Astrophysics with Milagro

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Abstract.
Milagro is a TeV gamma-ray observatory that utilizes a large water Cherenkov detector to observe extensive air showers produced by high energy particles impacting the Earth's atmosphere. A 4000 m^2 pond instrumented with 723 8" PMTs detects Cherenkov light produced by secondary air-shower particles. A sparse array of 175 4000l water tanks surrounding the central pond detector has recently been added which will extend the physical area of Milagro to 40,000 m^2 and substantially increase the sensitivity of the instrument. Based on three years of operation, Milagro has established its sensitivity through the detection of the Crab plerion and active galaxy Markarian 421. Milagro's distinct advantage compared to other TeV gamma-ray detectors is that it views a wide field (2 steradian over-head sky) and it continuously operates (>90% live time). These factors give Milagro the potential for discovery of new sources with unknown positions and times, such as gamma-ray bursts, flaring AGN, and observation of diffuse extended sources like the Galactic plane or large supernova remnants. A summary of the recent results from the Milagro collaboration is presented with a focus on evidence for two newly observed TeV sources: diffuse emission from the Cygnus Region, and evidence for a diffuse TeV hot spot near the EGRET unidentified 3EG J0520+2556.

INTRODUCTION

Milagro is a unique TeV gamma-ray observatory capable of continuously monitoring the overhead sky. The directions of gamma-rays impacting the earth's atmosphere are reconstructed through the detection of air-shower particles that reach the earth. 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 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 in direction reconstruction. The angular resolution for gamma-ray induced air-showers is $\approx$0.75° without the outriggers and $\approx$0.45° with the outriggers. The muon layer is located at about 6m below the surface. The greater depth (17 radiation lengths) is utilized 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. The median energy of gamma rays detected

[1] R. Atkins, W. Benbow, D. Berley, E. Blaufuss, D. G. Coyne, T. DeYoung, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, L. Fleysher, R. Fleysher, M. M. Gonzalez, J. A. Goodman, T. J. Haines, E. Hays, C. M. Hoffman, L. A. Kelley, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, R. S. Miller, A. I. Mincer, M. F. Morales, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, P. M. Saz Parkinson, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, D. A. Williams, M. E. Wilson, X. W. Xu and G. B. Yodh

from a crab like spectrum is $\approx$ 3 TeV.

The Milagro Gamma Ray Observatory has been operational since August 2000. The detector functions both during the day and night and observes the entire overhead sky ($\approx$ 2 steradians). Cosmic ray events are collected and logged at a rate of roughly 1500Hz. Nearly all of the events collected are due to air-showers induced by cosmic ray protons and nuclei. These charged particles are useless for astronomy because the interstellar magnetic fields bend charged particle trajectories decoupling their momentum from their direction of origin. Gamma-ray sources are identified as statistically significant excesses on the nearly uniform cosmic ray background.

The Milagro detector's large field of view and continuous duty cycle make it an ideal instrument for the discovery of previously unknown sources. Recent publications cover topics including detection of the Crab Nebula[2], limits on TeV emission from GRB [3] and a TeV all-sky survey of the northern celestial hemisphere[4]. At this conference, papers were presented on the detection of diffuse TeV emission from the Galactic plane[8], limits on TeV emission from satellite detected GRB[11], a study of nearby AGN[10] and limits on relic neutralino annihilation derived from TeV flux limits from the sun[9]. The focus of this paper is the search for diffuse sources of TeV gamma rays with the Milagro detector.

Milagro's wide field makes it well suited to observe diffuse sources. Although Milagro has a relatively poor angular resolution compared to Atmospheric Cherenkov Telescopes (ACTs), this disadvantage is eliminated when studying sources with angular extent $>\geq$ Milagro's angular resolution. At least two categories of diffuse very high-energy gamma-ray sources are known to exist at GeV[6] and TeV energies: Supernova remnants (SNR)[7] and the Galactic plane. In the analysis presented here, the northern sky ($0^\circ < \delta < 60^\circ$) is searched for TeV sources with angular extent up to $\approx 5^\circ$ by re-binning the Milagro data to optimize the existing all-sky search methods for detection of diffuse gamma-ray emission.

DATA ANALYSIS

The Milagro collaboration has developed a standard set of cuts that this analysis utilizes. The cuts were optimized using studies of the detector simulation and confirmed through observation of the Crab Nebula [2] and Markarian 421[10]. Events with greater than or equal to 20 PMT hits utilized by the shower angle fitter ($NFIT/geq20$) and the "compactness" parameter (C) greater than 2.5 are retained. The $NFIT$ cut preserves about 80% of the data, only removing events with obviously poor angle fits. About 8% of the background data pass the compactness cut. This cut has has been determined from simulations to have an efficiency of $\approx$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 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 (θ, ϕ), 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[12] is used to compute the final 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 an angular resolution of ≈0.75°. To search for diffuse gamma-ray sources with angular extent greater than or equal to the angular resolution, the standard Milagro sky maps are searched 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. The results, however, are highly correlated. For each bin size, points with probability $>5\sigma$ are recorded for further study. Monte Carlo simulations of the map analysis process are used to compute the post-trials probability for each source candidate.

Data collected between 17 August 2000 and 5 May 2004 are used in this analysis. In total, 1305 live days are included.

RESULTS

In addition to the high significance detection of the Crab and Mrk421, the analysis also identifies two additional excesses that substantially distinguish themselves from background. The most significant candidate has P=5.9σ and is located at RA=78.8° and δ=26.0° (l=178.8,b=-7.3) and was identified with a 2.9° bin size. This candidate is spatially coincident with EGRET unidentified source 3EG J0520+2556. Monte Carlo simulations indicate that the probability of observing an excess this significant at any point in the sky at any bin size is 0.8%. Figure 1 shows a significance map in the region of the Crab, showing this source. The second most improbable point has P=5.5σ, is located at RA=308° and δ=42° (l=81°,b=1°) and was identified with a 5.9° bin. This source candidate lies in the Galactic plane and is spatially coincident with the Cygnus Arm. The probability of observing an excess this significant at any point in the sky at any bin size is 2.0%. Figure 3 shows a significance map of the region of the sky containing the Cygnus Arm.

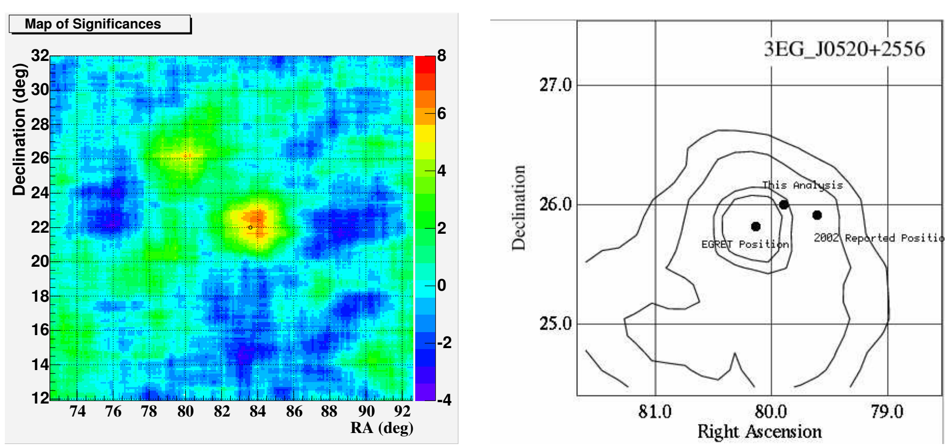

FIGURE 1. Significance map of the region containing the Crab nebula (RA=84.6°,δ=22.0°) and the highly improbable excess coincident with the EGRET unidentified source 3EG J0520+2556 (RA=78.8°,δ=26.0°). Also shown is the EGRET significance contour for 3EG J0520+2556.

3EG J0520+2556

The first candidate is spatially coincident with the EGRET unidentified source 3EG J0520+2556. This candidate was first reported by Milagro in 2002 [13] as a possible TeV gamma-ray source. In the initial Milagro all-sky search, a larger more conservative bin size of 3.0° was used. With this bin size, this source candidate was identified as a "hot spot" worth investigating further. Greater understanding of the performance of the Milagro detector lead to a reduction in the standard bin size for gamma-ray point sources searches from 3.0° to 2.1°. The reduction in bin size diminished the observed significance, however, the point remained one of the most significant in the sky and is one of only 11 points with significance greater than 4σ in the published Milagro sky survey[4]. As this source candidate was originally identified in 2002, it is reasonable to break the data into 2 subsets, events used in the initial all-sky search and events collected since. The data set used in the analysis reported in 2002 contained data collected between 17 August 2000 and 9 December 2001 (465 days of detector on time). Data collected since the initial report and used in this analysis include 840 days of detector on time from 10 December 2001 to 5 May 2004. In the 465 day sample, a 4.4σ excess is observed. At the exact position of the maximum in the 465 day sample, a 3.7σ excess is observed in the 840 day sample, and a local maximum is found a few tenths of a degree away with a significance of 4.4σ. Figure 2 shows the significance maps for the two data subsets.

To estimate the spatial extent of the excess associated with this source candidate the excess was fit to a Gaussian convoluted with Milagro's point spread function. A four parameter fit was performed where the width (σ), position (RA,δ) and amplitude were allowed to vary. The best estimate of the source position and width are RA=$78.8^o \pm 0.4^o$, δ = $26.0^o \pm 0.4°$, and $\sigma = (0.8 \pm 0.4)°$. The excess is inconsistent with a point source hypothesis at the $\approx 2\sigma$ level. The flux of this candidate is 85% of the Crab. The excess was also found to grow steadily over time. There is no evidence of episodic emission.

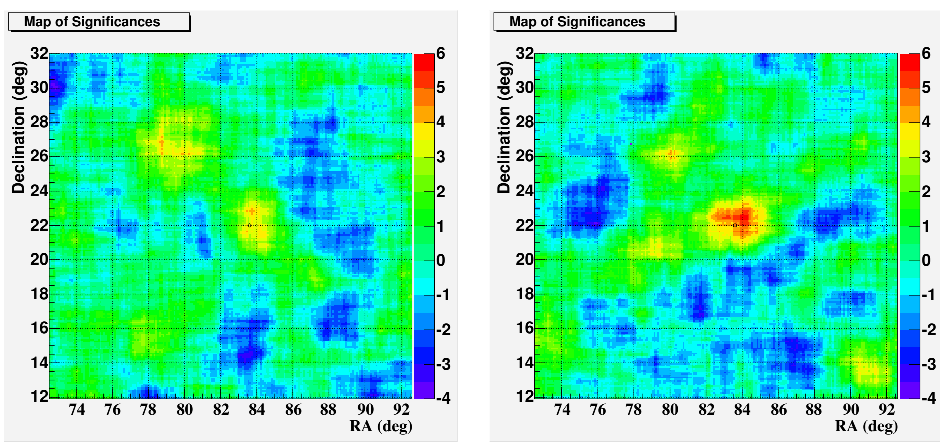

FIGURE 2. Significance map for the Crab and Milagro "Hot Spot". The panel on the left shows the data set utilized in the initial all-sky survey. The panel on the right shows that data collected after the hot spot was reported.

The 2002 announcement this source candidate coincident with 3EG J0520+2556 lead to follow-up observations[14] by the Whipple collaboration which found no evidence of a gamma-ray point source at the position reported by the Milagro Collaboration and at the position of 3EG J0520+2556. The flux upper limits set by Whipple rule out the hypothesis that the Milagro excess is due to a gamma-ray point source, but Whipple did not publish a limit on the diffuse gamma ray flux. The sensitivity of the Whipple telescope to diffuse sources is substantially lower than to point sources, due to its outstanding angular resolution, so it is likely that if this source is diffuse, with an angular extensions greater than $\approx 0.5^o$, it would not be detectable by Whipple with the limited telescope time dedicated to it.

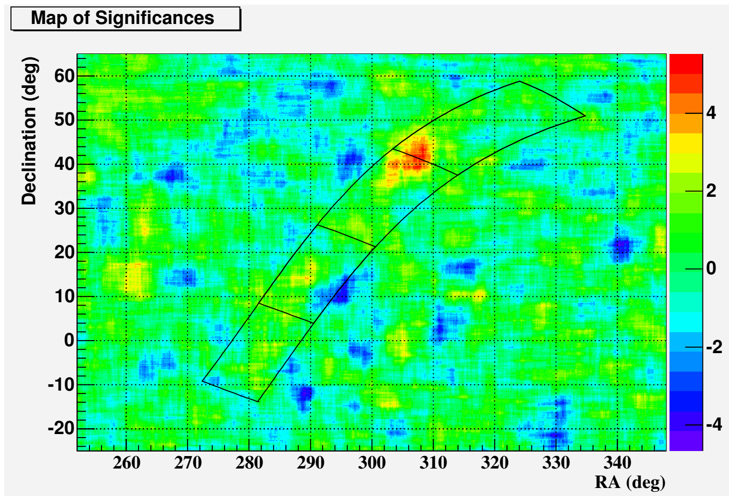

FIGURE 3. Significance Map showing the Galactic plane as it transverses the mid northern declinations. The excess in the vicinity of the Cygnus region is clearly visible at RA=308.°,δ=42.°. The Galactic plane from l=20° to l=100° and b=±5° is superimposed on the plot.

Cygnus Arm

The second diffuse gamma-ray source candidate is found to be coincident with the Cygnus Arm. The Cygnus Arm is a spiral arm within our Galaxy that extends radially away from observers on the earth. This is a known dense region of gas and dust and is observed by EGRET to have diffuse GeV gamma-ray emission comparable to the Galactic bulge, making it the brightest region of GeV gamma rays in the northern sky[5]. Similar to the GeV and TeV [8] emission from the broader Galactic plane, VHE emission from the Cygnus region is believed to be dominated by interactions of cosmic ray hadrons with interstellar gas and dust. The 5.5σ excess observed at this location is broad and inconsistent with a single point source hypothesis. The excess has a flux appromximately teice the Crab. Despite the seemingly large flux, this known gamma-ray source is a difficult target for ACTs because of its size. No ACT has a camera large enough to image the entire source region. The excess is observed to grow steadily over time. There is no evidence of episodic emission.

CONCLUSION

Presented here is evidence for the detection of two previously unknown sources of TeV gamma rays, one coincident with 3EG J0520+2556, and another coincident with the Cygnus Arm. These new sources are found to be diffuse. The two source candidates have probabilities of 5.9σ and 5.5σ respectively. When all the trials of the all-sky search with a range of 20 bin sizes are counted the probabilities of observing these excesses are reduced to 0.8% and 2.0% respecively. The source candidate coincident with 3EG J0520+2556 was reported as a "hot spot" by the Milagro collaboration in 2002. Data collected since the initial report show a 3.7σ excess. The Cygnus Arm is the brightest source of GeV gamma rays in the northern sky. The observed location and shape of the Milagro excess coincide with the GeV observations.

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