Evidence for TeV Emission from GRB 970417a

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ABSTRACT

Milagrito, a detector sensitive to very high energy gamma rays, monitored the northern sky from February 1997 through May 1998. With a large field of view and a high duty cycle, this instrument was well suited to perform a search for TeV gamma-ray bursts (GRBs). We report on a search made for TeV counterparts to GRBs observed by BATSE. BATSE detected 54 GRBs within the field of view of Milagrito during this period. An excess of events coincident in time and space with one of these bursts, GRB 970417a, was observed by Milagrito. The excess has a chance probability of 2.8×10^{-5} of being a fluctuation of the background. The probability for observing an excess at least this large from any of the 54 bursts is 1.5×10^{-3}. No significant correlations were detected from the other bursts.

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1. Introduction

Gamma-ray bursts were discovered over 30 years ago (Klebesadel, Strong & Olson 1973). Although thousands of GRBs have been observed the physical processes responsible for them are still unknown. The understanding of these objects was greatly enhanced by results from the Compton Gamma Ray Observatory, which contained experiments sensitive to photons from 50 keV to 30 GeV. One of these experiments, BATSE, a wide field instrument sensitive to gamma rays from 50 keV to above 300 keV (Paciesas et al. 1999), has detected several thousand GRBs. EGRET (Esposito et al. 1999) detected 7 GRBs with photon energies ranging from 100 MeV to 18 GeV (Dingus, Catelli & Schneid 1998). No high energy cutoff above a few MeV has been observed in any GRB spectrum, and emission up to TeV energies is predicted in several models (Dermer, Chiang & Mitman 1999; Pilla & Loeb 1998; Totani 1998a; Meszaros & Rees 1994).

Very high energy gamma-ray emission may not be observable for sources at redshifts much greater than 0.5 because of pair production with infrared extragalactic background photons (Jelley 1966; Gould & Schreder 1966). Recent observations of lower-energy afterglows associated with several GRBs have allowed the measurement of 9 redshifts, either by measuring the spectrum of the optical afterglow, or by measuring the spectrum of the putative host galaxy. These redshifts cover a range between 0.4 and 3.4, and imply that the distribution of intrinsic luminosities is broad (Lamb & Reichert 1999). This suggests that the intensity of TeV gamma-ray emission from a GRB (which requires a relatively nearby source) may not be well correlated with the intensity of the sub-MeV emission detected by BATSE.

At energies greater than 30 GeV, gamma-ray fluxes from most astrophysical sources become too small for current satellite-based experiments to detect because of their small sensitive areas. Only ground-based experiments (Hoffman, Sinnis, Fleury & Punch 1999; Ong 1998; Catanese & Weekes 1999) have areas large enough to detect these sources. 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 (Connaughton et al. 1997). 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.

At energies greater than 10 TeV, the Tibet collaboration reported a possibly significant deviation of the probability distribution from background, for the superposition of all the bursts within their field of view. However, no single burst showed a convincing signal (Amenomori et al. 1996). Two GRBs occurred within the field of view of the HEGRA AIROBICC Cherenkov array. One very long duration burst showed an excess over background from a direction not entirely consistent with the sub-MeV emission, so this was not claimed as a firm detection (Padilla et al. 1998).

Milagro, a new type of TeV gamma-ray observatory with a field of view greater than one steradian and a high duty cycle, began operation in December 1999 near Los Alamos, New Mexico. A prototype detector, Milagrito (Atkins et al. 1999a), operated from February 1997 to May 1998, during which 54 GRBs detected by BATSE were within 45° of zenith of Milagrito. This paper reports on the search for TeV gamma-ray emission from these 54 gamma-ray bursts, but concentrates more specifically on GRB 970417a.

2. The Milagrito Detector

Milagrito consisted of a planar array of 228 8-inch photomultiplier tubes (PMTs) submerged in a light-tight water reservoir (Atkins et al. 1999a). The PMTs were located on a square grid with 2.8 m spacing, covering a total area of 1800 m^2. Data were collected at water depths of 0.9, 1.5 and 2.0 m above the PMTs. The PMTs detected the Cherenkov light produced as charged shower particles traversed the water. The abundant gamma rays in the air shower interact with the water via pair production and Compton scattering to produce additional relativistic charged particles, increasing the Cherenkov light yield. The continuous medium and large Cherenkov angle (41°) result in the efficient detection of shower particles incident on the reservoir with the array of PMTs. Simulations show that Milagrito was sensitive to showers produced by primary gamma 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 direction of the incoming air shower. The trigger required $>$100 PMTs to register at least one photoelectron within a 300 ns time window. Events were collected at a rate of $\sim$300 s^{-1}; almost all of these triggers were caused by the hadronic cosmic-ray background. The capability of Milagrito to detect TeV gamma rays was demonstrated by the observation of the active galaxy Markarian 501 during its 1997 flare (Atkins et al. 1999b). The instrument had an angular resolution of about 1°.

3. Observations and Results

A search was conducted in the Milagrito data for an excess of events, above those due to the background of cosmic rays, coincident with BATSE GRBs. Only bursts within 45° of zenith of Milagrito were considered because the sensitivity of Milagrito fell rapidly with increasing zenith angle. For each burst, a circular search region on the sky was defined by the BATSE 90% confidence interval, which incorporates both the statistical and systematic position errors (Briggs et al. 1999).

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 appropriate for the measured angular resolution of Milagrito (Atkins et al. 1999b; Atkins et al. 1999a). The number of events falling within each of the 1.6° bins was summed for the duration of the burst defined by the T90 interval reported by BATSE. This time period is that in which the BATSE fluence rose from 5% to 95% of its total. T90 was chosen, *a priori*, because the EGRET detections were much more significant during T90 than during longer time intervals (Hurley et al. 1994).

For each GRB, 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. The resulting background data were also binned in the same 1.6° overlapping bins as the initial data. Each bin in the actual data was compared to the corresponding bin in the background map. The Poisson probability of a background fluctuation giving rise to an excess at least as large as that observed was calculated. The bin with the lowest such probability was then taken as the most likely position of a very high energy gamma-ray counterpart to that particular BATSE burst.

The chance probability of obtaining at least the observed significance anywhere 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 the most significant excess within the search region defined by the BATSE 90% confidence interval. 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 in the actual data to the total number of simulated data sets. The distribution of the chance probabilities obtained by this method for the 54 GRBs is given in Figure 1. Details of a somewhat different analysis, which yields consistent results with those reported here, as well as more detailed results from the other 53 bursts, will be described elsewhere (Leonor 2000).

One of these bursts, GRB 970417a, shows a large excess above background in the Milagrito data. The BATSE detection of this burst shows it to be a relatively weak burst 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 = 295.7°, DEC = 55.8°. The low BATSE fluence results in a large positional uncertainty of 6.2° (1σ). The resulting search region for TeV emission has a radius of 9.4°. The 1.6° radius bin with the largest excess in the Milagrito data is centered at RA = 289.9° and DEC = 54.0°, corresponding to a Milagrito zenith angle of 21°. This location is consistent with the position determined by BATSE. The uncertainty in the candidate location is approximately 0.5° (1σ), much better than the BATSE uncertainty. 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 an excess at least this large due to a background fluctuation is 2.9×10^{-8}. The probability of such an excess or greater anywhere within the search region for this burst was found by the Monte Carlo simulation described above to be 2.8×10^{-5} (see Figure 1). For 54 bursts, the chance probability of background fluctuating to at least the level observed for GRB 970417a for at least one of these bursts is 1.5×10^{-3}. The individual events contributing to this excess were examined. The distributions of the number of tubes hit per event and the shower front reconstructions were consistent with those from other shower events. There is no evidence that the detector was malfunctioning during the burst analysis time period.

Although the initial search was limited to T90, upon identifying GRB 970417a as a candidate, longer time intervals were also examined. EGRET observed longer duration GeV emission (Hurley et al. 1994), and TeV afterglows are predicted by several models (Meszaros & Rees 1994; Totani 1998b). A search for TeV gamma rays integrated over time intervals of one hour, two hours and a day after the GRB start time did not show any significant excesses. Histograms of shorter time intervals, where the data are binned in intervals of one second, are shown in Figure 3. An analysis of the data also revealed no statistically significant 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. The energy spectrum and maximum energy of emission are difficult to determine from Milagrito data. The small size of the pond compared to the lateral extent of typical air showers, along with the poor ability of this instrument to measure the amount of energy deposited in the pond, make the estimation of shower energy on an event by event basis nearly impossible. The very high energy fluence implied by this observation depends on the spectrum and upper energy cutoff of the emission, which Milagrito is unable to determine. Monte Carlo simulations of gamma-ray-initiated air showers show that the effective area of Milagrito increases slowly with energy, so that the energy threshold is undefined (Atkins et al. 1999a). However, Milagrito had very little sensitivity below 100 GeV, so this observation indicates the emission of photons with energies greater than a few hundred GeV from GRB 970417a. Figure 4 shows the implied fluence of this observation above 50 GeV as a function of upper cutoff energy for several assumed differential power-law spectra. The observed cosmic-ray event rate agrees well with the rate predicted by simulations (Atkins et al. 1999b) implying that the systematic error on the energy scale for Milagrito is $<30\%$.

Several studies (Salamon & Stecker 1998; Primack, Bullock, Somerville & Macminn 1999) find that the opacity due to pair production for >200 GeV gamma rays exceeds one for redshifts larger than ~ 0.3. Thus, if Milagrito has detected high energy photons from GRB 970417a, it must be a relatively nearby object. The observed excess implies a fluence above 50 GeV between 10^{-3} and 10^{-6} ergs/cm^2 and the spectrum must extend to at least a few hundred GeV. The very high energy gamma-ray fluence (> 50 GeV) inferred from this result is at least an order of magnitude greater than the sub-MeV fluence.

To summarize, an excess of events with chance probability 2.8×10^{-5} coincident both spatially and temporally with the BATSE observation for GRB 970417a was observed using Milagrito. The chance probability that an excess of at least this significance would be observed from the entire sample of 54 bursts is 1.5×10^{-3}. If the observed excess coincident with GRB 970417a is not an unlikely fluctuation of the background, then a GRB bright at TeV energies has been identified. A search for other coincidences with BATSE will be continued with the current instrument, Milagro, which has significantly increased sensitivity to GRBs between 0.1 and 10 TeV.

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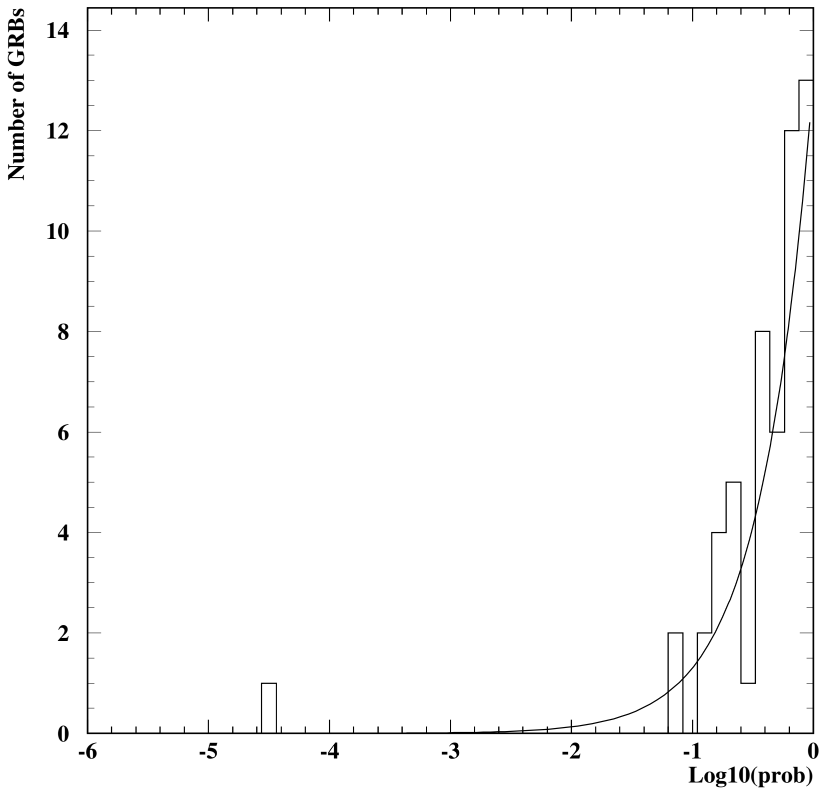

Fig. 1.— The distribution of probabilities, that the observed excess number of events at the candidate TeV position was a background fluctuation, for each of the 54 bursts. The curve indicates the expected distribution of probabilities for a sample drawn from background. The entry at -4.5 corresponds to GRB 970417a.

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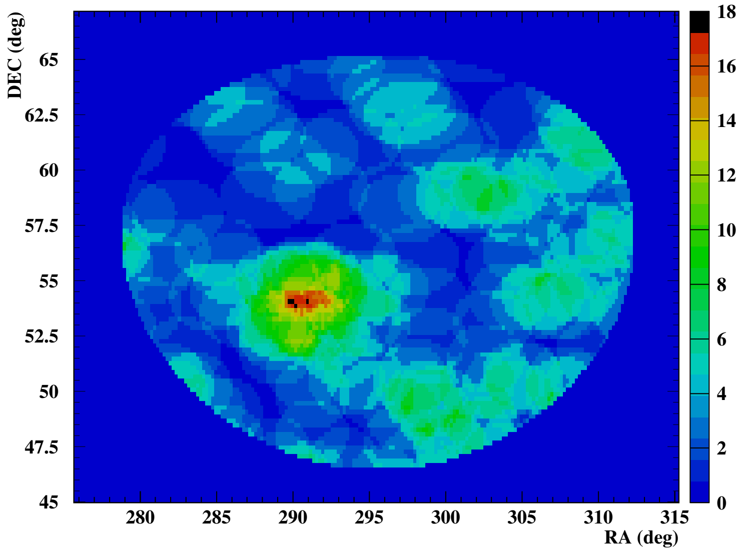

Fig. 2.— Number of events recorded by Milagrito during T90 in overlapping 1.6° radius bins in the vicinity of GRB 970417a.

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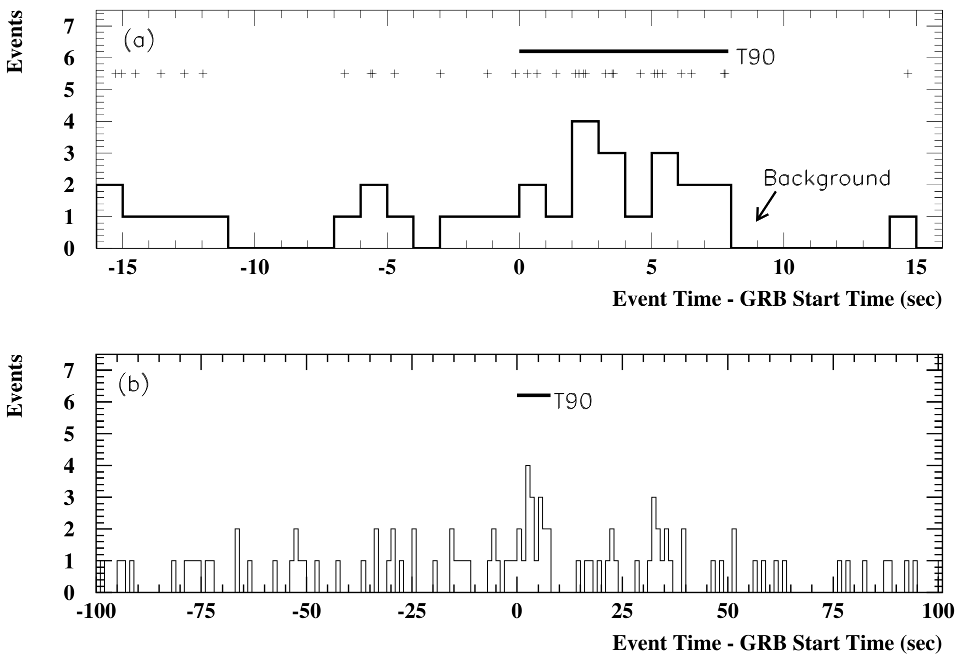

Fig. 3.— GRB 970417a: (a) The crosses indicate the arrival time of events from within a 1.6° radius of the candidate TeV counterpart for ±15 s around the start of T90. The histogram shows the same data binned in 1 second intervals. (b) The Milagrito data integrated in 1 sec intervals for ±100 s around the start of T90 (13:53:35.689 UT).

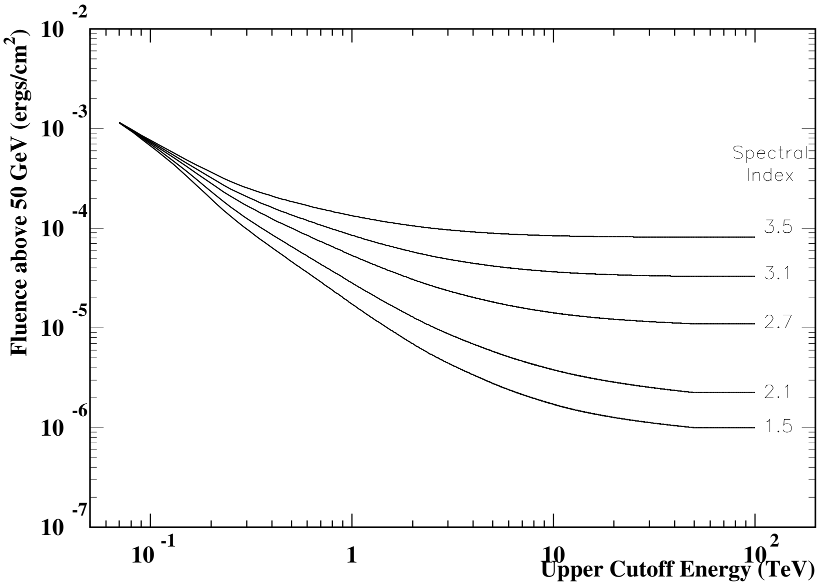

Fig. 4.— The implied fluence (> 50 GeV) of very high energy emission from GRB 970417a as a function of high-energy cutoff for five assumed differential spectral indices.