A Study of Very-High-Energy Emission from Gamma-Ray Bursts

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ABSTRACT

Milagrito, a detector sensitive to γ-rays at very high energies (VHE) monitored the northern sky from February 1997 through May 1998. With a large field of view and high duty cycle, this instrument was well-suited to perform a search for VHE counterparts to γ-ray bursts (GRBs). In this paper we report on a search made with Milagrito for such counterparts to bursts originally observed by the Burst and Transient Source Experiment (BATSE). BATSE observed 54 GRBs within the Milagrito field of view during the above period. Milagrito detected a substantial excess of events coincident in time and space with one of these bursts, GRB 970417a. The excess had chance probability 2.8×10^{-5} for being a fluctuation of the background; the probabilioty for observing an excess at least this large from any of the 54 bursts is 1.5×10^{-3}. No other significant correlations were detected from the remaining bursts. The statistical aspects and possible physical implications of this result are discussed.

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1. Introduction

Since their discovery in the 1970's (1), GRBs have remained among the most enigmatic objects in the Universe. Our understanding of these objects was greatly enhanced by results from the Compton Gamma-Ray Observatory (CGRO), which contained experiments sensitive to photons at energies from 50 keV to 30 GeV. One of these, BATSE, a wide field instrument sensitive at energies from 50 keV to above 300 keV, has detected several thousand γ-ray bursts. A crucial question is whether GRB spectra extend to TeV energies. The EGRET experiment on board CGRO detected 8 γ-ray bursts with photon energies ranging from 100 MeV to 18 GeV; to date, there is no evidence of a high energy cutoff in any γ-ray burst spectrum.

However, for sources at redshifts much greater than z=0.5, then VHE γ-ray emission may not be observable because of absorbitive pair production interactions with the infrared extragalactic background photons (5; 6). Recent measurements of several γ-ray bursts with optical afterglows have shown redsifts of $z > 0.8$ with only one exception (REFS ?). These measurements indicate that the measured intensity of the γ-ray emission is not well-correlated with distance. This suggests that observation of TeV emission from a γ-ray burst, which requires a relatively nearby source, may not be correlated with the intensity of the sub-MeV BATSE emission.

At energies greater than 30 GeV, photon fluxes from most astrophysical sources become too low for the satellite-based experiments to detect, because their detectors are constrained to have small area. Instead, ground based experiments detect these γ-rays by observing the extensive air showers they induce in the atmosphere. 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.

Detection of VHE γ-rays from astrophysical sources has been firmly established by atmospheric Cherenkov telescopes (7; 8). These telescopes have extremely large collection areas ($\sim 10^5 m^2$) and good cosmic ray rejection and are therefore able to detect low fluxes of γ-rays. However, they have a relatively narrow field and can operate only on dark, clear nights resulting in a duty cycle of 10%. Searches for γ-ray bursts at energies above 300 GeV have been made by slewing these telescopes within a few minutes after the notification of the γ-ray burst location (9). No detections of γ-ray bursts were reported, and the narrow field, coupled with the delay in slewing to the correct position does not allow the calculation of stringent upper limits.

At higher energies, wide field instruments have reported possibly significant deviation of the probability distribution from the background when combining data from all satellite-detected γ-ray bursts within their field of view; however, no single burst showed a convincing signal (13). The HEGRA AIROBICC Cherenkov array had two bursts within its field of view, and one burst showed an excess over background in a time interval longer than the sub-MeV emission. But the observed excess was not consistent with satellite measurements and was not claimed as a firm detection (12).

Milagro, a new type of VHE γ-ray observatory, with a field of view of over one steradian and a

high duty cycle, began operation in February 1999, near Los Alamos, New Mexico. Milagrito (11), a limited prototype operated from February 1997 to May 1998. During this time interval, 54 γ-ray bursts detected by BATSE were within Milagrito's field of view. This paper reports on the search for TeV γ-ray emission from these 54 γ-ray bursts, but concentrates more specifically on the significance of one GRB candidate.

2. The Milagrito Detector

Milagrito consisted of 228 8-inch photomultiplier tubes (PMTs) submerged in the purified water of a 30 m x 50 m covered reservoir, with the tubes at the vertices of a square grid with spacing 2.8 m. Data were collected at water depths of 0.9, 1.5 and 2.0 m above this layer of PMTs. These sensors detected the Cherenkov light produced as the charged shower particles traversed the water. In addition, the interaction with the water transfers the energy of the abundant γ-rays in the air shower via pair production and Compton scattering to relativistic charged particles, which then produce Cherenkov light. The continuous medium allows for the efficient detection of the shower particle incident on the reservoir, even though the sensors are not contiguous. Milagrito was sensitive to showers produced by primary γ-rays with energies as low as $\sim$100 GeV. The relative arrival times of the shower front at the PMTs were used to reconstruct the angle of the incoming air showers. Milagrito triggered when 100 PMTs or more in the reservoir each detected at least one photoelectron within a 300 ns time window. Events were collected at a rate of $\sim$300 Hz; almost all of these triggers are caused by the isotropic cosmic ray background. The ability of this instrument to detect VHE γ-rays was verified by the observation of active galaxy Markarian 501 during its 1997 flare (10). These and other tests showed that the instrument had an angular resolution of about 1°.

3. Observations and Results

A search was conducted for excesses of events above the isotropic background cosmic rays in the Milagrito data and coincident with some BATSE γ-ray burst within 45° of the zenith of Milagrito; this angular region is where Milagrito had the best combination of sensitivity and low effective energy threshold. For each burst, a circular search region was defined by adding the BATSE systematic and statistical location errors in quadrature to obtain the 90% confidence interval. The search region was tiled with an array of overlapping 1.6° radius bins spaced 0.2° apart in RA and DEC. This radius was derived from the measured angular resolution of Milagrito (10; 11) and was selected prior to the search. The number of events falling within each of the 1.6° bins was tallied for the duration of the burst reported by BATSE. This time period, known as T90, is that in which the BATSE flux rose from 5% to 95% of its total. T90 was chosen because EGRET detected γ-rays above a GeV at higher fluxes during T90 than for longer durations(2). The size of the search bin, 1.6°, was derived from the measured angular resolution of Milagrito (10; 11) and was selected prior

to the search.

In order to establish the significance of an excess, the background due to cosmic ray-induced showers must be estimated and fluctuations, both statistical and systematic, must be understood. The angular distribution of background events on the sky was characterized using two hours of data surrounding each burst. This distribution was then normalized to the number of events (N_{T90}) detected by Milagrito over the entire sky during T90 (N_{T90}). The resulting background data were also binned in 1.6° bins spaced 0.2° apart. The Poisson probability that the number of events in each 1.6° bin was due to a background fluctuation was calculated and the bin with lowest such probability was then taken as the candidate position of a VHE γ-ray counterpart to the BATSE burst.

The probability of obtaining the observed significance within the entire search region was determined by Monte Carlo simulations using the following procedure. For each burst a set of simulated signal maps was obtained by randomly drawing N_{T90} events from the background distribution. These maps were searched, as before, for a significant excess within the search region defined by BATSE. The probability after accounting for the size of the search region is given by the ratio of the number of simulated data sets with probability less than that observed for the actual data to the total number of simulated data sets. The distribution of the probabilities for the 54 γ-ray bursts after correcting each for the size of its search area is given in figure 1.

Of the 54 bursts, one GRB 970417a, shows a four sigma excess above background in the Milagrito data. The BATSE detection of this burst shows it to be relatively weak burst, but typical, with a fluence in the 50–300 keV energy range of 1.5×10^{-7} ergs/cm^2 and T90 of 7.9 seconds. BATSE determined the burst position to be RA = 295.66°, DEC = 55.77°. The low BATSE fluence results in a large 1 σ positional uncertainty of 6.23° (1-sigma) and leads to search region for TeV emission with radius 9.4°. The 1.6° radius bin with the largest excess in the Milagrito data is centered at RA = 289.89° and DEC = 54.0°, corresponding to a zenith angle of 21°. This Milagrito-determined location is 3.8° away from the BATSE-determined position and has a 1-sigma uncertainty of approximately 0.5°, so it is both completely consistent with, and much better determined, than that of the BATSE burst. Figure 2 shows the number of counts in this search region for the array of 1.6° bins. The bin with the largest excess has 18 events with an expected background of 3.46 ± 0.11 (statistical error based on the background calculation method used). The Poisson probability for observing a signal at least this large due to a background fluctuation is 2.89×10^{-8}. The probability of such a detection within the entire 9.4° search region for this burst was found by Monte Carlo simulation to be 2.8×10^{-5}. Because 54 bursts were examined, the chance probability of background fluctuating to the level observed for GRB 970417a for any of these bursts is 1.5×10^{-3}. The individual events contributing to this excess were examined for systematic or instrumental causes of this excess and none were found.

Although the initial search was limited to T90, for GRB 970417a longer time intervals were examined. EGRET observed longer duration GeV emission (2), and TeV afterglows are predicted

by several models (3). To allow for the positional uncertainty of the TeV γ-ray detection during T90, the radius of the search bin was increased to 2.2°, shown by simulation to be optimal for the given parameters. A search for TeV γ-rays integrated over long time intervals of one hour, two hours and a day after the GRB start time did not show any significant excess. Lightcurves of shorter time interval searches where the data are binned in intervals of one second and of T90 (7.9 s) are shown in figure 3. A preliminary analysis of these data reveal no statistically compelling evidence for TeV after-flares.

4. Discussion

If the observed excess of events in Milagrito is indeed associated with GRB 970417a then it represents the highest energy photons yet detected from a GRB in coincidence with the sub-MeV emission. The TeV spectrum and maximum energy of emission is difficult to determine from Milagrito data (11). Monte Carlo simulations of γ-ray-initiated air showers show that the effective area increases smoothly with energy, so that the precise energy threshold is undefined. Figure 4 shows the implied fluence of this observation as a function of upper cutoff energy for a range of power-law input spectra.

Some information about the energies of the γ-rays observed for GRB 970417a can be obtained by considering the response of the combined untriggered counting rates of the individual PMTs in Milagrito. Detector simulations of the dependence of PMT counting rates to γ-ray induced air-showers indicate that, despite the large background, these rates are more sensitive than the standard shower data at energies of a few hundred GeV, but are only sensitive to very large fluxes (11). No excess was observed in these rates, which implies that the air-showers detected by Milagrito were due to γ-rays at energies above several hundred GeV.

High energy γ-rays from sources at cosmological distances will be absorbed via electron-positron pair production. Several studies find that the opacity due to pair production for >200 GeV γ-rays exceeds one for redshifts larger than 0.3 (5; 6). This allows us to place an upper limit on the redshift of GRB 970417a to be less than $\sim$0.3, making this a relatively nearby event.

5. Conclusion

An excess of events with chance probability 2.8×10^{-5} coincident both spatially and temporally with the BATSE emission for GRB 970417a was observed using Milagrito. The probability that an excess of this significance would be observed from the entire sample of 54 bursts is 1.5×10^{-3}. This result was found, almost simultaneously by two independent analyses (14; 15). The fluence above 10 GeV is in the range 10^{-4} to 10^{-6} ergs/cm^2 and the spectrum must extend with no cutoff to at least a few hundred GeV. The TeV fluence inferred from this result is at least an order of magnitude greater than the sub-MeV fluence, and the maximum energy of emission extends to

hundreds of GeV.

If the observed excess coincident with GRB 970417a is not a fluctuation of the background, then a new class of γ-ray bursts bright at TeV energies has been observed. A search for other coincidences with BATSE, to verify this result, will be continued with the current instrument, Milagro, which has increased sensitivity to γ-ray bursts at energies between 0.1 and 10 TeV.

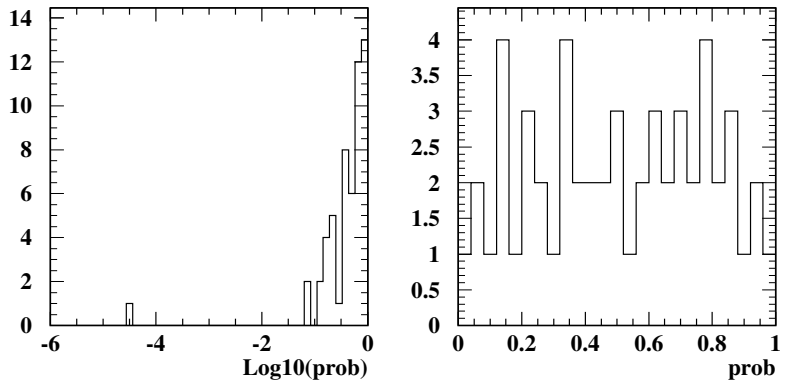

Fig. 1.— The distribution of probabilities, for each of the 54 bursts, that the observed signal at the candidate TeV position was a background fluctuation. Both plots show the same data, with a linear and logarithmic scale for the x-axis

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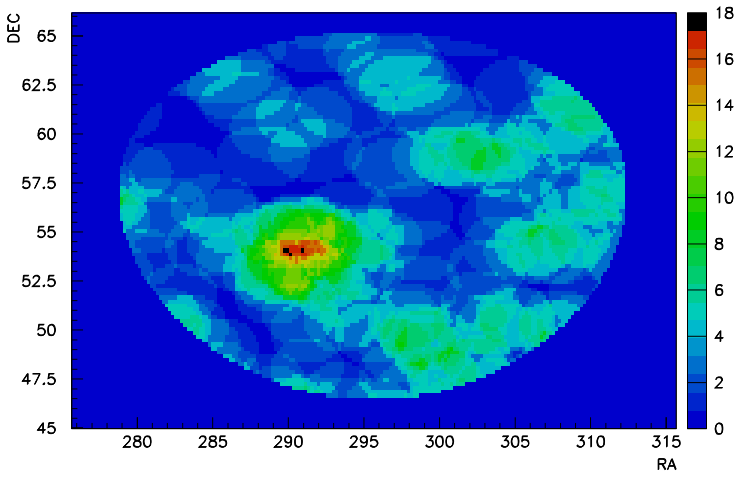

Fig. 2.— Number of events recorded by Milagrito during T90 in the region of GRB 970417, each bin contains the number of events in a 1.6 degree radius.

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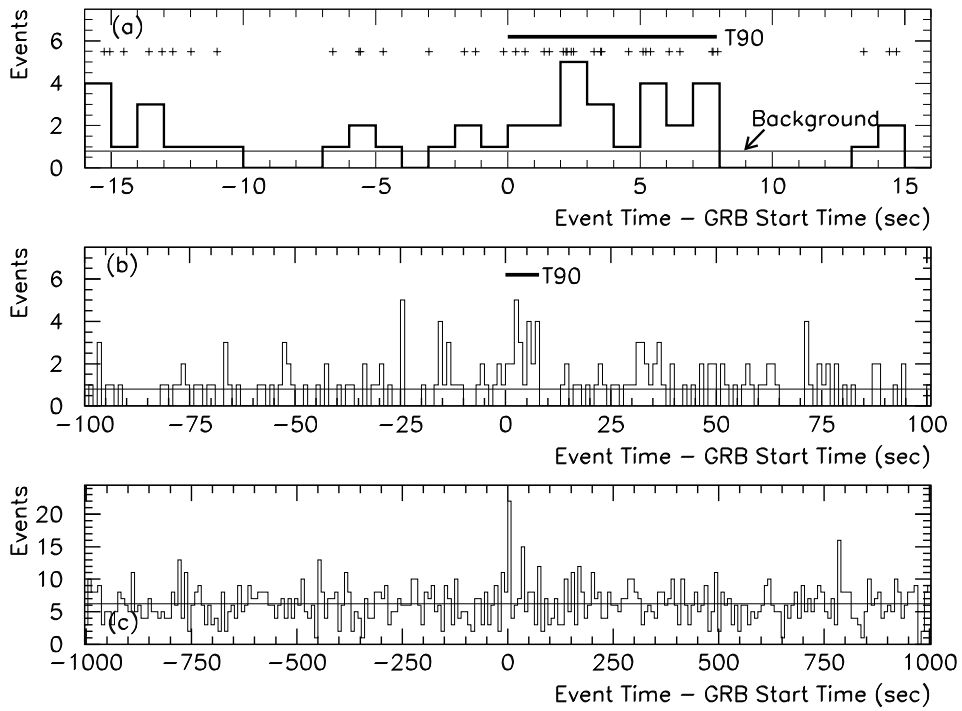

Fig. 3.— Lightcurves for GRB 970417a: (a) The crosses indicate the arrival time of events from the position of the candidate TeV counterpart for 30 seconds surrounding the BATSE trigger time. The histogram showed the same data binned in 1 second intervals,(b) Integrated in 1 sec intervals for 200 seconds surrounding the burst and (c) integrated in bins of 7.9 seconds (T90) for 2000 seconds

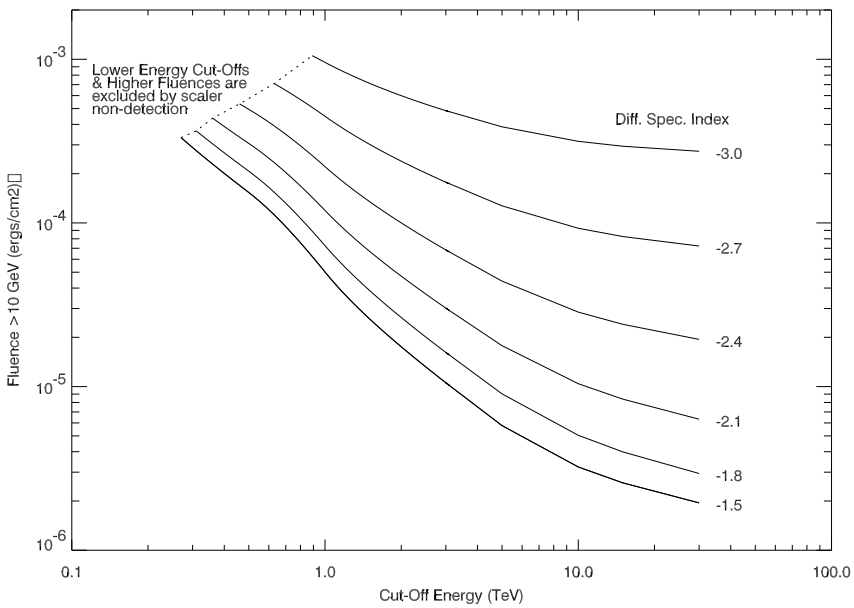

Fig. 4.— Implied fluences of this candidate for a range of input spectra and high energy cutoffs