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 most luminous 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 a localized unidentified TeV source in the Cygnus Region with flux of 30 mCrab[2]. We report the detection of diffuse TeV gamma-ray emission from the Cygnus region using 4.5 years of data from the Milagro Gamma-Ray Observatory. The significance of the detection is 9.1σ and has a flux above 3 TeV of 2 times the Crab. The emission region is ≈5 degrees across, much larger than the angular resolution of the Milagro detector, which permits the imaging of this diffuse source.

Introduction

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 × 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 the Crab is ≈ 3.5 TeV, but varies strongly with zenith angle.

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 ≈ $1.6(= \frac{0.5}{\sqrt{0.08}})$. The efficacy of this cut has been verified through study of Crab data.

The ability to distinguish gamma-ray induced events from hadron induced background is a strong function

of the number of hits in the Milagro detector. Events that produce a large number of hits are likely to be accompanied by a large number of penetrating muons. The non-observation of penetrating particles in a large event provides a much more stringent Compactness cut. For very large events, the optimal Compactness cut rejects more than 99.9% of hadron background. However, the paucity of large events make the source detection sensitivity with hard cuts on NFIT and C similar to the standard cuts despite the much improved signal to background ratio. To exploit the broad range of event quality (S/B ratio) in our data, we have have developed an alternative analysis method that weights events based on the relative probability that the event was due to a gamma-ray. Events with large NFIT and C are assigned high weights, while events with low NFIT and C are assigned lower weights. Application of this method increases sensitivity by $\approx 30\%$.

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 $\approx 0.75°$. 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 extend our blind survey analysis to search for extended diffuse sources of gamma-ray emission. 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 procedure.

Observations

Data collected during the period from 20 July 2000 to 5 May 2005 are used in this analysis. In total, 1644 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. Maps are produced using both the standard analysis and the weighting analysis.

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 $\delta \approx 36°$, corresponding to the latitude of the Milagro detector. In the map produced the $5.9°$ bin size, a diffuse gamma-ray source is found coincident with the Cygnus region consistent with the EGRET position. A 9.1 (6.7) σ excess is observed at this location with that weighted (standard) analysis method. 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 5σ 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 9.1 (6.7)σ 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 1.0×10^{-5} for the standard analysis or 2×10^{-14} for the weighted analysis.
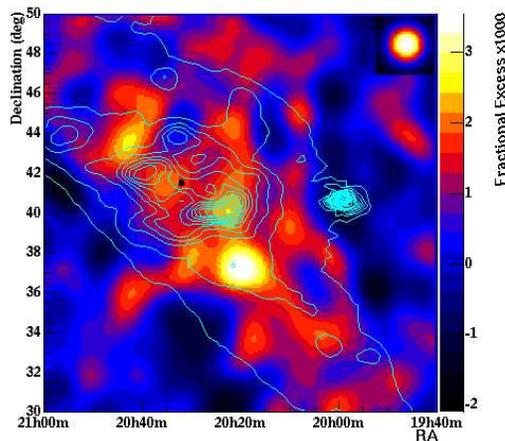
Figure 2 shows the distribution of fractional event excess observed in the Cygnus region. Instead of significance, the density of the event excess is plotted. The positions of the events in this map have been convolved with the Milagro detector's point spread function (PSF) to illustrate the morphology of the observed excess. 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
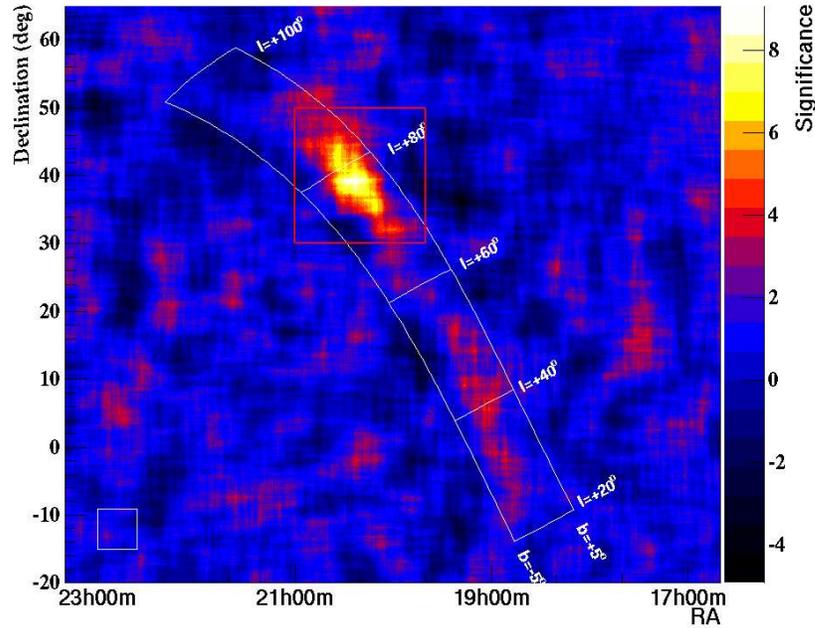
Figure 1. Significance map of the sky showing the region of the Galactic plane containing the Cygnus region using the weighted analysis. The black box in the lower left hand corner show the bin size, 5.9°. The distribution of the excess in in the red box is shown in figure 2.

correlated with the the diffuse matter density. Although we observe a large broad region of diffuse excess consistent with the matter distribution, the largest localized excesses are found lie along the galactic plane, but with slightly lower and higher longitude than the bulk of the radio emission. Panel 2 of the same figure shows the same Milagro with the positions of the 7 EGRET unidentified sources in the Cygnus region. Two of the EGRET sources (3EG J2021+3716 and 3EG J2016+3657) are spatially coincident with the position of maximum TeV gamma-ray excess.

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, assuming that the source emission region is completely contained within a 5.9∘ bin. 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. The extent of this diffuse source is likely to extend beyond the bin boundaries. We estimate the flux of the entire region to be 2.0 times the flux of the Crab for an expanded source region.

Figure 2. Fractional 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.
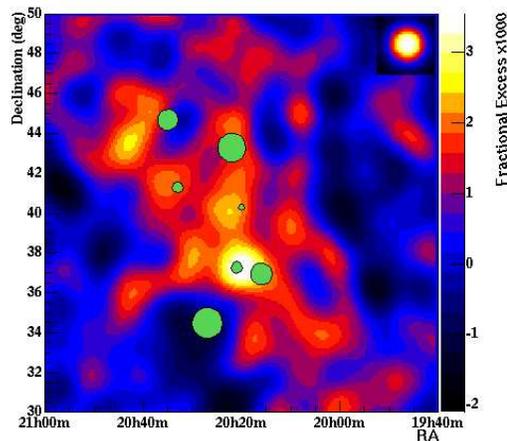
Figure 3. Fractional event excess distribution in the Cygnus region. Overlaid on the plot are the positions of 7 EGRET unidentified sources detected in the Cygnus region. The size of the circle indicates the 95% EGRET position error. Two of the 7 EGRET sources are spatially coincident with the point of highest significance detected by Milagro.

Acknowledgments

References

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