Milagro: A TeV Gamma-Ray Monitor of the Northern Hemisphere Sky

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Abstract. A new type of very high energy (> a few 100 GeV) gamma-ray observatory, Milagro, has been built with a large field of view of > 1 steradian and nearly 24 hours/day operation. Milagrito, a prototype for Milagro, was operated from February 1997 to May 1998. During the summer of 1998, Milagrito was dismantled and Milagro was built. Both detectors use a 80 m x 60 m x 8 m pond of water in which a 3 m x 3 m grid of photomultiplier tubes detects the Cherenkov light produced in the water by the relativistic particles in extensive air showers. Milagrito was smaller and had only one layer of photomultipliers, but allowed the technique to be tested. Milagrito observations of the Moon's shadow and Mrk 501 are consistent with the Monte Carlo prediction of the telescopes parameters, such as effective area and angular resolution. Milagro is larger and consists of two layers of photomultiplier tubes. The bottom layer detects penetrating particles that are used to reject the background of cosmic-ray initiated showers.

I A NEW TYPE OF TEV γ-RAY OBSERVATORY

Several active galactic nuclei and supernova remnants have now been observed to emit TeV gamma-rays. [1], [2], [3] These TeV observations were made by detecting the atmospheric Cherenkov light produced by the extensive air shower of particles created when a high energy gamma ray interacts in the atmosphere. Due to the limitations of this detection technique, these observatories only operate on clear, moonless nights and must point at the source using a large mirror. Therefore, observations of unpredictable, short duration transients, such as gamma-ray bursts, and all sky surveys are difficult.

A new type of TeV γ-ray observatory with a large field of view and continuous operation has recently been built in the Jemez Mountains near Los Alamos, NM (106.7^o W, 35.9^o N, 2650 m above sea level). The observatory is called Milagro, and the prototype which operated at the same site from February 1997 to May 1998 is called Milagrito [4].

Both detectors used the large pond of water 80 m x 60 m x 8 m which can be seen in the photograph of Figure 1. The pond has a light-tight cover. Milagro contains 723 photomultiplier tubes (PMTs) which are placed on a 3 m x 3 m grid in 2 layers at 1.5 m and 7 m below the surface. The prototype Milagrito had only one layer of 228 PMTs on a 3 m x 3 m grid spread over the smaller area of 30 m x 50 m.

FIGURE 1. Aerial photograph of the 60 m x 80 m x 8 m pond and cover used by Milagro and Milagrito. The pond as instrumented for Milagro contains 5 million gallons of water.

An extensive air shower is detected when the relativistic particles radiate Cherenkov light in the water causing several tens of PMTs to observe the light within a few 100 nsec of each other. From the relative timing of the photomultiplier tube signals, the direction of the particle or gamma-ray initiating the shower can be determined to $\sim$1 degree depending on the number of PMTs hit. The field of view is such that 50% of the showers detected are within 20 degrees of zenith and

90% are within 50 degrees. Almost all of these triggers are due to the background of showers that are initiated by charged cosmic rays. Monte Carlo simulations correctly predict the observed rate and zenith angle distribution of cosmic-ray initiated showers. Simulations of γ-ray initiated showers show sensitivity to γ-rays as low as $\sim$100 GeV with the effective area increasing as E $^{\sim 2}$, where E is the γ-ray energy, and flattening near 10 TeV.

II MILAGRITO OBSERVATIONS

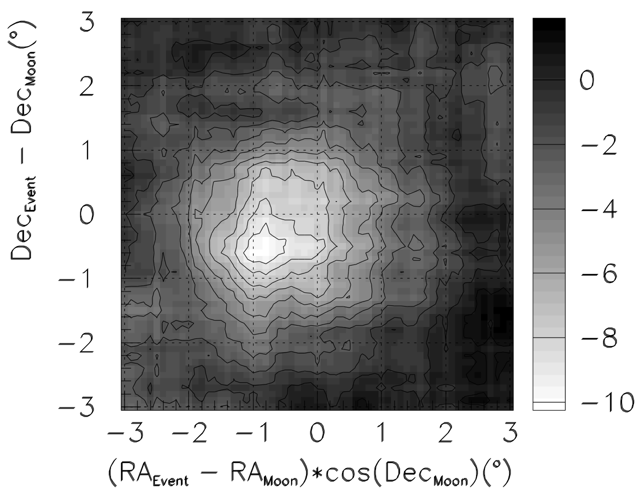

FIGURE 2. The shadow of the Moon due to the blockage of cosmic rays. The scale is in standard deviations of the Gaussian distributed background. The deficit is not located at the direction to the Moon, but is deflected in R.A. because the trajectories of the charged cosmic rays are bent by the Earth's magnetic field.

The performance of Milagrito has been confirmed by observations. The Moon blocks cosmic rays and a deficit of showers has been detected, which is a 10 sigma deviation from the background (Figure 2) [5]. The shape and size of the deficit is consistent with the Moon's angular size and Milagrito's angular resolution, and the deflection in Right Ascension is consistent with the Earth's magnetic field and the energy of the cosmic rays detected by Milagrito.

The simulations of gamma-ray initiated showers were verified by Milagrito observations of Mrk501, an x-ray selected BL Lac, which was a bright TeV source during 1997. The Milagrito detection of Mrk501 shown in Figure 3 was a 3.7 sigma deviation from the cosmic-ray background [6]. The flux and spectrum were well measured by several atmospheric Cherenkov telescopes and the significance of the Milagrito detection agrees with this spectrum folded with the Milagrito effective area. Simulations also indicate that the sensitivity of Milagrito was too low to detect the Crab nebula, the standard candle of TeV astronomy.

New observations have been performed by Milagrito that atmospheric Cherenkov telescopes have not been able to do because of their low duty cycle (5-10%) and small field of view (2-4 degrees in radius). Specifically, an all sky survey of the Northern Hemisphere was performed and no sources brighter than 5 times the Crab nebular flux were detected [7]. An all-sky search for 10 second duration transients was also done and none were found [8], which can place limits on the local density of evaporating primordial black holes. However, the most interesting results have

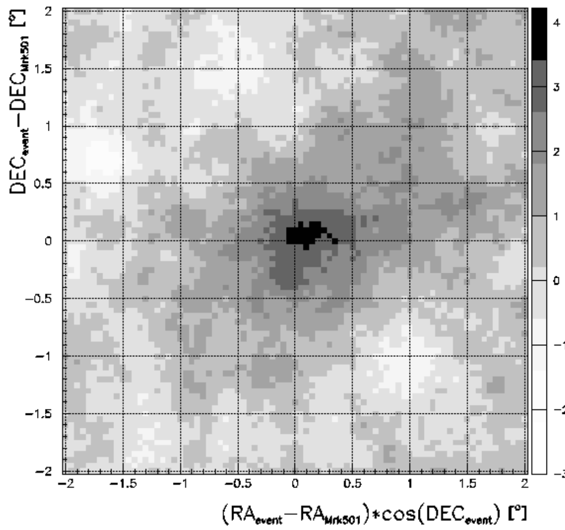

FIGURE 3. The number of showers in the vicinity of Mrk501 plotted in standard deviations of the background. For each position the number of showers is determined for directions within one degree of that position; thus neighboring bins are highly correlated. The position of Mrk 501 is at the center of the plot. The excess at Mrk 501 is 3624±990 events, or 3.7 σ.

been from the search for TeV emission correlated with BATSE detected bursts [9] and the detection of a coronal mass ejection from the Sun [10]. These analyses were both reported separately at this conference.

III MILAGRO EXPECTATIONS

Simulations and preliminary data indicate that Milagro will be more than 5 times more sensitive than Milagrito. The improvement comes from a combination of factors – larger area, improved angular resolution, and cosmic-ray background rejection. Milagro will be fully operational Fall 1999 with a data taking rate of 2000 showers per second resulting in more than 100 GBytes of data per day.

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