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

or

Evidence for TeV Emission from a Gamma-Ray Burst

or

A Possible TeV Counterpart to GRB 970417a

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ABSTRACT

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Milagrito, a detector sensitive to very high energy γ-rays, 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 TeV counterparts to γ-ray bursts (GRBs). In this paper we report on a search made with Milagrito for such counterparts to GRBs observed by the Burst and Transient Source Experiment (BATSE). BATSE observed 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. The analysis is presented and the implications are discussed.

1. Introduction

Since the discovery of the first GRB in 1968 (Klebesadel Strong & Olson 1973), and despite thousands of examples, the physical processes producing γ-ray bursts is not yet known. 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(Paciesas et al. 1999), a wide field instrument sensitive to γ-rays with energies between 50 keV to above 300 keV, has detected several thousand γ-ray bursts. EGRET(Esposito et al. 1999) detected 7 γ-ray bursts 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 1998). This paper reports on evidence for >200 GeV emission from a GRB as observed by Milagrito, a recently built, large field of view, TeV observatory.

TeV γ-ray emission may not be observable for sources at redshifts much greater than 0.5 because of pair production with infrared extragalactic background photons (Gould & Schreder 1966; Jelley 1966). Recent measurements of lower-energy afterglows associated with several γ-ray bursts have allowed the measurement of 9 redshifts, either by measuring the spectrum of the optical afterglow, or by measuring the spectrum of the host galaxy. These redshifts cover a wide range between $0.4 < z < 3.42$, and imply that the distribution of luminosities is broad (Lamb & Reichert 1999). This suggests that observation of TeV emission from a γ-ray burst, 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, γ-ray fluxes from most astrophysical sources become too small for the 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 by observing the extensive air showers they produce 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 γ-ray emission from astrophysical sources has been detected using atmospheric Cherenkov telescopes. These instruments have extremely large collection areas ($\sim 10^5$ m^2) and good hadronic background rejection and are therefore able to detect low fluxes of γ-rays. However, they have relatively narrow fields (a few degrees) and can operate only on dark clear nights, resulting in a duty cycle of $< 10\%$. 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; but the narrow field, coupled with the delay in slewing to the correct position has resulted in no prompt TeV observations at the GRB location.

At energies greater than 10 TeV, the Tibet collaboration reported a possibly significant deviation of the probability distribution from the background of all the bursts within their field of view. However, no single burst showed a convincing signal (The Tibet As Gamma Collaboration: 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 in a time interval not entirely consistent with the sub-MeV emission. The location of the excess was somewhat offset from the satellite measurements so this was not claimed as a firm detection (Padilla et al. 1998).

Milagro, a new type of TeV γ-ray observatory, with a field of view of greater than one steradian and a high duty cycle, began operation in February 1999, near Los Alamos, New Mexico. A prototype detector, Milagrito (Atkins et al. 1999), was operated from February 1997 to May 1998, during which 54 GRBs detected by BATSE were within its 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 one GRB candidate.

2. The Milagrito Detector

Milagrito consisted of a planar array of 228 8-inch photomultiplier tubes (PMTs) submerged in a light-tight water reservoir. The PMTs were located on a square grid with spacing 2.8m, 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. In addition, Cherenkov light is produced by relativistic charged particles resulting from the interaction of the abundant γ-rays in the air shower with the water via pair production and Compton scattering. The continuous medium and large Cherenkov angle (41^o) allows for the efficient detection of shower particles incident on the reservoir with a sparse array of PMTs. 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 direction of the incoming air showers. The trigger required >100 PMTs registering 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 γ-rays was demonstrated by the the observation of the active galaxy Markarian 501 during its 1997 flare (Atkins et al. 1999). The instrument had an angular resolution of about 1°.

3. Observations and Results

A search was conducted for an excess of events above those due to the background of cosmic rays in the Milagrito data coincident with BATSE GRBs. Bursts detected by BATSE within 45° of the zenith of Milagrito were considered. This angular range was chosen because the sensitivity of Milagrito fell rapidly with increasing zenith angle. For each burst, a circular search region 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 derived from the measured angular resolution of Milagrito (Atkins et al. 1999; Atkins et al. 1999). 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 when the data were integrated over longer time intervals (Hurley et al. 1994).

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 detected by Milagrito over the entire sky during T90 (N_{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, and the Poisson probability that the number of events in the bin was due to a background fluctuation was calculated. The bin with lowest such probability was then taken as the candidate position of a very-high-energy γ-ray counterpart to that particular BATSE burst.

The chance probability of obtaining 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 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 in the actual data to the total number of simulated data sets. The distribution of the chance probabilities for the 54 GRBs obtained by this method 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 location is approximately 0.5° (1σ), much better than that determined by BATSE. The water depth above the PMTs in Milagrito during this event was 0.9 m. 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 2.9×10^{-8}. The probability of such an observation 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 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 for systematic or instrumental causes of this excess and none were found.

Although the initial search was limited to T90, upon identifying GRB 970417a as a candidate, longer time intervals were examined. EGRET observed longer duration GeV emission (Hurley et al. 1994), and TeV afterglows are predicted by several models (Meszaros & Rees 1994; Totani 1998). To allow for the positional uncertainty of the TeV γ-ray candidate during T90, the radius of the search bin was increased for this study to 2.2°, shown by simulation to be optimal for the given parameters. A search for TeV γ-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 and of T90 (7.9 s), are shown in Figure 3. An analysis of these 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 (Atkins et al. 1999). Monte Carlo simulations of γ-ray-initiated air showers show that the effective area of Milagrito increases slowly with energy, so that the precise energy threshold is undefined. In addition there may be as much as 30% uncertainty in the absolute energy scale. Figure 4 shows the implied fluence of this observation as a function of upper cutoff energy for a range of assumed power-law spectra.

Several studies (Salamon & Stecker 1998; Primack Bullock Somerville & Macminn 1999) find that the opacity due to pair production for >200 GeV γ-rays exceeds one for redshifts larger than

0.3. Thus, if Milagrito has indeed detected high energy photons from GRB 970417a, it must be from a relatively nearby object.

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 chance probability that an excess of this significance would be observed from the entire sample of 54 bursts is 1.5×10^{-3}. The observed excess corresponds to a fluence above 10 GeV is in the range 10^{-3} 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.

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 may have been identified. A search for other coincidences with BATSE, to verify this result, will be continued with the current instrument, Milagro, which has significantly increased sensitivity to GRBs between 0.1 and 10 TeV.

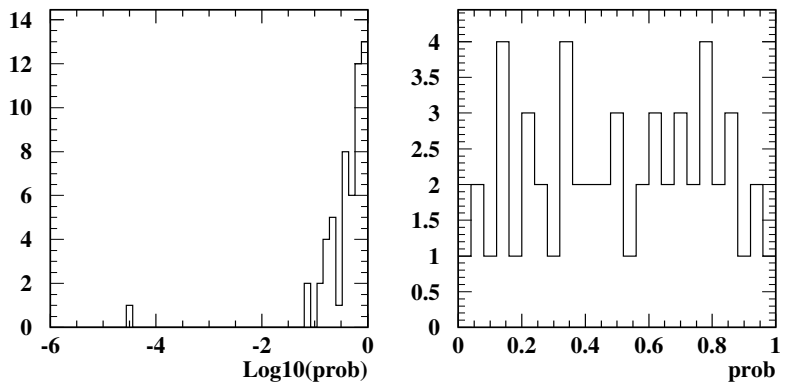

Fig. 1.— The distribution of probabilities for each of the 54 bursts, that the observed signal at the candidate TeV position was a background fluctuation. Both plots show the same data, with a linear and logarithmic scale for the x-axis.

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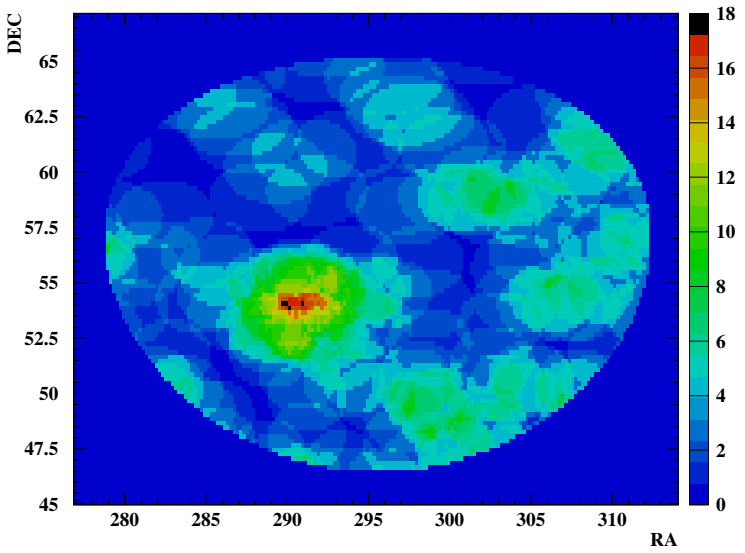

Fig. 2.— Number of events recorded by Milagrito during T90 in overlapping 1.6^o radius bins in the vicinity of GRB 970417a.

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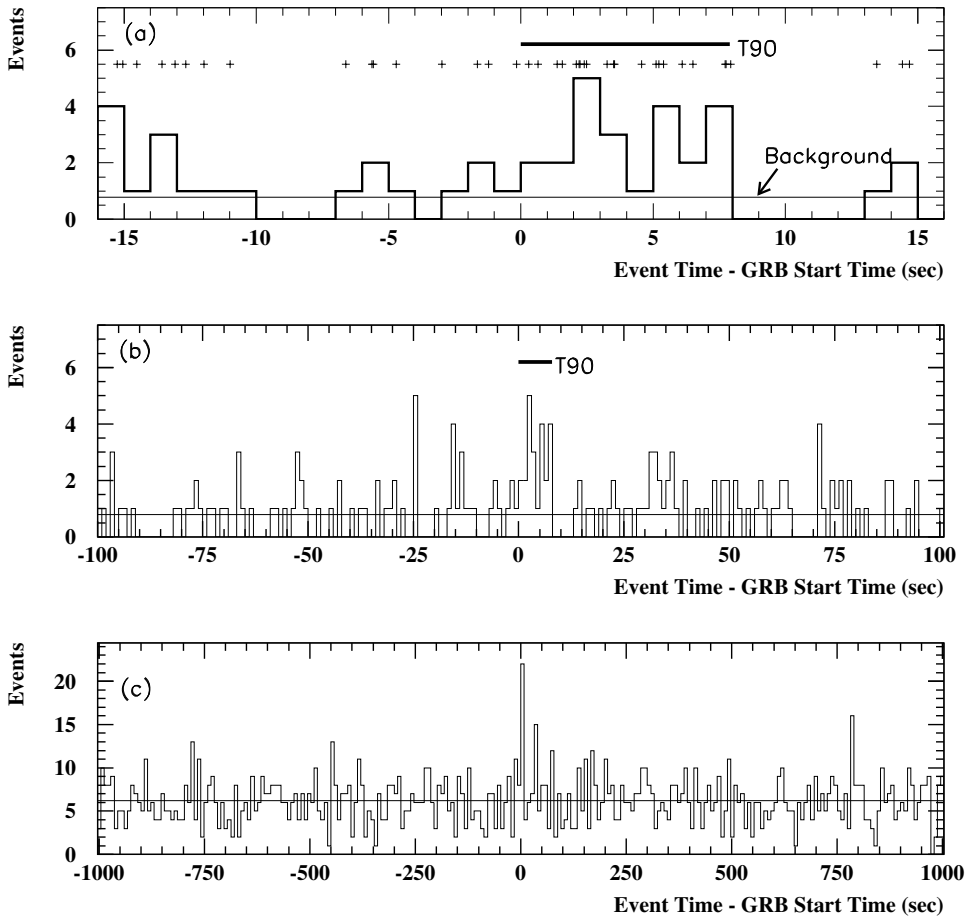

Fig. 3.— GRB 970417a: (a) The crosses indicate the arrival time of events from within a 2.2 radius of the candidate TeV counterpart for ±15 s around the start of T90. The histogram shows the same data binned in 1 second intervals. (b) The Milagrito data integrated in 1 sec intervals for ±100 s around the start of T90 and (c) integrated in bins of 7.9 seconds (T90) for ±1000 s.

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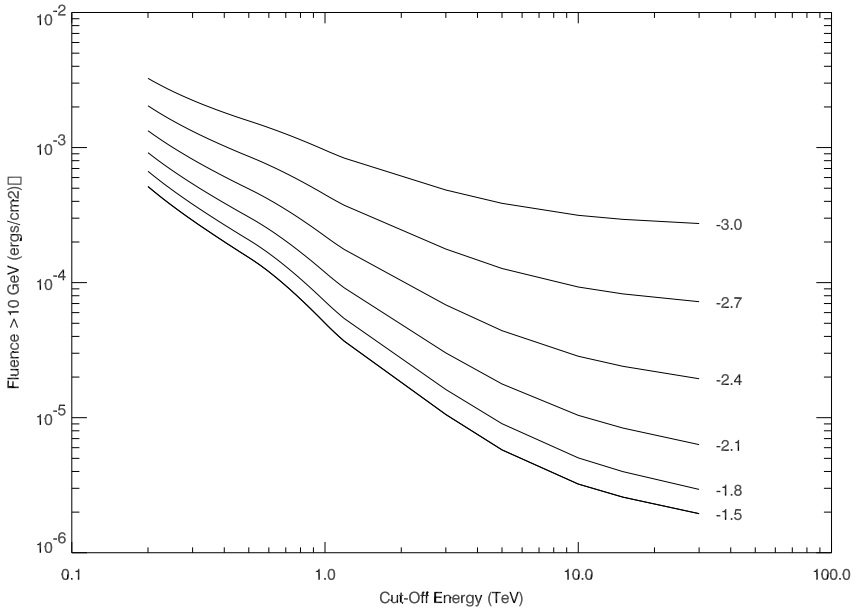

Fig. 4.— The implied fluences of candidate TeV counterpart for a range of input spectra and high energy cutoffs.

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