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Status of the Milagro Gamma Ray Observatory

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Abstract. 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 continuous monitoring of the entire sky at gamma-ray energies near 1 TeV. It is uniquely capable of searching for transient sources of VHE gamma-ray emission. The core of the detector, a 60m x 80m x 8m pond instrumented with 723 PMTs in two layers, has been completed and is operational. Initial studies including searches for gamma-ray sources are ongoing, and preliminary results are available. The final stage of construction is under way. We are deploying 170 auxiliary "outrigger" water Cherenkov detectors in an area of 40,000 square-meters surrounding the pond, which will significantly enhance our ability to reject background and more accurately reconstruct the gamma-ray direction and energy. In addition, we are lowering the energy threshold of the detector by using custom processing to enable real-time intelligent triggering. The lower energy threshold will 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.

1 Introduction

High-energy gamma-ray astronomy uniquely probes non thermal, energetic acceleration processes in the Universe. The list of established gamma-ray sources includes active galaxies, supernova remnants, and gamma ray bursts (GRB). Gamma rays are also produced when high-energy cosmic rays interact with matter in our galaxy. Other potential sources include more esoteric objects such as evaporating primordial black holes, topological defects, and dark matter particle annihilation and decay. Recently, 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).

Fig. 1. Aerial view of the Milagro detector.

At higher energies, the gamma-ray flux from even the brightest source is too low to be measured in the relatively small detectors that can be placed in satellites: thus earth-based techniques are used. High-energy gamma rays interact high in the atmosphere, producing a cascade of particles, called an extensive air shower (EAS). Ground-based gamma-ray telescopes detect the products of an EAS that survive to ground level, either the Cherenkov light produced in the atmosphere by the shower particles (by atmospheric Cherenkov telescopes [ACTs]) or the shower particles that reach ground level (by extensive air-shower arrays [EAS-arrays]).

The excellent angular resolution and sensitivity of ACTs make them ideal to study steady VHE emission as well as short-term flaring from known sources. However, ACTs can only be used on clear, dark nights, and can only view one source at a time (and only during that part of the year when that source is in the night sky). Thus they are not well suited to perform an all-sky survey, to monitor on a daily basis a known source for episodic emission, or to search for emission from a source at an unknown direction (such as from a GRB). An EAS-array can operate 24 hours per day, regard-

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less of weather, and can observe the entire overhead sky; an EAS-array is able to observe every source in its field of view every day of the year. Previous EAS arrays have been sensitive to showers above 10's of TeV while Milagro is the first EAS detector which is sensitive below 1 TeV. Our prototype detector, Milagrito, has produced results on the outburst of the Active Galactic N ucleus (AGN) Mrk501 and given suggestive evidence for TeV emission associated with a gamma-ray burst (Atkins et al., 1999,2000).

1.1 Scientific Goals of Milagro

Milagro will perform high-duty-factor, all-sky observations in the VHE region. We propose to use the Milagro detector to:

– Perform a survey of the Northern sky for steady and episodic sources.

– Perform the first sensitive search for emission from GRBs for energies from 100 GeV to many TeV.

– Detect VHE emission from the Crab and study its energy spectrum with a new, independent technique.

– Perform an all-year monitoring of TeV emission from the known flaring sources Markarian 421 and Markarian 501.

– Search for emission from the galactic plane.

– Detect the shadow on the moon with high significance and use it to calibrate the energy response of the detector and to perform a search for high-energy cosmic antiprotons.

– Detect the shadow of the sun with high significance and use it to continuously monitor the strength of the transverse component of the solar magnetic field.

– Perform a search for evaporating primordial black holes.

– Search for solar coronal mass ejections in an unprecedented energy regime over unprecedented time scales.

2 The Milagro Detector

The Milagro project will be sensitive to cosmic gamma rays below 1 TeV with the all-sky, high duty-factor capabilities of an EAS-array. 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 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 times at which the individual PMTs are struck by the light produced by particles in the shower front.

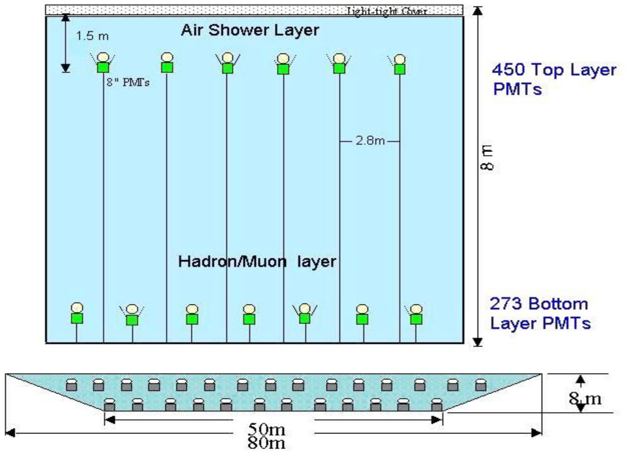

Fig. 2. Schematic cross section of the Milagro detector.

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.

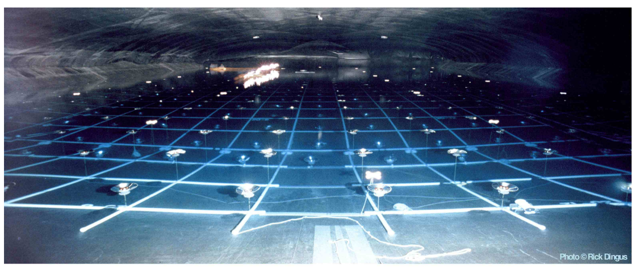

Fig. 3. A view of the Milagro pond under the cover showing the PMTs in the water.

The Milagro pond is covered by a light-tight barrier and instrumented with an array of 450 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 will be 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 (figures 2 & 3). The PMTs in both layers are secured by a Kevlar string to a 2.8m x 2.8m grid of sand-filled PVC pipe on the bottom of the pond. Milagro uses 20-cm-diameter Hamamatsu 10-stage R5912SEL PMTs. Custom-made front-end electronics boards provide timing and charge information for each PMT channel. The front-end boards also provide triggering information.

An event display for a typical air shower event in the Milagro pond is shown in figure 4. The line above the pond indicates the best fit direction of the shower front using the relative arrival times of the shower layer PMTs.

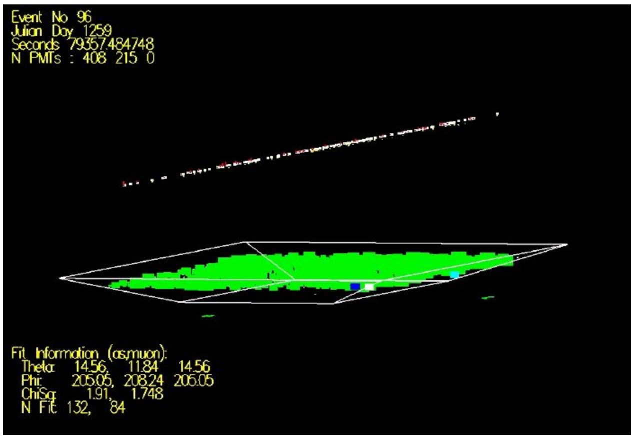

Fig. 4. Air Shower event in Milagro. The line is the timing fits from the Shower layer. The green squares are proportional in size to the signal in the Shower layer.

The Milagro detector becomes sensitive to gamma-ray induced showers of an energy of ∼200 GeV. For a gamma-ray energy spectrum of $E^{-2.4}$ the median energy for all triggers that reconstruct and pass our gamma-hadron separation is 4.7 TeV. A measure for the angular resolution of the Milagro detector is the DELEO/2 distribution of figure 5. 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. Although the resolution is dependent on the number of PMTs that are hit, on average for all triggers reconstructed the angular resolution is $\sim 0.75°$.

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. The detector triggers at about 2kHz, and the 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. It takes approximately 1.3 Terabytes of disk to store one year of all-sky data. In addition to the all-sky data set, there are "source" files that contain the full data for selected sources and the sun and moon. These files are recorded on DLT tape.

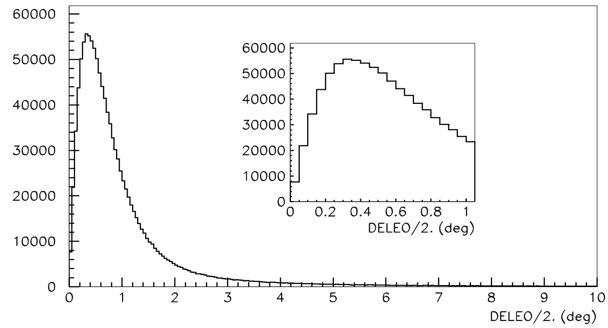

Fig. 5. Distribution of "DELEO/2" for Milagro. The intrinsic angular resolution of the shower fit is giving by the peak of this distribution. This indicates that Milagro's intrinsic angular resolution is approximately 0.35 degrees.

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 greater detail elsewhere in these proceedings (Sinnis, 2001). Figure 6 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.

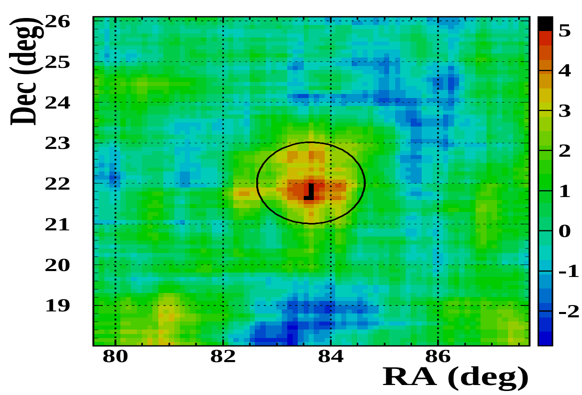

Fig. 6. Sky-map of the signal around the Crab. The colors represent the excess in sigmas, with the scale at the right of the plot. The black circle is centered on the true Crab position.

We have also looked for 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. The Milagro data for the region of the sky around MRK421 during the period Jan 17, 2001 - April 26, 2001 are shown in figure 7. At the position of Mrk421 there is a 2741 event excess corresponding to 5.2σ.

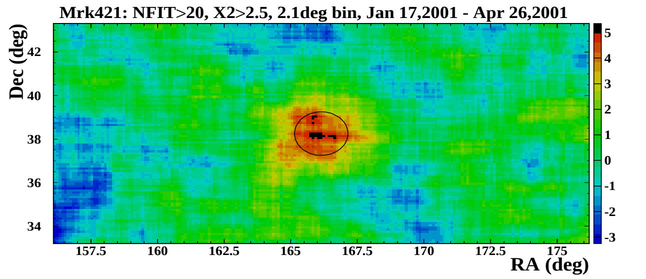

Fig. 7. Sky-map of the signal excess near MRK421. The scale at the right indicates the excess in sigmas for that color.

4 Future Improvements

Since construction of the Milagro pond was completed the detector has become operational and successfully observed several 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 ∼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.

4.1 Outrigger Water Tank Array

Approximately 70% of the showers that trigger the Milagro detector have cores that do not fall directly on the pond. It is vital to be able to determine the shower core position to substantially improve the performance of Milagro with respect to angular resolution, gamma-hadron separation and energy determination of each event. Without knowing the actual position of the core it is difficult to tell a low energy shower hitting the pond from a larger energy shower with a core 100m away. Additionally, because the shower front of the EAS is not truly flat but curved, not knowing the core position can give a systematic pointing error ($\sim 1°$) reducing the angular resolution and therefore sensitivity. Finally, our ability to perform gamma-hadron separation using the muon layer will be enhanced by an increased knowledge of the true core position.

In order to identify the core position we are deploying ∼170 individual cylindrical water tanks 3'h x 8'd made of fiberglass and lined with tivek. 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. These tanks will surround the pond in an area approximately 200m x 200m with the layout shown in figure 8. In addition to improving our energy resolution, studies show that the outrigger array will increase are sensitivity to gamma-ray sources by at least a factor of two.

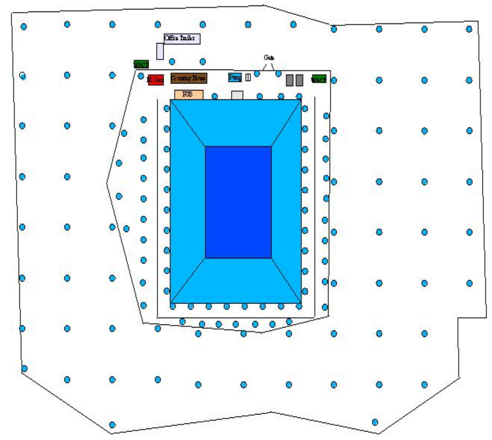

Fig. 8. Plan for the final layout of the Milagro detector. The pond will be surrounded by ∼170 outriggers.

4.2 Lowering The Energy Threshold

The Milagro detector is capable of high reconstruction efficiency and good angular resolution for gamma-ray showers down to ∼10 PMTs. Currently, the low energy reach is limited by the trigger system. We currently operate at the limit of the DAQ system's readout capability of about 2kHz. Using a simple multiplicity trigger this rate is reached at ∼60 PMTs, well below the detector's capability. Lowering it below 60 PMTs the trigger rate becomes rapidly dominated by non-shower events such as single muons, and is higher then our ability to read out. In order to reject these non-shower events, we are developing custom trigger processors using the time signature of the PMTs hit and muon layer information to reduce our threshold. We are currently implementing these custom processors.

A lower energy threshold will 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.

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