

Recent results from the Milagro TeV gamma-ray observatory

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Milagro is a gamma-ray observatory employing a water Cherenkov detector to observe extensive air showers produced by high-energy particles impacting in the Earth's atmosphere. We discuss the first detection of TeV gamma-rays from the Galactic plane and report the detection of an extended TeV source coincident with the EGRET source 3EG J0520+2556, and the observation of TeV emission from the Cygnus region of our Galaxy. We also summarize the status of our search for Very High Energy (VHE) emission from satellite-triggered Gamma Ray Bursts (GRBs) and discuss plans for the next generation water Cherenkov detector.

1 Introduction: The Milagro Observatory

Milagro¹ is a TeV gamma-ray detector which uses the water Cherenkov technique to detect extensive air-showers produced by Very High Energy (VHE, >100 GeV) gamma rays as they interact with the Earth's atmosphere. Milagro is located in the Jemez mountains of northern New Mexico, at an altitude of 2630 m. It has a field of view of ~ 2 sr and a duty cycle greater than 90%. The effective area of Milagro is a function of zenith angle and ranges from ~ 10 m² at 100 GeV to $\sim 10^5$ m² at 10 TeV. A sparse array of 175 4000-l water tanks, each containing an individual PMT, was added in 2002. These additional detectors, known as "outriggers," extend the physical area of Milagro to 40000 m², substantially increasing the sensitivity of the instrument and lowering the energy threshold. The angular resolution is approximately 0.75° .

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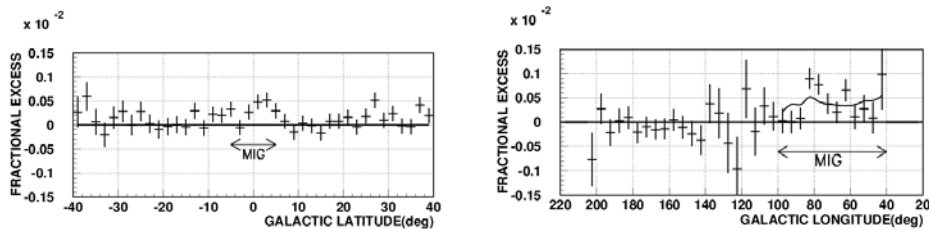


Figure 1: **Left** – Profile of the fractional excess as a function of Galactic latitude (for Galactic longitude 40° to 100°). **Right** – Profile of the fractional excess as a function of Galactic longitude (for Galactic latitude -5° to 5°). The EGRET longitudinal source shape is superposed. (Figs. from Atkins et al. 2005)

2 Recent Results

2.1 Diffuse VHE emission from the Galactic Plane

Diffuse emission from the Galactic plane is the dominant source in the gamma-ray sky.² Most of the diffuse VHE emission from the Galactic plane is thought to be produced by the interaction of cosmic-ray hadrons with interstellar matter. The flux measured by EGRET below 1 GeV fits models well, but that measured between 1 and 40 GeV is significantly larger than what is predicted by most models. One possible explanation for this enhanced emission is the inverse-Compton scattering of cosmic-ray electrons.³ If this turns out to be the dominant source of diffuse gamma-ray emission from the Galactic plane, then the flux at TeV energies could be an order of magnitude higher than previously thought. Using 36 months of data, from 19 July 2000 to 18 July 2003, we looked at the inner ($40\text{--}100^\circ$) and outer ($140\text{--}220^\circ$) regions of the Galaxy. While the outer Galaxy shows no significant excess, the inner Galaxy shows a 5σ (5 standard deviations). excess.^{4,5} Fig. 1 shows the profile in latitude for the longitude band ($40\text{--}100^\circ$) of the inner Galactic region (left panel) and the profile in longitude for the latitude band (-5° to 5°) of the inner Galactic region (right panel), where the enhancement can be seen just north of the equator. The region of the inner Galaxy shows an enhancement along and just north of the Galactic equator. This is the same region where EGRET detected the strongest signal in the 100 MeV energy range. The 5σ excess is seen by summing the entire inner Galaxy with a $\pm 5^\circ$ latitude band, as suggested by the EGRET results. The Milagro observation of the Galactic plane remains significant even when the region around the Cygnus Arm is excluded. This constitutes the first detection of the Galactic plane at TeV energies.

2.2 Other extended sources

A search for extended emission was carried out for the Milagro data collected between 17 August 2000 and 5 May 2004.⁶ A set of standard cuts has been validated by observations of the Crab⁷ and Mkn 421.⁸ The background is computed from data collected at the same local detector coordinates, but at a different time, ensuring the celestial angles of the background event sample do not overlap with the source position under consideration. The method of Li & Ma⁹ is used to compute the significance of each excess. While the optimal square bin for detection of point sources with Milagro is 2.1° on each side,⁸ to look for diffuse sources, the standard Milagro sky maps were searched using a range of bin sizes from 2.1° to 5.9° in steps of 0.2° . 20 separate searches were performed on the same maps, though the results are highly correlated. Monte Carlo simulations were used to compute the post-trials probability for each source candidate.

3EG J0520+2556 The most significant candidate found in our search had a pre-trials significance of 5.9σ , located at RA= 79.8° and Dec= 26.0° and was identified using a 2.9° bin size. The probability of observing an excess this significant at any point in the sky at any bin size is

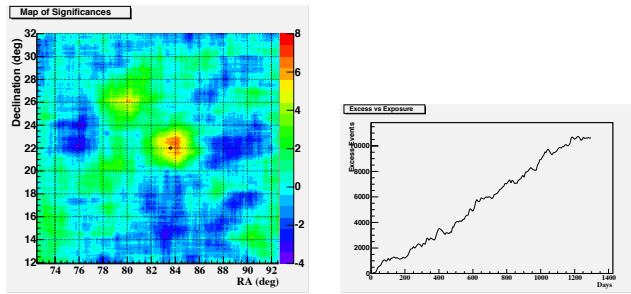


Figure 2: **Left** – Milagro significance map, with the Crab in the center and a TeV source coincident with 3EGJ0520+2556 to the left. **Right** – Cumulative excess as a function of time (Figs. from Smith et al. 2004)

0.8%. Fig. 2 (left panel) shows the map of significances around the source, which is located $\sim 5.5^\circ$ from the Crab. This candidate was first reported in 2002.¹⁰ The cumulative significance using only data since it was first reported is 3.7σ . The right panel of Fig. 2 shows the accumulation of excess events with time, indicating that the source shows no periods of significant flaring. This candidate is coincident with the EGRET unidentified source 3EG J0520+2556.

The Cygnus Arm The second extended source candidate is coincident with the region known as the Cygnus Arm, a spiral arm within our Galaxy that extends radially away from Earth. This is a dense region of gas and dust which was observed by EGRET as the brightest source of GeV gamma rays in the northern sky, with a diffuse GeV emission comparable to the Galactic bulge. Like in the Galactic plane region, VHE emission from the Cygnus Arm is thought to originate mainly from interactions of cosmic rays with the interstellar gas and dust. A 5.5σ excess was detected using a 5.9° bin, at RA=308° and Dec=42°. The probability of observing an excess this significant at any point in the sky at any bin size is 2.0%. The excess observed with Milagro is inconsistent with a point source, and the number of excess events within the 5.9° bin corresponds to approximately twice the Crab flux. Like the case of 3EG J0520+2556, the accumulation of the excess is steady, and no evidence for flaring is observed. While this is an extremely bright region, making it the hottest spot in the Galactic plane, it is not surprising that it has not been detected yet by any of the Atmospheric Cerenkov Telescopes (ACTs), given the diffuse nature of the source and the limited field of view of such telescopes.

2.3 Gamma Ray Bursts

Many GRB models predict a fluence at TeV comparable to that at MeV scales.^{11,12,13} Almost all GRBs are detected between 20 keV and 1 MeV, though several have been observed above 100 MeV by EGRET, indicating that their spectrum extends at least out to 1 GeV.¹⁴ Recently, a second component was found in one burst¹⁵ extending out to at least 200 MeV and with a much slower temporal decay than the main burst. It is unclear how high in energy this component extends and whether it is similar to the inverse Compton peak seen in TeV sources. Above 100 GeV, no conclusive emission has been detected for any single GRB. A search for counterparts to 54 BATSE bursts with Milagro, a prototype of Milagro, found evidence for emission from one burst, with a significance slightly greater than 3σ .¹⁶ Twenty-five satellite-triggered GRBs occurred within the field of view of Milagro between January 2000 and December 2001. Due to the absorption of high-energy gamma rays by the extragalactic background light,^{17,18} detections are only expected to be possible for redshifts less than ~ 0.5 . No significant emission was detected from any of these bursts.¹⁹ Between January 2002 and December 2004 only 10 well-localized GRBs were within 45° of zenith at Milagro, due to the demise of BATSE.²⁰ However, in the five months since the launch of the Swift satellite, there have been an additional 10 well-localized

bursts, several of them with redshift information^b. Analysis of the most recent bursts is still under way but this much larger sample of bursts provided by Swift, especially those with a measured redshift, will allow us to either conclusively detect emission from bursts or place powerful constraints on the VHE emission from these bursts.

3 Future

Milagro has pioneered the water Cherenkov technique for the detection of extensive air showers and has demonstrated the advantages that such a technique has over traditional ACTs (e.g. higher duty cycle and much larger field of view). The HAWC (High Altitude Water Cherenkov)^{21,22} array is the next generation all-sky VHE gamma-ray telescope. This future detector would be located at an extreme altitude (>4km asl) and have a large area (~40,000 m²), making it able to detect GRBs at redshifts >1, observe flares from active galaxies as short as 15 minutes in duration, and survey the overhead sky at a level of ~ 30 mCrab in a year.

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^b A great resource for GRB localizations is J. Greiner's web page <http://www.mpe.mpg.de/jcg/grbgen.html>