First Results of a Study of TeV emission of GRBs in Milagrito

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Abstract. Milagrito, a detector sensitive to γ-rays at TeV energies, monitored the northern sky during the period February 1997 through May 1998. With a large field of view and high duty cycle, this instrument was used to perform a search for TeV counterparts to γ-ray bursts. Within the Milagrito field of view 54 γ-ray bursts at keV energies were observed by the Burst And Transient Satellite Experiment (BATSE) aboard the Compton Gamma-Ray Observatory. This paper describes the results of a preliminary analysis to search for TeV emission correlated with BATSE detected bursts. Milagrito detected an excess of events coincident both spatially and temporally with GRB 970417a, with chance probability 2.8×10^{-5} within the BATSE error radius. No other significant correlations were detected. Since 54 bursts were examined the chance probability of observing an excess with this significance in any of these bursts is 1.5×10^{-3}. The statistical aspects and physical implications of this result are discussed.

I OBSERVATIONS AND ANALYSIS

Milagro, a new type of TeV γ-ray observatory sensitive at energies above 100 GeV, with a field of view of over one steradian and a high duty cycle, began operation in February 1999, near Los Alamos, NM. A predecessor of Milagro, Milagrito [6], operated from February 1997 to May 1998. During this time interval, 54 γ-ray bursts (GRBs) detected by BATSE [1] were within Milagrito's field of view (less than 45° zenith angle).

A search was conducted in the Milagrito data for an excess of events above the cosmic-ray background coincident with each of these γ-ray bursts. For each burst, a circular search region was defined by the BATSE 90% confidence interval, which incorporates both the statistical and systematic position errors [2]. The size of this 90% confidence interval ranged from 4° to 26° for the 54 GRBs in the sample. The search region was tiled with an array of overlapping 1.6° radius bins centered on a $0.2° \times 0.2°$grid. This radius was derived from the measured angular resolution of Milagrito 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 duration is defined as the time required for BATSE to accumulate 90% of the γ-rays(T90). T90 ranged from 0.1 seconds to 195 seconds for the 54 bursts examined.

The angular distribution of background events on the sky was characterized using two hours of data surrounding each burst. This distribution was normalized to the number of events detected by Milagrito over the entire sky during the T90 interval (N_{T90}). The resulting background data were also binned in 1.6° bins spaced 0.2° apart. The Poisson probability that the excess of events in each 1.6° bin was due to a background fluctuation was calculated and the bin with lowest probability was taken as the candidate position of a TeV γ-ray counterpart to the BATSE burst. The background and signal counts in this bin were used to calculate a fluence or fluence upper limit for each burst.

II RESULTS

The flux sensitivity of Milagrito to γ-ray bursts depends on the zenith angle and duration of the burst, and on the instrument conditions at the time. During the lifetime of the Milagrito detector data were taken with three different water depths (0.9 m, 1.5 m and 2.0 m). In addition, for the period February 1997 through the end of March 1997 a considerable amount of snow collected on the cover of the pond. Detector simulations were used to obtain effective area as a function of zenith angle for an assumed $E^{-2.0}$ spectrum for each of these configurations . These were then used to calculate flux upper limits for each burst. Flux upper limits in the range $10^{-6} - 10^{-8}$ $\gamma/\mathrm{cm}^2/s$ were obtained for 53 of the 54 bursts in the sample.

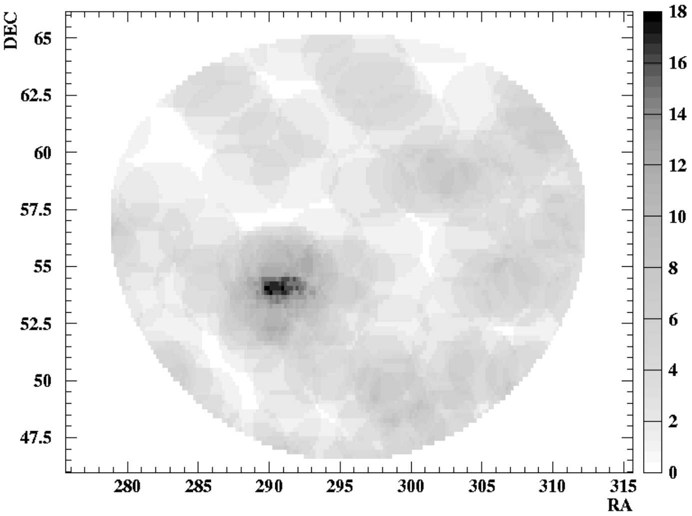

FIGURE 1. Number of events recorded by Milagrito during T90 in the BATSE 90% error radius for GRB 970417, each bin contains the number of events detected by Milagrito within a 1.6 degree radius.

Of the 54 bursts one, GRB 970417a, shows a substantial excess above background in the Milagrito data. The BATSE detection of this burst is a typical 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 = 295.66°, DEC = 55.77°. The 90% positional uncertainty was 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 position is 3.8° away from the position reported by BATSE, well within the BATSE 1-sigma position error 6.2°. The uncertainty in the candidate TeV position was determined by Monte-Carlo simulations to be approximately 0.5°. Figure 1 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. The Poisson probability for observing a signal at least this large due to a background fluctuation is 2.89×10^{-8}.

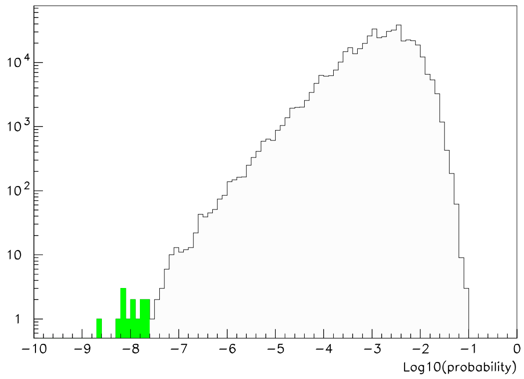

FIGURE 2. The distribution of minimum probabilities for the ensemble of simulated data-sets for GRB 970417a.

To obtain the significance of this result one must account for the size of the search region. The probability of obtaining the observed significance anywhere within the entire search region was determined by Monte Carlo simulations. A set of simulated signal maps was made by randomly drawing N_{T90} events from the background distribution. The data were searched, as before, for a significant excess within the search region defined by BATSE. The probability of this observation being due to a fluctuation in the background, 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 of 4.65×10^6 simulated data sets is shown in figure 2, thirteen of which had chance probability less than 2.89×10^{-8}. We therefore find that the chance probability of such a detection within the entire 9.4° search region for GRB 970417a to be 2.8×10^{-5}. The probabilities for each of the other 53 bursts in the sample were obtained using the same method, the distribution of these probabilities, after correcting for the size of the search region, is shown in figure 3. The histogram on the left, plotted on a log-linear scale, illustrates the significance of the excess for GRB 970417a relative to the rest of the sample. The histogram on the right of this figure, plotted on a linear scale is flat, as expected. 54 bursts were examined, therefore the chance probability of observing such significant excess due to fluctuations in the background for any of these bursts is 1.5×10^{-3}.

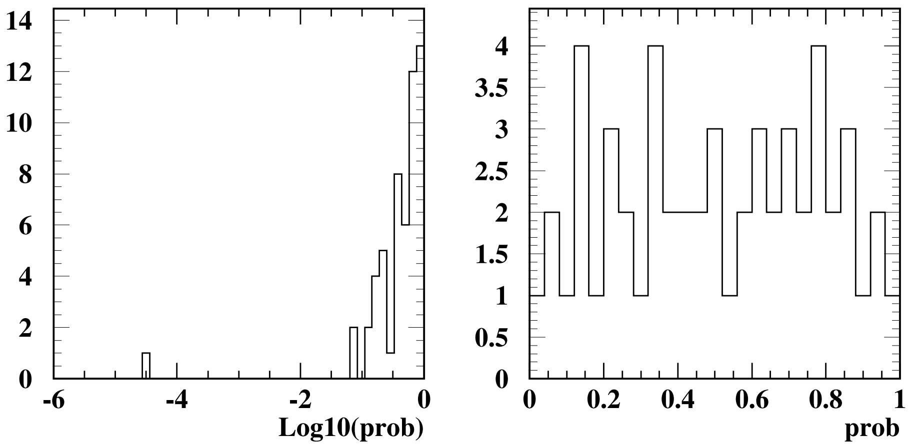

FIGURE 3. The distribution of probabilities, corrected for the size of the search region for the 54 GRBs in the sample, both plots show the same data with a linear and logarithmic scale for the x-axis

Although the initial search was limited to T90, for GRB 970417a longer time intervals were also examined. To allow for the positional uncertainty of the excess observed by Milagrito, the radius of the search bin was increased to 2.2° for this search. 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 where the data are binned in intervals of one second and of T90 (7.9 s) are shown in figure 4. A complete analysis to search for TeV afterflares has not been completed.

III 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 following discussion assumes that the excess observed by Milagrito was due to TeV γ-rays from GRB 970417a. The TeV

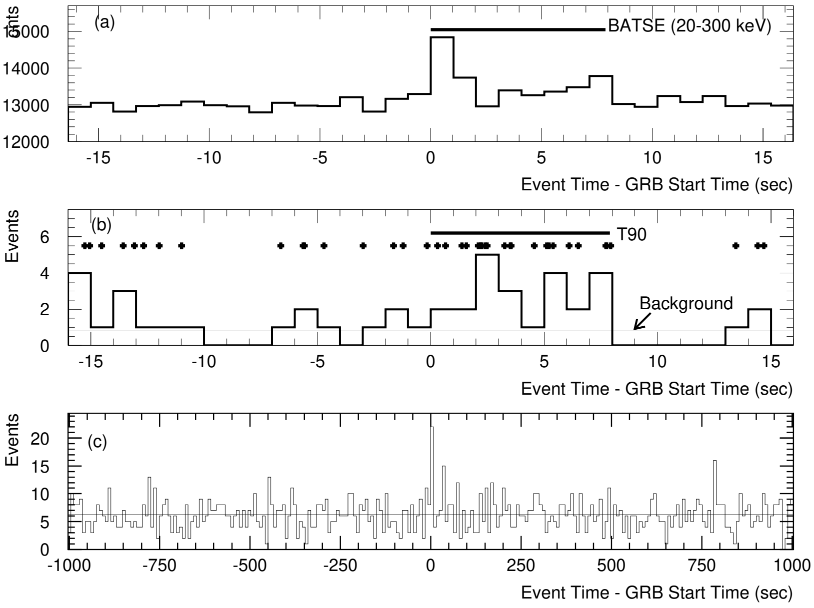

FIGURE 4. GRB 970417a: (a) The BATSE lightcurve, (b) Milagrito data within a 2.2° radius of GRB 970417a integrated in 1 second bins, the crosses indicate the arrival times of the events and (c) integrated in bins of 7.9 seconds (T90) for 2000 seconds

spectrum and maximum energy of emission is difficult to determine from Milagrito data [6]. Monte Carlo simulations of γ-ray initiated air showers show that the effective area increases smoothly with energy, making the definition of an energy threshold ambiguous. Figure 5 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 events observed for GRB 970417a can be obtained by considering the response of the summed untriggered counting rate of the individual PMTs in Milagrito. Detector simulations of the dependence of PMT counting rates to γ-ray induced air-showers indicate that these rates are more sensitive than the standard shower data at energies below a few hundred GeV, but are only sensitive to very large fluxes [6]. No excess was observed in these rates, which implies that the air-showers detected by Milagrito were probably 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 with infrared photons in the intergalactic medium. Several studies find that the opacity due to pair production for above 200 GeV γ-rays exceeds one for redshifts larger than 0.3 [3,4]. This implies an upper limit on the redshift of GRB 970417a, making this a relatively nearby event.

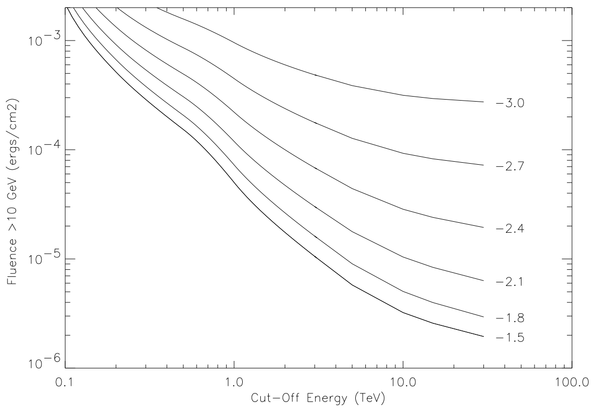

FIGURE 5. Implied fluences of this candidate for a range of input spectra and high energy cutoffs (preliminary)

IV 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 by 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 spectrum must extend with no cutoff to at least a few hundred GeV. The inferred TeV fluence from this result 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 from GRB 970417a is not a fluctuation of the background, then a new class of γ-ray bursts bright at TeV energies may have 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 TeV γ-ray bursts.

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