THE MILAGRO GAMMA RAY OBSERVATORY

Jordan A. Goodman
Milagro Collaboration
Department of Physics, University of Maryland,
College Park, Maryland, 20742, USA

The Milagro Gamma Ray Observatory, located at an altitude of 8,600 feet in the Jemez Mountains of New Mexico, is the world's first large-area water Cherenkov detector capable of continuously monitoring the entire sky for sources of TeV gamma rays. It is uniquely capable of searching for transient sources of VHE gamma rays. The core of the detector is a 60m x 80m x 8m pond instrumented with 723 PMTs deployed in two layers. This part of the detector is complete and has operated continuously since Jan. 2000. Initial studies including searches for gamma-ray sources are ongoing, and preliminary results are available.

1 Introduction

The observation of high-energy gamma ray sources has helped us to gain a better understanding of the energetic acceleration processes in the Universe. The known gamma ray sources include supernova remnants, active galactic nuclei (AGN), and gamma ray bursts (GRB). In addition, more exotic sources like topological defects, evaporating primordial black holes, and dark matter particle annihilation and decay could be sources of high-energy gamma ray emission. Several reviews of the techniques, science, and recent results in high-energy gamma-ray astronomy have been published (Hoffman et al. 1999, Ong 1998, Weekes 2000).

The Milagro detector is a new type of instrument designed to search for continuous and episodic sources of VHE gamma ray sources. Milagro is the first detector sensitive to cosmic gamma rays below 1 TeV with the all-sky, high duty-factor capabilities of an extended air shower (EAS) array. Our prototype detector, Milagrito, has produced results on the outburst of the AGN Mrk501 and given suggestive evidence for TeV emission associated with a GRB (Atkins et al., 1999, 2000).

Figure 1: Aerial view of the Milagro pond with the light-tight cover inflated for work inside.

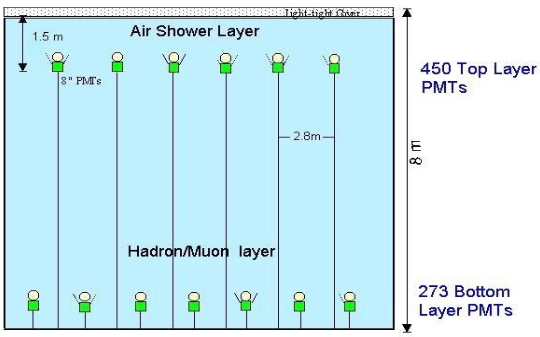

Figure 2: Schematic cross section of the Milagro detector.

Milagro performs high-duty-factor, all-sky observations in the VHE region. This gives us the opportunity to use Milagro to: survey the Northern sky for steady and episodic sources, search for emission from GRBs in the energy range 100 GeV to 20 TeV, and detect VHE emission from the Crab and study its energy spectrum with a new, independent technique. Plus we can continuously monitor the entire sky for flaring sources such as Markarian 421 and Markarian 501.

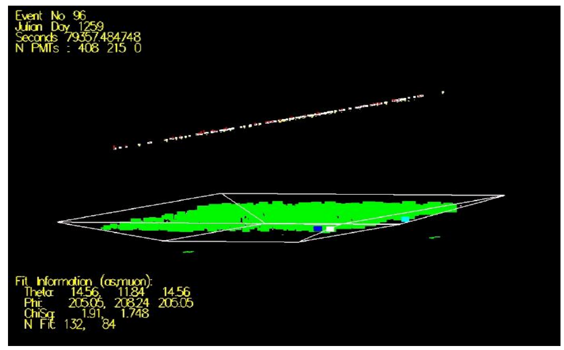

Figure 3: Air Shower event in Milagro. The line above the pond is the timing fits from the Shower layer. The green squares are proportional in size to the signal in the Shower layer.

2 The Milagro Detector

Milagro uses photomultiplier tubes (PMTs) deployed under water to detect the Cherenkov radiation produced in the water by relativistic charged shower particles. Because water is inexpensive and the Cherenkov cone spreads out the light, one is able to construct a large instrument that can detect nearly every charged shower particle falling within its area. Furthermore, the plentiful EAS photons convert to electron-positron pairs (or to electrons via Compton scattering). These electrons, in turn, produce Cherenkov radiation that can be detected. Consequently, Milagro has an unprecedented low energy threshold for an EAS-array. As in a conventional EAS-array, the direction of the primary gamma ray is reconstructed in Milagro by measuring the relative arrival time of the shower front across the detector.

The Milagro detector is located at an altitude of 8,600 feet (750 g/cm^2) at the Fenton Hill site in the Jemez Mountains of New Mexico (Figure 1). The core of the detector is a 6-million gallon pond measuring 60m x 80m x 8m (depth), which is used as a large area water Cherenkov detector. When completed the pond will be surrounded by 170 individual water Cherenkov detectors, called "outriggers", over a 200m x 200m area.

The Milagro pond is covered by a light-tight barrier and instrumented with an array of 450 20-cm-diameter photomultiplier tubes deployed under 1.5-m of water to detect air-shower particles reaching the ground. These PMTs measure the arrival time and density of the air-shower particles. In addition, 273 PMTs are located at the bottom of the pond under 6m of water and are used to distinguish photon-induced showers from hadron-induced showers. The top array of PMTs is called the shower layer and the bottom array is the muon layer. On the bottom of the pond is a 2.8m x 2.8m grid of sand-filled PVC pipe to which The PMTs in both layers are secured by a Kevlar string, as shown in Figure 2.

An event display for a typical air shower event in the Milagro pond is shown in Figure 3. The line above the pond indicates the best fit direction of the shower front using the relative arrival times of the shower layer PMTs.

2.1 Detector performance

A measure for the angular resolution of the Milagro detector is the DELEO/2 distribution. DELEO/2 is one half the space angle difference between the fits using the odd and even tubes in the array and is approximately the angular uncertainty (excluding certain systematics). The final resolution of the detector will be degraded by uncertainties in the shower's core position coupled with the shower-front's small curvature. The angular resolution is dependent on the number of PMTs that are in the fit; the resulting average angular resolution for all reconstructed events is $\sim 0.75^\circ$.

3 Current Operations and Results

The construction of the Milagro pond was completed in early 1999, and operations began in mid 1999. After a three month shut down in the fall, the detector has operated nearly continuously since November 1999. Since Jan. 2000 the detector has operated at a trigger rate of 1,500-2,000 Hz, depending on experimental and meteorological conditions. All events are reconstructed in real time at the site. The entire data set of reconstructed events is copied over the network to our archival data storage disk array and stored in a highly compressed format.

In Milagro, a gamma-ray signal from a source appears as an excess of events from the source direction, compared with the background from hadronic cosmic-ray showers. An important feature of the Milagro detector is its ability to reduce this hadronic background by using the muon layer in the pond. This gamma-hadron separation is described in detail elsewhere (Sinnis, 2001).

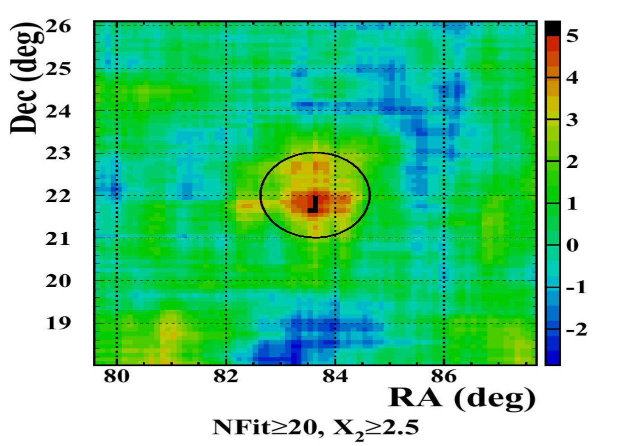

Figure 4: Sky-map of the signal around the Crab. The colors represent the excess in sigma, with the scale at the right of the plot. The black circle is centered on the true Crab position.

Figure 4 shows the significance of the event excess in the vicinity of the Crab during the period June 8, 1999 to April 24, 2001. At the source position, an excess of 4443 events is observed, corresponding to a significance of 4.8σ.We have also observed gamma-ray emission from Mrk421, which has recently been observed to be active in both the X-ray, by the All-Sky Monitor(ASM), and at TeV energies by HEGRA and Whipple. During the period Jan 17, 2001 - April 26, 2001 we find a 2741 event excess corresponding to 5.2σ (Benbow, 2001). We have also observed the shadow of the moon (Samuelson, 2001), and performed a search for GRB (Smith, 2001).

4 Future Improvements

Since the construction of the Milagro pond was completed the detector has become operational and successfully observed VHE gamma-ray sources. However, there are two significant improvements that are now being implemented at Milagro, which will significantly improve its sensitivity. The first improvement is to finish the construction of the detector by deploying $\sim$170 individual water tanks as Cherenkov detectors, called "outriggers", surrounding the pond. The second is the implementation of smart triggering processors that will significantly lower the energy threshold.

The outriggers are cylindrical water tanks, 0.91 m in height by 2.4 m in diameter, made of polyethelene and lined with Tyvek. The tanks are instrumented with a single PMT facing down from the top, which enable them to act as individual water Cherenkov detectors to measure the particles in the EAS with high efficiency. Studies show that the outrigger array in addition to improving our energy resolution will increase our sensitivity to gamma-ray sources by at least a factor of two.

Our new trigger processor should enable us to reduce our trigger threshold from the current 60 PMTs down to as few as $\sim$10 PMTs without being triggered by muons. This will give us a lower energy threshold that should significantly increase our sensitivity to gamma-ray sources, and in particular to sources of cosmological origin, such as GRBs, where the higher energy gamma-rays have sizable attenuation due to the interaction with the intergalactic infra-red light.

5 Conclusion

Milagro is the first EAS detector with an all-sky, high duty-factor capability, to be sensitive to gamma rays in the TeV energy range. The Milagro pond, which is the core of the detector, has been operational continuously since Jan. 2000 and has observed two TeV gamma-ray sources. Planned improvements will further increase our sensitivity, and put us in a unique position to monitor the sky for episodic emission of VHE gamma ray sources.

6 Acknowledgements

This work is supported by the US National Science Foundation, and also by the DoE, the LDRD program at LANL, and the IGPP. We would also like to recognize the hard work of Scott Delay and Michael Schnieder, whose dedication has been instrumental in operating Milagro.

1. Atkins, R. et al., NIM A, 449, p 478, 2000.
2. Atkins, R. et al., Ap. J. Lett 525:L25-L28, 1999
3. Atkins, R. et al., Ap. J., 533:L119-L122, 2000
4. Benbow, W., To be published in the proceedings of the 27th International Cosmic Ray Conference (ICRC), Hamburg, 2001
5. Hoffman, C. M., Sinnis, C., Fleury, P., and Punch, M., Rev Mod Phys, Vol. 71, No. 4, p 897. 1999
6. Ong, R., Phys. Rep., 305, p 13, 1998.
7. Samuelson, F., To be published in the proceedings of the 27th ICRC, Hamburg, 2001
8. Sinnis, C., To be published in the proceedings of the 27th ICRC, Hamburg, 2001
9. Smith, A., To be published in the proceedings of the 27th ICRC, Hamburg, 2001
10. Weekes, T. C., Physica Scripta, T85, p 195, 2000