Milagro: A TeV Observatory for Gamma-Ray Bursts

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Abstract. Observation of prompt TeV γ-rays from GRBs requires a new type of detector to overcome the low duty factor and small field of view of current TeV observatories. Milagro is such a new type of very high energy ($>$ a few 100 GeV) gamma-ray observatory, which has 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 telescope's parameters, such as effective area and angular resolution. Milagro will have improved flux sensitivity over Milagrito due to larger effective area, better angular resolution and cosmic-ray background rejection.

TeV gamma-rays are a logical consequence of fireball models of gamma-ray bursts [1]. In these models the gamma rays can be created by synchrotron radiation of protons [2] or inverse Compton scattering of electrons accelerated in internal [3] or external [4] shocks of the ultra-relativistic energy flow. In most of these scenarios determining the upper energy end of the spectra provides strong constraints on the physical conditions of the emitting region. EGRET observations of GRBs show no indication of a high-energy cut off, and the average spectrum of the four brightest bursts detected by EGRET has a differential spectral index of 1.95 ± 0.25 extending up to 10 GeV [5].

However, gamma-ray emission above a few 100 GeV may not be observable for sources at redshifts much greater than 0.5 because of pair production with infrared extragalactic background photons [6,7]. Alternatively, if the distance to a gamma-ray burst source can be identified by optical redshift measurements, then the absorption of high-energy gamma-rays due to pair production can be used to measure the infrared intergalactic photon density. The spectrum produced by interactions with intergalactic photons will have a sharp exponential cutoff, and can be distinguished from the attenuation due to photons in the source, which result in a slower bend in the spectrum [8]. TeV gamma rays from GRBs can also be used to constrain theories of quantum gravity by measuring the constancy of the velocity of light for different energy photons [9].

At energies greater than 30 GeV, gamma-ray fluxes become too small for current satellite-based experiments to detect because of their small sensitive areas. Only ground-based experiments have large enough areas [10]. These instruments detect the extensive air showers produced by the high energy photons in the atmosphere, thus giving them a much larger effective area at high energies. These showers can be observed by detecting the Cherenkov light emitted by the cascading relativistic particles as they traverse the atmosphere, or by detecting the particles which reach ground level.

TeV gamma-ray emission from several astrophysical sources has been detected using atmospheric Cherenkov telescopes. These instruments have extremely large collection areas ($\sim 10^5$ m^2) and good hadronic rejection. Unfortunately, they have relatively narrow fields of view (a few degrees) and can operate only on dark clear nights, resulting in a low duty cycle. They are therefore ill suited to search for transient sources such as GRBs. Searches for GRBs at energies above 300 GeV have been made by slewing these telescopes within a few minutes of the notification of the GRB location [11]. No detections have been reported. However, because of the narrow field of view, coupled with the delay in slewing to the correct position, there have not been any prompt TeV gamma-ray observations at the GRB location.

I A NEW TYPE OF TEV γ-RAY OBSERVATORY

Milagro, a new type of TeV gamma-ray observatory, is ideally suited to observe TeV emission from gamma-ray bursts due to it's large field of view of > 1 sr and

$> 90\%$ duty factor. Milagro is located in the Jemez Mountains near Los Alamos, NM (106.7^o W, 35.9^o N, 2650 m above sea level). The observatory just became operational in Fall 1999, but a smaller the prototype, called Milagrito, was operated at the same site from February 1997 to May 1998 [12].

Both detectors used the large pond of water 80m x 60m x 8m 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 1.5m and 7m below the surface. The prototype Milagrito had only one layer of 228 PMTs on a 3m x 3m grid spread over the smaller area of 30m x 50m.

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

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) [13]. 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.

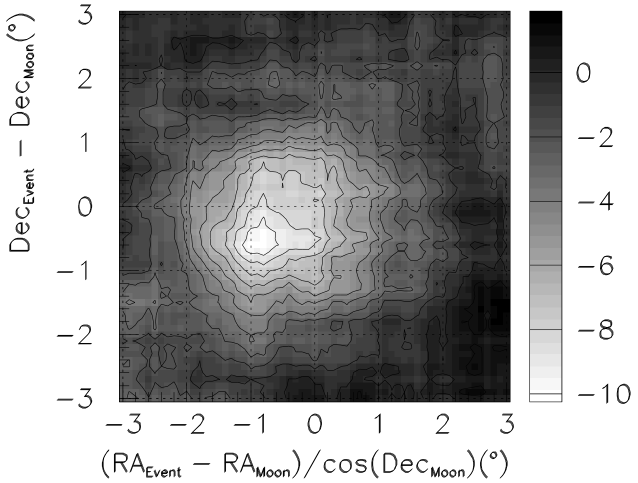

FIGURE 2. The shadow of the Moon due to the blockage of cosmic rays. The scale is in standard deviations of the Gaussian distributed background. The deficit is not located at the direction to the Moon, but is deflected in R.A. because the trajectories of the charged cosmic rays are bent by the Earth's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

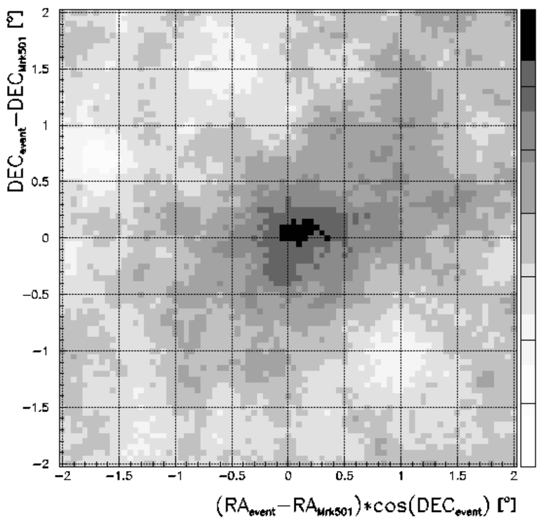

FIGURE 3. The number of showers near Mrk501 plotted in standard deviations of the background.

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 [14]. 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. Specifically, an all sky survey of the Northern Hemisphere was performed and no sources brighter than 5 times the Crab nebula flux were detected [15]. An all-sky search for 10 second duration transients was also done and none were found [16], which places limits on the local density of evaporating primordial black holes. However, the most interesting result was the evidence of TeV emission from GRB970417a. During T90, 18 events were observed when 3.46 ± 0.11 were expected for a direction 3.8^o from the position determined by BATSE. The probability is 2.8×10^{-5} that such an excess is due to a fluctuation of the background anywhere within the BATSE 90% confidence interval (statistical +

systematic) of 9.4^o radius. And the probability for any of the 54 bursts that were within Milagrito's field of view to have such an improbable excess is 54 $\times$ 2.8$\times10^{-5}$ = 1.5$\times10^{-3}$. More details were reported separately at this conference [17].

III MILAGRO EXPECTATIONS

Milagro has a larger effective area and better angular resolution than Milagrito. Milagro is also be able to reject some of the cosmic ray background due to the addition of a lower layer of photomultiplier tubes, which Milagrito did not have. Milagro began taking data in Fall 1999 and will soon be operating at at a rate of ∼2000 showers per second (Milagrito triggered on ∼300 showers per second) resulting in more than 100 GBytes of data per day.

If the Milagrito result from GRB970417a is not a random fluctuation of the background, then the improvements of Milagro over Milagrito will produce exciting results about gamma-ray bursts. The increased effective area will result in observations of weaker, but still low-redshift, bursts, and more TeV γ-rays in brighter bursts will allow correlations between TeV and sub-MeV light curves. The improved angular resolution will yield localizations for rapid TeV, x-ray, optical, and radio afterglow observations. And the improved energy resolution will measure the highest energy γ-rays from a gamma-ray burst.

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