point source of VHE γ-rays with Crab-like spectra at the center of the field of view, the VERITAS point source flux limits (typically $F_\gamma <$ 40 mCrab) are inconsistent with the reported MGRO source fluxes (typically F_γ > 400 mCrab, $E_\gamma >$ 20 TeV). Our results might imply the MGRO sources have spectral indices which are substantially harder than the Crab (α~-2.55). A spectral index of α~-2.2 would give MGRO source fluxes a factor of ~5 larger fraction of the Crab flux for E_γ >20 TeV than at VERITAS energies (E_γ ~350 GeV), thereby reducing the inconsistencies between the

MGRO observations and these observations. It should be noted that hard-spectrum Galactic plane VHE sources have been reported by the HESS collaboration(α~-2.32)[17].

The location of a potential point source within the VERITAS observation field of view will also affect the observed flux limits. For example, at an offset of 1° from the camera center, the sensitivity of VERITAS [18] to a point γ-ray source is reduced by approximately 50%. The above VERITAS flux limits should therefore be multiplied by a factor between 1-2, depending upon the offset between the potential point source region and the camera center.

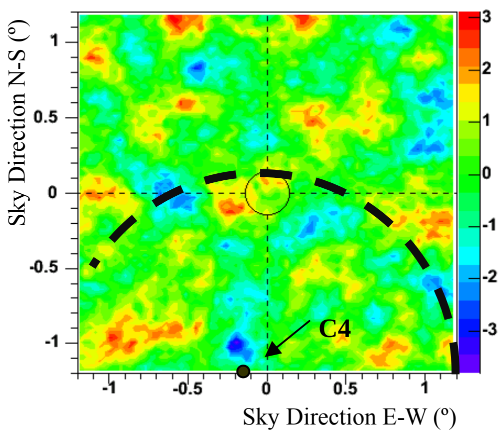

Figure 3: 2-D sky-plot of statistical significance of excess for C4 region. The color scale is the excess in count rate over background inσ. The extent of C4 is enclosed by the dashed line.

Finally, the diffuse extent of a γ-ray source also affects the ability of VERITAS to detect the angularly extended emission [19]. The combination of the uncertainty in the MGRO source locations, energy spectra, and diffuse extent makes it premature for VERITAS to quote an upper flux limits for MGRO sources over the presented 2-D fields of view. At the ICRC, we will provide a more comprehensive approach to estimating these upper limits.

In summary, these VERITAS point source flux limits suggest that the three MGRO sources may have a hard energy spectrum and/or diffuse extent. The VERITAS upper limits also could be consistent with significant time-variability of one or more of the MGRO sources.

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