Results from the Milagro Gamma-Ray Observatory

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Abstract

The Milagro Gamma-Ray Observatory, located at an altitude of $2630m$ in the mountains of northern New Mexico, is the world's first large-area water Cherenkov detector capable of continuously monitoring the overhead sky for sources of TeV gamma rays. At the center of the detector is a $60m \times 80m \times 8m$ pond instrumented with 723 photomultiplier tubes in two layers. For improved sensitivity, 175 outrigger water tanks have recently been added surrounding the pond and span an area of $40,000m^2$. Preliminary results presented here include results from an all sky survey performed at TeV energies, and a search for transient emission above ∼100 GeV from gamma-ray bursts.

1 Introduction

The observation of high-energy gamma rays has aided in our understanding of some of the most energetic acceleration processes known. Sources of these gamma rays included active galactic nuclei (AGN), supernova remnants and gamma-ray bursts (GRB). Gamma rays are also produced when high-energy cosmic rays interact with matter in the galaxy.

The flux of gamma rays with energies in excess of ∼100 GeV is too small to be detected with the relatively small detector areas available on satellite-based detectors. Therefore, these large detectors must be earth-based. At these energies, gamma rays interact with the Earth's atmosphere, producing a cascade of particles, known as an extensive air shower (EAS). Two techniques have previously been used to detect these showers. First, an array of ground-based detectors can detect the particles in the shower that survive to ground level,

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a type of detector known as an EAS array. Second, the Cherenkov light produced by the particles in the EAS as it propagates through the atmosphere can be detected by an Atmospheric Cherenkov Telescope (ACT). ACTs pioneered the field of TeV astronomy(1) and have identified many sources of TeV gamma rays(2; 3).

The excellent angular resolution and background rejection capabilities of ACTs make them well suited for studying the gamma-ray emission from known sources. However, ACTs have relatively narrow fields of view (∼3-4 degrees) and can only be operated on clear, dark nights. Therefore, they are not well suited to perform all sky surveys to search for unknown sources, including short term transient sources such as GRBs, or perform daily monitoring of multiple sources for episodic emission, such as searching for flaring AGN. On the other hand, an EAS ground detector can operate 24 hours a day, in any weather or sky conditions, and can observe the entire overhead sky. Previous EAS arrays were sparse scintillation detectors that were only sensitive to gamma-ray showers above 10's of TeV.

Milagro is the first EAS array to have sensitivity to gamma rays down to ∼100 GeV. This makes Milagro an ideal instrument for performing all sky searches for yet-undiscovered gamma-ray sources, and searches for TeV emission from GRBs. This paper presents results and sensitivities from an all sky survey and GRB search performed with Milagro.

2 The Milagro Detector

The Milagro Gamma-Ray Observatory is located in the Jemez Mountains just outside of Los Alamos, NM at an altitude of $2630m$ (8600'). The detector consists of a central pond, which serves as a water Cherenkov EAS detector, and an array of outrigger tanks surrounding the central pond.

The central pond is fully instrumented and uses water as the detection medium, making the entire area of the pond sensitive to particles in an EAS that reach ground-level, and 50% of the particles that enter the pond are detected. Milagro is sensitive to gamma-ray induced EAS with primary energies above 100 GeV, has a wide field of view and is able to operate 24 hours a day.

2.1 Detector Description

The core of the detector is a 6 million gallon water pond measuring $60m \times 80m \times 8m$ (depth), which is used as a large area water Cherenkov detector.

The Milagro pond is topped by a light-tight cover and instrumented with an array of 450 photomultiplier tubes (PMTs) deployed under $1.5m$ of water to detect air-shower particles reaching the ground (air shower layer). These PMTs measure the arrival time and density of the air-shower particles. This information is used to reconstruct the shower direction and determine, along with the outrigger array, the shower core location. Additionally, an array of 273 PMTs are located at at a depth of $7m$ in the pond (muon layer) and are used to distinguish photon-induced showers from hadron-induced showers. Construction of the pond was completed in 1999, and data has been taken since then with a trigger rate of about 2 kHz.

Surrounding the central pond and covering an area of $\sim 40,000m^2$, is an array of outrigger tanks. Each tank is $4.6m^2$ in area and $1m$ high and is instrumented with a single PMT. The inside of each tank is lined with Tyvek for increased light collection. Construction of the outrigger array was completed in 2002. The outriggers are now being used, along with the air shower layer of the pond, to determine the location of the core of air showers. Better knowledge of the core location will yield improved angular resolution and improved gamma-hadron separation. These improvements from the addition of the outriggers is expected to increase the significance from a Crab-like source by roughly a factor of 2.

The data acquisition system has a maximum trigger rate of 2 kHz. As the trigger threshold is decreased, the rate of events caused by single, near-horizontal muons increases greatly. These background events limit the ability to collect air shower events with fewer than 60 PMTs hit in the air shower layer, even though the event reconstruction has high efficiency down to ∼20 PMTs hit.

In 2002, an intelligent trigger system was installed that uses a FADC to measure the risetime of the trigger analog sum. True air shower events, especially those from near zenith, contain particles that reach the pond nearly simultaneously, and consequently have very short risetimes in the analog sum. Single muon events, that deposit large amount of light at a single point, which propagates to many tubes have much longer risetimes. By only keeping events with short risetimes, we were able to reduce the trigger threshold to ∼20 PMTs, while keeping the trigger rate below the 2 kHz maximum. This results in a factor of 4 increase in effective area near 100 GeV.

2.2 Gamma-Hadron Separation

In Milagro, a gamma-ray signal from a source appears as an excess of events in the source direction above the isotropic background from hadronic cosmic-ray showers. An important feature of the Milagro detector is its ability to reduce this hadronic background by using the pattern of the hits in the muon layer of the pond. A typical background (hadron shower) will have a clumpy pulse height distribution, indicating the presence of muons or hadrons penetrating deep into the pond. These clumps show up as patches of a few hit tubes in the muon layer, some hits with high pulse height values. Gamma-ray showers, for the most part, are composed primary of low energy gamma rays and electrons, which tend not to penetrate to the muon layer. Consequently, the pulse height distribution is more smooth and uniform.

A parameter has been developed(4) that exploits these differences, X_2 (compactness). The X_2 value of each event is determined by calculating the ratio of the number of tubes in the muon layer hit with more than 2 photoelectrons to the maximum charge seen in any tube in the muon layer. Events with patches of high pulse heights will have relatively small values of X_2, while gamma events, with more uniform pulse height distributions in the muon layer will have larger values. The optimal cut value of 2.5 removes 90% of the background while keeping 50% of the signal, an increase in sensitivity ($sig/\sqrt{bkg}$) of 1.6.

2.3 Energy Sensitivity

The energy sensitivity of the Milagro detector is determined using simulations of gamma-ray events taken from a spectrum (spectral index of 2.6) and transit that matches the Crab Nebula. The energy distribution of events that trigger the detector and are successfully reconstructed is shown in Figure 1. Unlike ACTs, Milagro's energy response does not have a well-defined threshold. The median energy is 3 TeV, but Milagro is still reconstructing events near 100 GeV. The median energy also depends on how far from zenith a source transits. Gamma-ray showers will pass through more atmosphere when far from zenith, resulting in a higher mean energy observed. This dependence on zenith angle is also shown in Figure 1. The observation of the shadow of the moon in the cosmic-ray background and simulations of cosmic rays and gamma rays are used to characterize the angular resolution. For gamma-ray showers, the angular resolution is found to be $\sim$0.75 degree.

3 Results and Sensitivities

All data collected at Milagro are reconstructed in real-time to determine the position on the sky where each event originated, the location of the core of the shower, and the values needed to calculate X_2. The results of this reconstruction for every event are retained and are searched for excesses from sources on

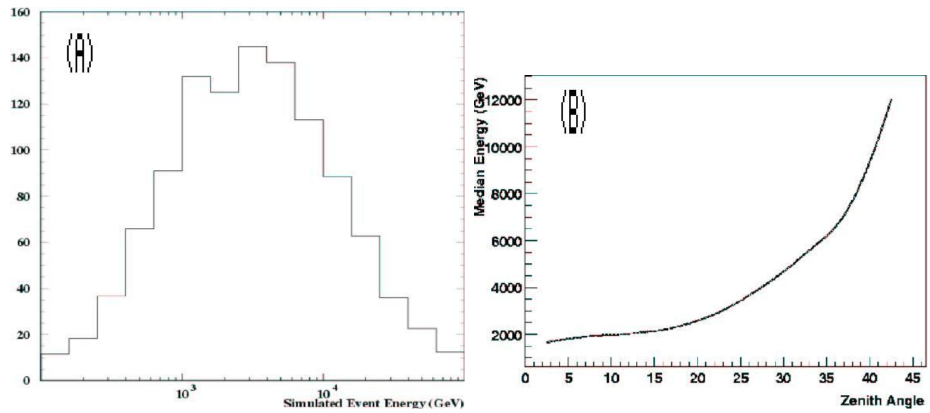

Fig. 1. (A) The energy distribution of simulated gamma-ray events taken from a "Crab-like" spectrum and transit. The median energy is 3 TeV. (B) The dependence of the median energy with the angular distance from zenith of a source transit.

numerous time scales, from short-term transient searches for GRBs to searches for steady sources of gamma rays that span the entire data set. The number of events found at each location on the sky (in right ascension and declination) is then compared with the background estimate for that location. The background is estimated using the data itself, assuming that the cosmic-ray background is isotropic and the acceptance of the detector in local coordinates is independent of the trigger rate(4; 5). To reduce the statistical uncertainty of the background, a 2 hour slice of data is used in the background calculation. In this manner, the excess at each point in the sky for each 2 hour time window can be calculated and 2 hour periods are summed to generate longer data sets.

3.1 TeV Survey of Northern Sky

Data collected between June 1999 and September 2002 have been used to search for excesses from point sources in the overhead sky. The brightest object observed during this period was the Crab Nebula, a well-established gamma-ray source(1). Events found in a 2.1 degree square bin were considered, with the bin centered on the location of the Crab Nebula. The observed number of events and excess at this location are presented in Table 1, for all events with at least 20 PMTs contributing to the angular reconstruction (nfit) and with the gamma-hadron separation cut also applied. A map of the significance for the region surrounding the Crab Nebula is shown in Figure 2. With the gamma-hadron separation applied, a 6.4σ excess is observed. As the data were collected prior to the completion of the outrigger array, these results does not reflect the full sensitivity of the Milagro detector.

Table 1
Results of the analysis of data from the Crab Nebula.

Data Set	ON Source	Background	Excess	Significance
All Data, nfit>20	18,374,036	18,365,694	8342	1.9σ
nfit>20, X_2 >2.5	2,119,449	2,109,732	9717	6.4σ

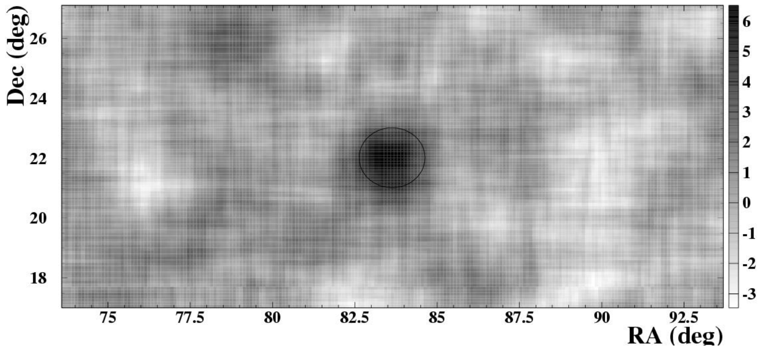

Fig. 2. Map of significance from the region of sky near the location of the Crab Nebula for data passing the nfit>20 and X_2 >2.5 cuts.

3.2 Sensitivity to Flaring Objects

Milagro can also search for objects, such as AGN, that are in a flaring state by searching for excesses in shorter time periods. The second brightest object observed in the all sky survey was Mrk 421, which was observed to be in a flaring state twice during this survey period(7). Figure 3 presents Milagro's sensitivity to flaring objects as a function of the flare duration for two assumed spectral indices. For a 30 day flare with a 2.0 spectral index, Milagro will observe a 5σ excess if the flux is greater than $6\times10^{-11}cm^{-2}s^{-1}TeV^{-1}$. Milagro continues to search the overhead sky on timescales from 2 hours to a full year online for the presence of flaring objects.

3.3 Gamma-Ray Burst Search Sensitivity

TeV gamma rays are a natural product in most models of gamma-ray bursts, with comparable fluence at the TeV and MeV energy scales(8; 9). The measurement of a TeV component to GRB emission would help determine the nature of the emission mechanism at work in the source. Any absorption of the highest energy gamma rays by the IR background light or in the emission region complicates the search for TeV emission.

Milagro searches for excesses from GRBs in two ways. The first is a triggered search, where a GRB position and time are determined by a satellite-

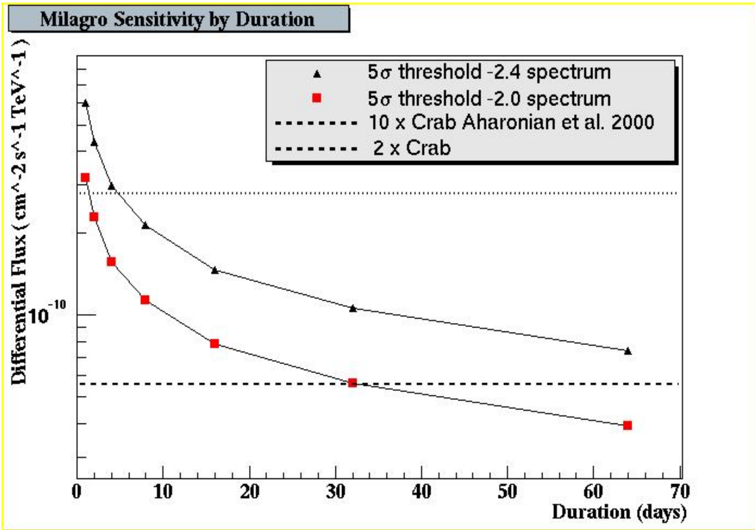

Fig. 3. The sensitivity of Milagro to flaring objects. Lines indicate the required flux as a function of flare duration in days for a 5σ observation for 2 different spectral indices. Also shown are 10 times and 2 times the Crab Nebula flux normalization value(6).

based experiment, and the Milagro data at this time and location are carefully searched. Since the end of the BATSE experiment, the number of these triggers has greatly decreased, but with the upcoming launches of Swift and GLAST, this number will increase. For a well-localized GRB trigger from one of these satellites, even the absence of an excess observed by Milagro would be a powerful constraint on the models describing GRBs. Additionally, Milagro also performs an untriggered search, where the overhead sky is searched on timescales from 250μsec to 2 hours for evidence of transient emission. An automated alert system is used for notification of any potential excesses. To date, no evidence of a TeV component to GRBs has been observed in Milagro. The sensitivity of Milagro to GRBs, compared with past and planned satellite-based detectors, is shown in Figure 4. Even in the presence of a cutoff of the highest energy component(>300 GeV), Milagro still has sensitivity to the highest fluence bursts observed.

4 Conclusions

The Milagro Gamma-Ray Observatory, in operation since 1999, has recently undergone several upgrades to increase Milagro's sensitivity to very high energy gamma rays. A recently completed outrigger array surrounding the central pond adds better core location ability, leading to improved angular resolution and gamma-hadron separation. A new intelligent trigger system has increased the effective area at the lowest energies by lowering the trigger threshold. Milagro has successfully detected emission from the Crab Nebula, and

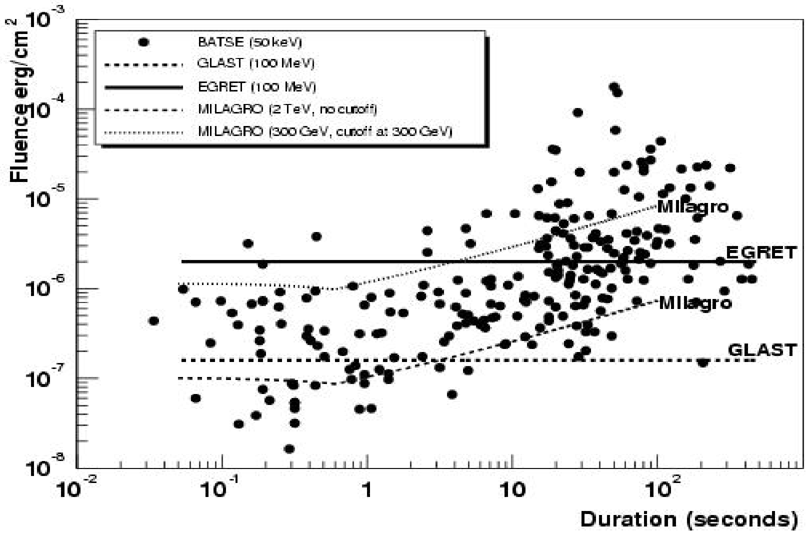

Fig. 4. The sensitivity of Milagro to GRBs with the assumption of equal fluence in the MeV and TeV energy regions. The black dots are the measured fluence and duration of bursts detected by the BATSE instrument at 50 keV. Solid and thick-dashed horizontal lines are the sensitivities of the EGRET and GLAST detectors at 100 MeV, respectively. Milagro's sensitivity, assuming that emission extends to TeV energies without a cutoff is shown as a thin-dashed line. If a cutoff energy of 300 GeV is assumed, the sensitivity is given by the dotted line. The Milagro sensitivities take into account the recently-added intelligent trigger.

continues to monitor the sky for TeV gamma-ray emission, on longer time scales from objects such as AGN, and on shorter time scales from GRB.

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