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# Detection of Diffuse Gamma-Ray Emission from the Cygnus Region with the Milagro Gamma-Ray Observatory

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The Cygnus region is the the brightest source of High Energy gamma rays in the northern sky at energies between 30 MeV and 100 GeV as reported by EGRET[1]. High energy gamma-ray emission from this region is complex and is likely due to the combination of both diffuse and point sources. A large contribution to the VHE emission must come from cosmic rays interacting with the relatively dense matter in the region and amplified by the observation angle, tangent to a Galactic spiral arm. The HEGRA experiment has detected an unidentified TeV point source in in the Cygnus Region with flux 30 mCrab[2]. We report the detection of diffuse TeV gamma-ray emission from the Cygnus region using 4 years of data from the Milagro Gamma-Ray Observatory. The significance of the detection is 6.7 sigma and has a flux above 2 TeV of 1.55 times the Crab. The emssion region is ≈5 degrees across, much larger than the angular resolution of the Milagro detector, which permits the imaging of this diffuse source.

Milagro is a unique VHE gamma-ray observatory capable of continuously monitoring the overhead sky. The directions of gamma rays hitting the atmosphere are reconstructed through the detection of air-shower particles that reach the ground level. The shower particles are detected with a 60m $\times$ 80m pond of purified water instrumented with an array of photomultiplier tubes arranged into two layers, the "air-shower" layer and the "muon" layer. The pond is located in the center of a sparse 200m x 200m array of 175 water Cherenkov "outrigger" tanks. The air-shower layer is situated at a depth of 1.4m below the surface of the pond. The shallow depth allows the accurate measurement of shower particle arrival times used for direction reconstruction and triggering. The angular resolution for gamma-ray induced air-showers is ≈0.75° without the outrigger array and was recently improved to ≈0.45° when the outriggers were added to the reconstruction. The muon layer is located 5m below the water's surface. The greater depth is used to detect the presence of penetrating muons and hadrons. Simple cuts have been developed to distinguish between gamma-ray induced and hadron induced air-showers using the pattern of hits in the bottom layer [3]. The median energy of gamma rays detected from a Crab-like spectrum is ≈ 3.5 TeV.

The Milagro collaboration has developed a standard set of data cuts which this analysis uses. The cuts were optimized through studies of the detector simulation and confirmed through observation of the Crab Nebula [3] and Markarian 421[4]. Two event selection cuts are applied to the data. Events are retained with greater than or equal to 20 PMT hits utilized by the shower angle fitter ($NFIT \geq 20$) and the "compactness" parameter (C) greater than 2.5. The $NFIT$ cut preserves about 80% of the data, only removing events that were poorly reconstructed. The compactness cut is used to separate gamma-like events from hadron-like background events. About 8% of the hadronic shower induced background data pass the compactness cut. This cut has been determined from simulations to have an efficiency of ≈50% for gamma rays. Application of this cut increases the sensitivity of Milagro by a factor of $\approx 1.6 (= \frac{0.5}{\sqrt{0.08}})$. The efficacy of this cut has been verified through study of Crab data. The excess at each position in the celestial sky is computed by counting the number events from that sky position and subtracting the estimated background. For a given point the background is computed from data collected at the same local detector coordinates $(\theta, \phi)$, but at a different time, so that the celestial angles of the background event sample do not overlap with the source position under consideration. The method of Li and Ma[5] is used to compute the probability of the observed excess or deficit.

The optimal square bin size for detection of a point gamma-ray source with Milagro is 2.1° on a side corresponding to a Gaussian angular resolution of ≈0.75°. The instrument's wide field allows for the "blind" search of the entire Northern sky for gamma-ray sources. The Milagro collaboration has reported on the results of a blind search for gamma-ray point sources [6]. By expanding the bin size, we can search our data for sources of diffuse gamma ray's with angular size greater than or equal to the instruments angular resolution. In this generalized "all-sky" analysis, the Milagro sky maps are scanned using a range of bin sizes from 2.1° to 5.9° in steps of 0.2°. In total, 20 separate searches are performed on the same maps. For each bin size, points with probability $>5\sigma$ are recorded for further study. The separate maps are highly correlates, so the number of trials is computed using Monte Carlo simulations of the map analysis process.

Data collected during the period from 20 July 2000 to 5 May 2005 are used in this analysis. In total, 1595 days of on-time data were included. Sources are only observable as they transit through the Milagro FOV, so a day of data represents approximately 4-6 hours of exposure for any given northern hemisphere source. The events were selected using the Milagro standard cuts ($NFIT \geq 20, > 2.5$) and placed in a sky map. A map containing the estimated background at each position in the sky is produced using the Milagro standard method. The significance at each point in the northern sky from $0° < \delta < 70°$ for each of the 20 separate searches.

A map showing the significance for the position of the sky containing the positive longitude arm of the Galactic plane is shown in figure 1. Note that the exposure to the sky varies as a function of declination, peaking at $\delta \approx 35°$, corresponding to the latitude of the Milagro detector. In the map derived from the 5.9° bin size, a diffuse gamma-ray source is found coincident with the Cygnus region consistent with the EGRET position. A $6.7\sigma$ excess is observed at this location. The excess is broad and inconsistent with a single point source hypothesis. The position of the bin center containing the highest significance is (RA=20h22m, DEC=39.4°). A broad region containing bin centers which yield more than $5\sigma$ extend over a large region consistent with with the observed broad maximum observed by EGRET centered at (RA=20h32m, DEC=41.0°). An ensemble of simulated sky maps was generated to compute the probability of observing an excess as improbable as the observed $6.7\sigma$ from any position in the Northern sky with any of the 20 bin sizes searched. The probability of such an excess occurring as result of a statistical fluctuation is $1.0 \times 10^{-5}$.

Figure 2 shows the distribution of event excess observed in the Cygnus region. Instead of significance, the density of the event excess is plotted. The positions of the events in this map have been convolved with the Milagro detector's point spread function (PSF) overlaid on the plot is the 1420MHz radio map which traces out the Galactic neutral Hydrogen distribution. If the observed diffuse emission is due to cosmic-ray interactions with matter, the emission should be spatially correlated with the the diffuse matter density. We observe that the maximum VHE excess occurs at roughly the same position as the maximum of the radio map, RA≈20h20m, DEC≈40°. Further correlation studies are beyond the scope of this analysis and may require a higher significance detection.

The spectrum of the diffuse emission from the Cygnus region is difficult to measure, both because the source is observed with a significance near the detection threshold and because of the inherent difficulty that extended air-shower detectors have in measuring the primary energy of detected gamma rays. Fluctuations in the depth of the first interaction of a VHE gamma ray in the atmosphere can lead to large variation in the amount of EM energy reaching the observation level. We can however distinguish between a hard and a soft spectrum by measuring the signal strength for both the standard cuts and a second analysis that uses more stringent cuts that yield a higher energy threshold. In this "hard" analysis, the NFIT cut is increased from 20 to 100 and the Compactness cut is increased from 2.5 to 5.0. Application of these harder cuts reduces the background by a factor of 50 and for a Crab-like spectrum reduces the number of signal events by a factor of ≈10 while raising the median energy from 3 TeV to 10 TeV. For a source with a Crab-like spectrum (spectral index $\alpha = 2.59$ with no cutoff) the reduction in sensitivity of the analysis is only about 30%. We define a hardness ratio $h$ as the

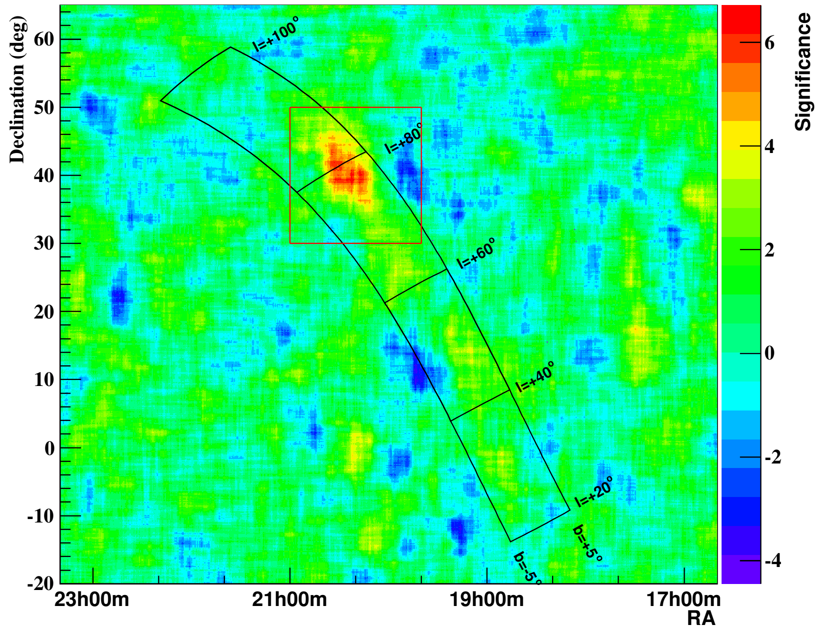


**Figure 1.** Significance map of the sky showing. Data is binned in $5.9^o$ bins, so neighboring points are highly correlated. A $6.7\sigma$ excess is observed at RA=21h14m, DEC=$39.5^o$. The black box in the lower left hand corner show the bin size $5.9°$. The distribution of the excess in in the red box is shown in figure 2.

quotient of the observed excess with the hard cuts to the excess with the standard cuts. A plot of the predicted $h$ vs spectral index ($\alpha$) is shown in figure 3. A power-law spectrum with no cutoff is assumed. Note, this analysis cannot distinguish between a soft spectrum and a hard spectrum with a cutoff. The measured hardness ratio for the Crab (observed at $8.0\sigma$ in this data set with the standard cuts) is $h_{Crab} = 0.097 \pm 0.021$ corresponding to a spectral index of $\alpha_{Crab} = 2.53 \pm 0.21$, which is consistent with measurements of the Crab spectrum [7] made by IACT's in this energy range. Detection of the Cygnus region with the hard cuts indicates that the spectrum of the VHE emission extends at least to 10 TeV. For the Cygnus region, $h_{Cygnus} = 0.095 \pm 0.030$, which corresponds to a spectral index of $\alpha_{Cygnus} = 2.55 \pm 0.30$. This harness ratio is consistent with both a soft spectrum indicative of cosmic-ray interactions [1] and a hard spectrum like those observed by the HESS collaboration in their survey of the Galactic plane [9] within the longitude range $-30 < l < 30$.

The flux of VHE emission from the Cygnus region is estimated by comparing the event excess to the observed excess at the Crab. Gamma-ray sources detected at the declination of the Cygnus region have a 1.40 times higher excess than an equivalent source at the declination of the Crab due entirely to the more favorable zenith angle during transit, nearly overhead. The flux of this source is $1.55 \pm 0.25_{stat} \pm 0.30_{syst}$ times the flux of the Crab. The statistical error is due to the uncertainty in the Milagro measured Crab excess, the uncertainty in the spectrum and the uncertainty in the spatial extent of this diffuse source.

[1] For cosmic-ray interaction $\alpha_{gamma-ray}$ is expected to closely track the cosmic-ray spectrum itself which is has $\alpha_{CR} = 2.75$ [8] in this energy range.

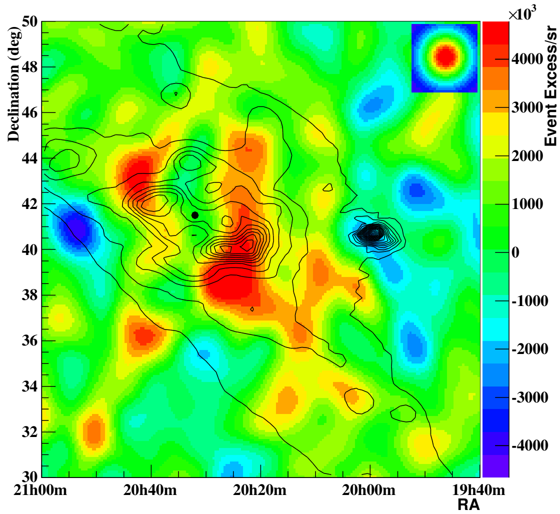


Figure 2. Event Excess distribution in the Cygnus region. The event positions have been smoothed with a function matching the Milagro PSF. Overlaid on the plot is the 1420MHz radio map of the region which is an indicator of neutral hydrogen. The PSF for Milagro is shown in the upper right hand corner of the plot. TeV 2032+4130 is shown as a black dot.

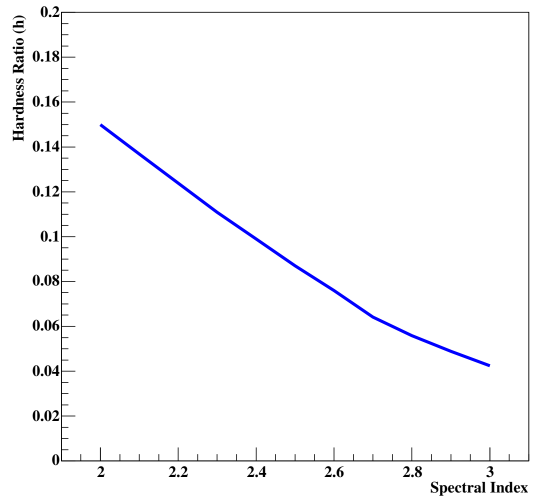


Figure 3. The hardness ratio (h) plotted as a function of spectral index assuming a power law spectrum with no cutoff. h is the ratio of the the event excess for the "hard" cuts divided by the event excess for "soft" cuts. As the steeper spectra (higher spetral index) give fewer high energy events and consequently fewer events passing the hard cuts compared to the soft cuts.

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