Evidence for TeV emission from GRB 970417a

J. E. McEnery[1], R. Atkins[1], W. Benbow[2], D. Berley[3,10], M.L. Chen[3,11], D.G. Coyne[2], B.L. Dingus[1], D.E. Dorfan[2], R.W. Ellsworth[5], D. Evans[3], A. Falcone[6], L. Fleysher[7], R. Fleysher[7], G. Gisler[8], J.A. Goodman[3], T.J. Haines[8], C.M. Hoffman[8], S. Hugenberger[4], L.A. Kelley[2], I. Leonor[4], M. McConnell[6], J.F. McCullough[2], R.S. Miller[8,6], A.I. Mincer[7], M.F. Morales[2], P. Nemethy[7], J.M. Ryan[6], B. Shen[9], A. Shoup[4], C. Sinnis[8], A.J. Smith[9], G.W. Sullivan[3], T. Tumer[9], K. Wang[9], M.O. Wascko[9], S. Westerhoff[2], D.A. Williams[2], T. Yang[2], G.B. Yodh[4]

(1) University of Utah, Salt Lake City, UT 84112, USA
(2) University of California, Santa Cruz, CA 95064, USA
(3) University of Maryland, College Park, MD 20742, USA
(4) University of California, Irvine, CA 92697, USA
(5) George Mason University, Fairfax, VA 22030, USA
(6) University of New Hampshire, Durham, NH 03824, USA
(7) New York University, New York, NY 10003, USA
(8) Los Alamos National Laboratory, Los Alamos, NM 87545, USA
(9) University of California, Riverside, CA 92521, USA
(10) Permanent Address: National Science Foundation, Arlington, VA ,22230, USA
(11) Now at Brookhaven National Laboratory, Upton, NY 11973, USA

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. BATSE detected 54 GRBs within the field of view of Milagrito during this period. This paper describes the results of an 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 at least this significance in any of these bursts is 1.5×10^{-3}.

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 [7], 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 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 spaced 0.2° apart. 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. T90 ranged from 0.1 seconds to 195 seconds for the 54 bursts examined.

For each GRB, the angular distribution of background events on the sky was characterized using two hours of data surrounding each burst [3]. This distribution was 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° 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 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 $\mathrm{E}^{-2.0}$ 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.

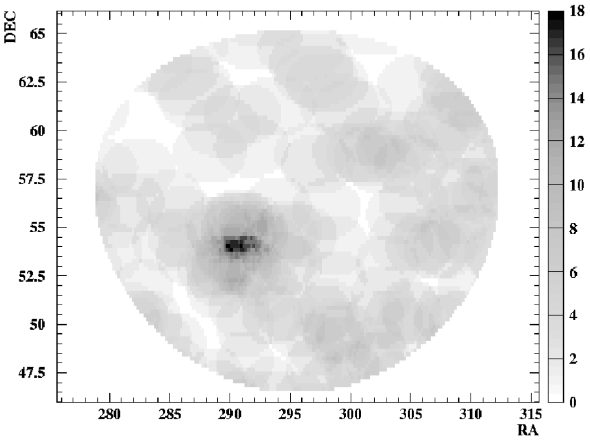

FIGURE 1. Number of events recorded by Milagrito during T90 in the BATSE 90% error radius for GRB 970417, each bin contains the number of events detected by Milagrito within a 1.6 degree radius.

One of the 54 bursts, GRB 970417a, shows a substantial excess above background in the Milagrito data [6]. The BATSE detection of this burst is a 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 position of the TeV candidate is 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}.

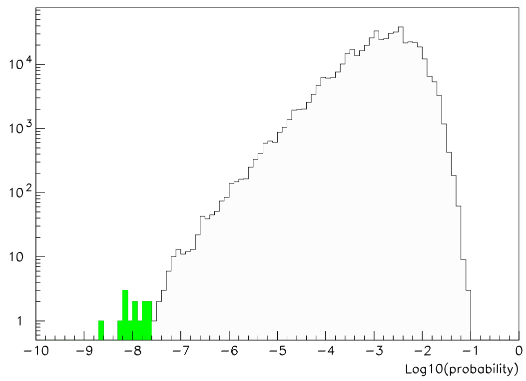

FIGURE 2. The distribution of minimum probabilities for the ensemble of simulated data-sets for GRB 970417a.

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. Each map was searched, as before, for a significant excess within the search region defined by BATSE. The probability of the observation in the actual data 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 for 4.65×10^6 simulated data sets is shown in figure 2; thirteen of which had Poisson 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. 54 bursts were examined. Therefore the chance probability of observing such a significant excess due to fluctuations in the background for any of these bursts is 1.5×10^{-3}.

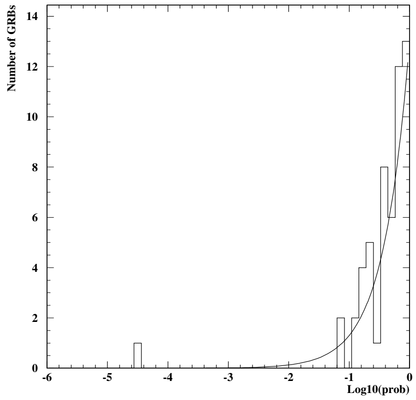

FIGURE 3. The distribution of probabilities, corrected for the size of the search region for the 54 GRBs in the sample. The solid curve shows the probability distribution expected from background data.

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.

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 spectrum and maximum energy of emission is difficult to determine from Milagrito data [7]. Monte Carlo simulations of γ-ray initiated air showers show that the effective area increases slowly with energy, so that the energy threshold is undefined. Figure 4 shows the implied fluence of this observation above 50 GeV as a function of upper cutoff energy for a range of power-law input spectra.

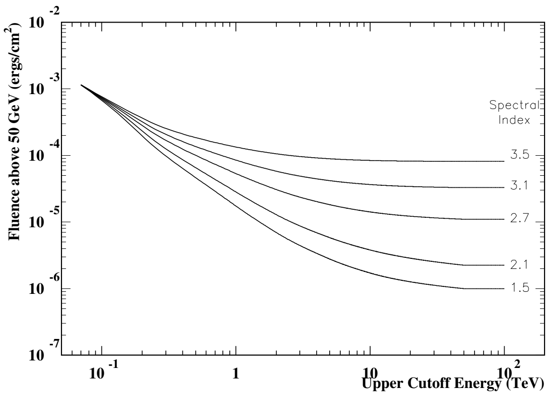

FIGURE 4. Implied fluence (> 50 GeV) as a function of high-energy cutoff for five assumed differential spectral indices

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 effect on PMT counting rates of 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 [7]. 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 500 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 500 GeV γ-rays exceeds one for redshifts larger than 0.3 [4,5]. Thus, if Milagrito has indeed detected high energy photons from GRB 990417a, it must be from a relatively nearby object.

To summarize, 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 ($>$ 50 GeV) from this result at least an order of magnitude greater than the sub-MeV fluence and the emission extends to at least several hundred GeV. If the observed excess from 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, to verify this result, will be continued with the current instrument, Milagro, which has increased sensitivity to TeV γ-ray bursts between 0.1 and 10 TeV.

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