Results from the Milagro Gamma-Ray Observatory

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The Milagro Gamma-Ray Observatory, located at an altitude of $2630m$ in the mountains of northern New Mexico, is a water-Cherenkov extensive air shower detector consisting of a $4800m^2$ covered pond instrumented with 723 PMTs. For improved sensitivity, 175 instrumented water tanks have recently been added surrounding the pond, covering an area of $40,000m^2$. Milagro continuously observes the entire overhead sky, making it the ideal instrument to perform an all-sky search for TeV gamma-ray sources. Results from this survey are presented here, as well as a search for TeV emission from the galactic plane, 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 are 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). A ground-based detector can detect the particles in the shower that survive to ground level. Milagro is the first ground-based detector to have sensitivity to gamma rays down to ∼100 GeV, that can operate 24 hours a day, in any weather or sky conditions, and can observe the entire overhead sky. This makes Milagro an ideal instrument for performing all sky searches for undiscovered gamma-ray sources, and searches for TeV emission from GRBs.

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 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 the background of hadron-induced showers [1]. Construction of the pond was completed in 1999, and data have been taken since then with a trigger rate of about 2 kHz. The median triggered energy for an object such as the Crab Nebula is 3 TeV. The angular resolution of Milagro, based on observations of the shadow of the moon in cosmic rays, is found to be ∼0.75

*Full collaboration list availablel in [1] degree for gamma rays.

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 addition of the outriggers has improved Milagro's core reconstruction accuracy. Better knowledge of the core location yields improved angular resolution and improved gamma-hadron separation. These improvements from the addition of the outriggers is expected to increase the significance from the Crab Nebula by roughly a factor of 2.

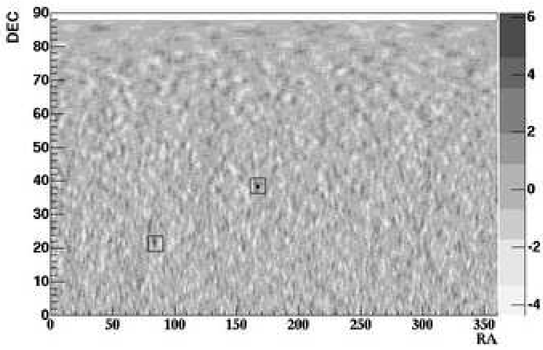

Figure 1. Map of significance from a TeV survey of the northern sky. The two brightest objects in the sky are boxed, the Crab Nebula (83.6, 22.0) and Mrk 421 (166.0,38.2).

3. TeV Survey of Northern Sky

Data collected between December 2000 and June 2003 have been used to search for excesses from point sources in the overhead sky. To accomplish this, the number of events found at each location on the sky (in right ascension and declination) is compared with the background estimate for that location. The background is estimated using a 2 hour slice of the data, assuming that the cosmic-ray background is isotropic and the acceptance of the detector in local coordinates is independent of the trigger rate[1,2]. At each position, a 2.1 degree square bin is considered, and the resulting significance map for the overhead sky is shown in Figure 1. The brightest object observed during this period was the Crab Nebula, a well-established gamma-ray source[3]. With the gamma-hadron separation applied, a 6.1σ excess is observed. Mrk 421, a source known to be in a flaring state during this period [4], is the second brightest object observed during this period. 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.

4. Emission from the Galactic Plane

The interaction of high energy cosmic rays with matter in our galaxy is another potential source of gamma rays, and has been observed with energies up to 30 GeV by the EGRET detector [5]. These interactions result in a diffuse gamma-ray signal centered on the galactic plane. Milagro, with its wide field of view, is an ideal instrument to search for a TeV component of gamma rays from the galactic plane. In order to accommodate a source region as large as the galactic plane, modifications to our standard background calculation method are made. These include exclusion of the galactic plane region from the background calculation, corrections for diurnal breathing of the atmosphere and corrections for observed anisotropies in the cosmic ray background. Data collected between December 2000 and December 2002 are used in this search. Since the galactic center is not visible at Milagro's location, the search is limited to a 10 degree wide region centered on the galactic plane and covering 20-100 degrees in galactic latitude. In this 2 years of data, Milagro observes a preliminary flux ratio of gamma rays to cosmic rays of $\frac{F_\gamma}{F_{cr}} = 5.3 \pm 1.9 \times 10^{-5}$. This can be interpreted as flux upper limit from this region of $F_\gamma < 8.0 \times 10^{-10} cm^{-2} sec^{-1} sr^{-1}$ at the 90% C.L. Further analysis and additional data will yield improved results.

5. 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[6,7]. 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 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-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. To date, no evidence of a TeV component to GRBs has been observed by Milagro. The sensitivity of Milagro to GRBs, compared with past and planned satellite-based detectors, is shown in Figure 2. In this comparison, equal fluence in the MeV and TeV energy regions is assumed. 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. Even in the presence of a cutoff of the highest energy component(>300 GeV), Milagro still has sensitivity to the highest fluence bursts observed.

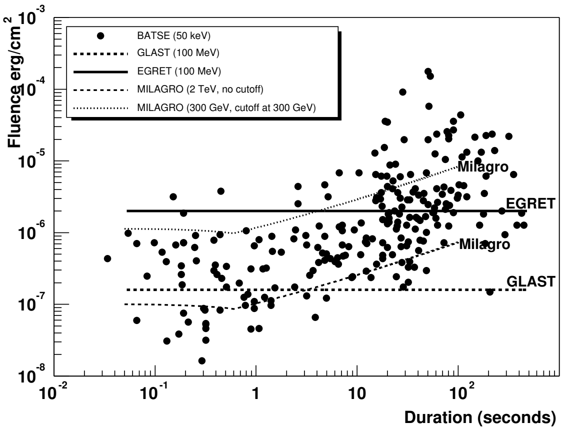

Figure 2. The sensitivity of Milagro to GRBs in comparison to other instruments.

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