Evidence for TeV emission from a Gamma-Ray Burst

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ABSTRACT

During the period February 1997 through May 1998, Milagrito, a detector sensitive to γ-rays at TeV energies monitored the northern sky. With a large field of view and high duty cycle, this instrument was ideally suited to 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). Milagrito detected an excess of events with chance probability 2.5×10^{-5} within the BATSE error radius of GRB 970417a coincident in time with the BATSE burst. Since 54 bursts were examined the probability of observing an excess with this significance in any of these bursts is $1.2 \times 10{-}3$. This result indicates there is emission at least as high as 200 GeV with fluence above 10 GeV between $\sim 10^{-4}$ and $\sim 10^{-6}$ depending on the spectrum and cutoff energy of the γ-ray emission. In addition, there is evidence for two TeV γ-ray flares of lesser intensity occurring 32 seconds and 782 seconds respectively after the BATSE trigger time

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1. Introduction

Since their discovery in the 70s, GRBs have remained one of 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 at energies from 50 keV to 30 GeV. One of these, BATSE, a large field of view instrument sensitive at energies from 50 keV to >300 keV, has detected several thousand γ-ray bursts. BATSE showed that these objects are distributed isotropically in space, thus providing initial evidence that GRBs may be cosmological in origin. This conclusion has recently been confirmed by measurements of redshifts from optical counterparts over the past 2 years. One of the crucial questions which remains unanswered is whether the spectra of these objects cuts off at high energies. The EGRET experiment on board CGRO saw 7 γ-ray bursts at energies above 100 MeV, including the observation of a 18 GeV photon from GRB 940217. All of the bursts observed by EGRET had large fluxes at BATSE energies and to date, there is no evidence of a high energy cutoff.

At energies greater than 30 GeV, photon fluxes from most astrophysical sources become sufficiently low that, due to collection area constraints, observations can no longer be made directly by detectors onboard satellites. Instead ground based experiments can detect these γ-rays by observing the extensive air showers they induce in the atmosphere. A high energy γ-ray entering the Earth's atmosphere interacts producing a cascade of particles. These showers can be detected via the Cherenkov light emitted by the relativistic particles as they traverse the atmosphere, or for primary γ-rays of sufficiently high energy by detecting the particles which reach ground level. Traditionally, scintillator arrays have been used as particle detectors, however they are only sensitive to showers induced by γ-rays with energies in excess of $\sim$ 10 TeV.

Additionally, if source distances are much greater than z=0.1, then TeV γ-ray emission may not be observable due to absorption via pair production interactions with the infrared extragalactic background photons (2**?**). Recent measurements of several gamma-ray bursts with optical afterglows have shown distances of z > 0.8 with only one exception (6; 7**?** **?**). This limited sample does not imply all bursts are at such large distances, but these measurements do indicate that the intensity of the γ-ray emission is not well correlated with distance. Therefore, observation of TeV emission from a gamma-ray burst, which requires a nearby source, may not be correlated with the intensity of the sub-MeV BATSE emission.

Detection of TeV gamma-rays from astrophysical sources has been firmly established by atmospheric Cherenkov telescopes (**?**). These telescopes have an extremely large collection area and are therefore able to detect low fluxes of γ-rays. However, they have a relatively small field of view of a few square degrees and can only operate on dark nights and thus have a low ($\sim$10%) duty cycle. Searches for γ-ray bursts at energies between 300 GeV and 5 TeV have been made by slewing the gamma-ray telescopes within a few minutes after the notification of the γ-ray burst location (3). No detections of γ-ray bursts were reported, and the small size of the field of view, coupled with the delay in slewing to the correct position does not allow the calculation of stringent upper limits.

At higher energies, 10-20 TeV, larger field of view instruments have reported possible evidence of γ-ray burst emission (5; 4). The Tibet extensive air shower array detected a non-statistical deviation of the probability distribution from the background by combining data from all satellite-detected gamma-ray bursts within their field of view; however, no single burst showed a convincing signal. The HEGRA AIROBICC Cherenkov array had two bursts within it's field of view, and one burst showed an excess over background in a time interval longer than the sub-MeV emission. But the TeV position was not coincident with that derived from the interplanetary network, and was not claimed as a detection.

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 very high duty cycle, began operation in February 1999, near Los Alamos, NM. A prototype of Milagro, Milagrito(REF NIM), operated from February 1997 to May 1998. During this time interval 54 gamma-ray bursts, detected by BATSE and other spacecraft, were within Milagrito's field of view. This paper reports on the search for TeV γ-ray emission from these 54 γ-ray bursts.

2. The Milagrito Detector

Milagrito detected extensive air shower particles via the Cherenkov light emitted in the water of a 30 m x 50 m covered pond. The pond contained a layer of 228 phototubes placed 0.9 meters below the water surface. These phototubes detected the Cherenkov light produced as the charge shower particles traverse the water. In addition, the water transfers the energy of γ-rays in the air shower via pair production and Compton scattering to relativistic charged particles, which then also produce Cherenkov light. The continuous medium allows virtually every shower particle incident on the pond can be detected, even with a quantized grid of phototubes. 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 layer of PMTs are used to reconstruct the angle of the incoming air-shower. Milagrito triggered when 100 PMTs in the pond were hit within a 300 ns timw window, events were collected at a rate of $\sim$300 Hz; almost all of these triggers are due to an isotropic background of showers induced by charged cosmic rays.

3. Observations and Results

A search was conducted for excesses of events above the isotropic background cosmic rays in the Milagrito data coincident with every BATSE γ-ray burst detection within 45° of the zenith of Milagrito. 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 centered on a $0.2^\circ \times 0.2^\circ$ grid. 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, this time period is known as T90. T90 was chosen because EGRET detects gamma-rays above a GeV at higher fluxes during T90 than for longer durations.

In order to establish the significance of a detection, the background due to cosmic ray induced showers must be estimated and statistical and non-statistical fluctuations 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 detected by Milagrito over the entire sky during the time period of interest. 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 probability was then taken as the candidate position of a TeV gamma-ray counterpart to the BATSE burst.

The true probability of obtaining the observed significance within the entire search region was determined by Monte Carlo simulations. For each burst a set of 'fake' signal maps were obtained 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 true probability after accounting for the size of the search region is given by the ratio of the number of simulated datasets with probability less that that observed for the actual data to the total number of simulated datasets. The distribution of these probabilities for the BATSE bursts in Milagrito's field of view after correcting for the size of the search region is given in figure 4.

One of the 54 bursts, GRB 970417a, shows an excess above background in the Milagrito data. The BATSE detection of this burst shows a typical weak burst with a fluence in the energy range 50-300 keV of 1.5×10^{-7} ergs/cm^2 and T90 of 7.9 seconds. The low BATSE flux results in a BATSE determined position of RA $= 295.66^\circ$, DEC $= 55.77^\circ$ with a large 1 sigma statistical uncertainty of 6.23°. The 1.6° radius bin with the largest excess in the Milagrito data is centered at RA $= 289.89^\circ$ and DEC $= 54.0^\circ$, corresponding to a zenith angle of 21°. The uncertainty in the TeV-determined position is approximately 0.5°. While this position is only 3.8° away from the BATSE determined position, the search region for the TeV emission was a circle of 9.4° radius. 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 ± 0.1. The Poisson probability for observing a signal 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 determined by Monte Carlo simulation was found to be 2.4×10^{-5}. Because 54 bursts were examined, the chance probability of detecting TeV emission for any of these bursts is 1.2×10^{-3}.

Although the initial search was limited to T90, for GRB 970417a longer time intervals were examined. EGRET observed longer duration GeV emission, and TeV afterglows are predicted by several models. To allow for the positional uncertainty of the TeV γ-ray detection during T90, the radius of the search bin was increased to 2°. 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 secs) are shown in figure 2. In addition to the excess of events observed at 0 secs for T90, the two most significant features can be seen starting 32 secs and 782 secs respectively after the γ-ray burst start time. In both cases 15 events were observed with an expected background level of 5.4 events. This corresponds to a probability of 5.0×10^{-4} for each of these intervals.

An unbinned maximum likelihood analysis has been performed which uses the γ-ray locations and the point spread function associated with each. The likelihood ratio is given by $(lnL_{S+B} - lnL_B)$, where L_{S+B} is the likelihood of the fit to a point source of unknown strength and known background and L_B is the likelihood of the fit to the background only. For any specific point source position two times the likelihood ratio is distributed as a chi-square with one degree of freedom. Figure 5 shows a map of the likelihood ratio, for a point source located at various positions within the BATSE error circle. The maximum value of the likelihood ratio is 13.05 which corresponds to a chance probability of 3.2×10^{-7} assuming a known position. The maximum value of the likelihood ratio was at $RA = 290.8^\circ$ and $DEC = 54.0^\circ$ and a signal of 17.8 events. Again simulations were used to determine that the probability is XXX of such an observation anywhere within the BATSE 90% confidence interval.

4. Discussion

An excess of events with chance probability 2.4×10^{-5} simultaneous with the BATSE emission for GRB 970417a observed by Milagrito. The probability that such a significant excess would be observed from the entire sample of 54 bursts is 1.2×10^{-3}. In addition evidence for two later flares, of lesser intensity, were also seen 32 seconds and 782 seconds respectively after the initial BATSE trigger.

The TeV spectrum or maximum energy of emission is difficult to determine from Milagrito data. The limited energy resolution is due to the poor ability of Milagrito to locate the cores of detected air-showers. 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 somewhat ambiguous.

However, some information about the energies of the γ-rays observed for GRB 970417a can be obtained by considering the response of the combined singles rates of the individual tubes in Milagrito. Detector simulations to investigate the response of these rates to γ-ray induced air-showers indicate that, despite the large background, at low energies these rates are more sensitive than the standard shower data. No excess was observed in these rates, therefore the air-showers detected by Milagrito were due to γ-rays at higher energies. Figure 3 shows the minimum allowed cutoff energy and the corresponding fluence for different input spectra. 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 100 GeV.

The inferred TeV fluence from this result is more than an order of magnitude greater than the sub-MeV fluence and the maximum energy of emission extends to 100s of GeV. Yet the distance to the source must be less than that observed in all but one of the bursts with optical counterparts, so the total luminosity is low. If z=0.5, then the luminosity is between xxxx and xxxx ergs. Two nearby galaxies are consistent with the TeV position - one at z=0.0xx and the other is unmeasured.

If the TeV emission from GRB 970417a is not an improbable fluctuation of the background, then a different 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 will have increased sensitivity to TeV γ-ray bursts.

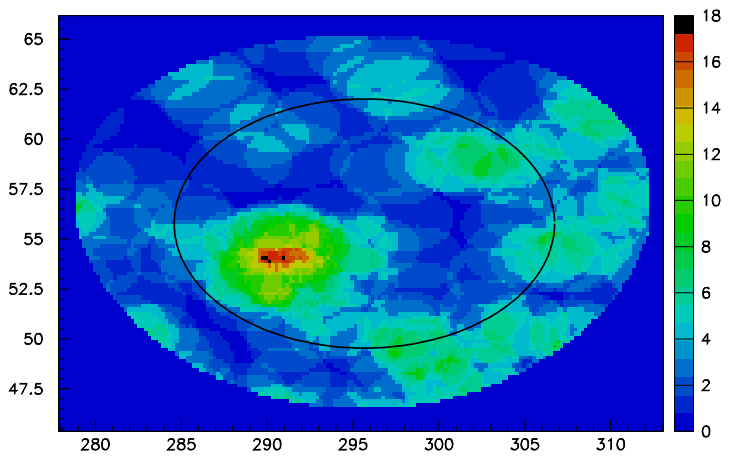

Fig. 1.— Number of events recorded by Milagrito during T90 in the region of GRB 970417, each bin contains the number of events in a 1.6 degree radius The black line indicates the BATSE statistical location error

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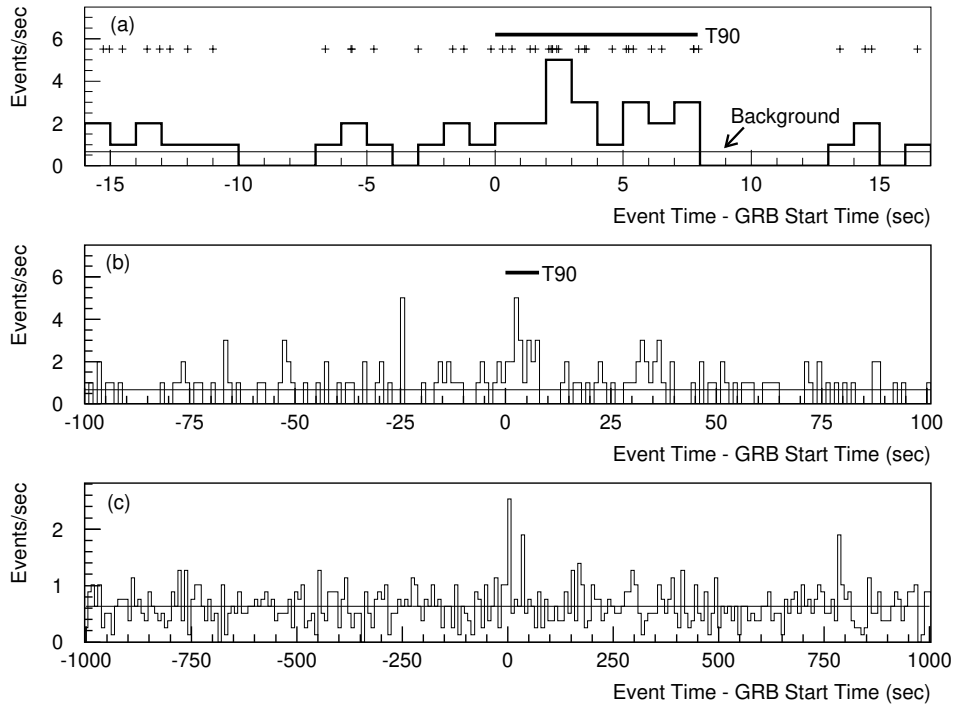

Fig. 2.— Lightcurves for GRB 6188: (a) The crosses indicate the arrival time of events from the position of the γ-ray burst for 30 seconds surrounding the BATSE trigger time. The histogram showed the same data binned in 1 second intervals,(b) Integrated in 1 sec intervals for 200 seconds surrounding the burst and (c) integrated in bins of 7.9 seconds (T90) for 2000 seconds

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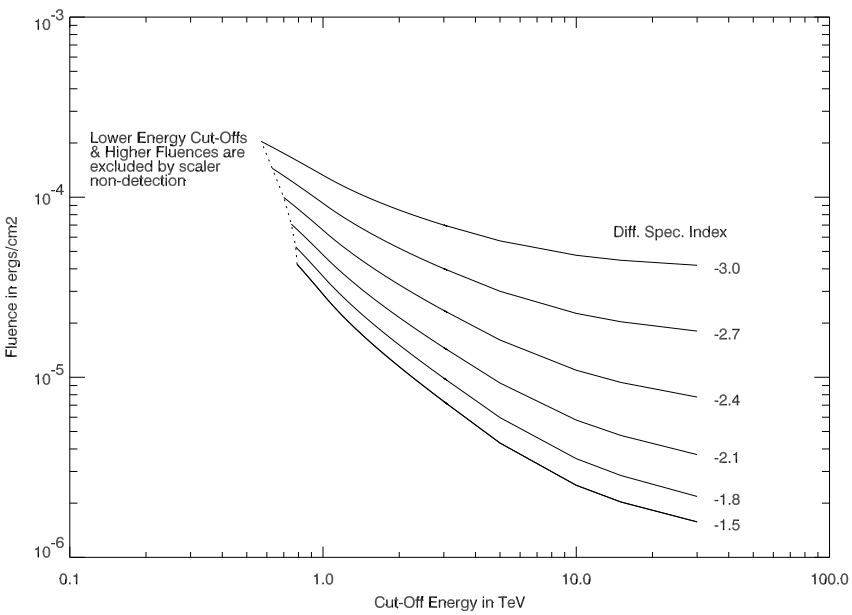

Fig. 3.— Implied fluences of this detection for a range of input spectra and high energy cutoffs

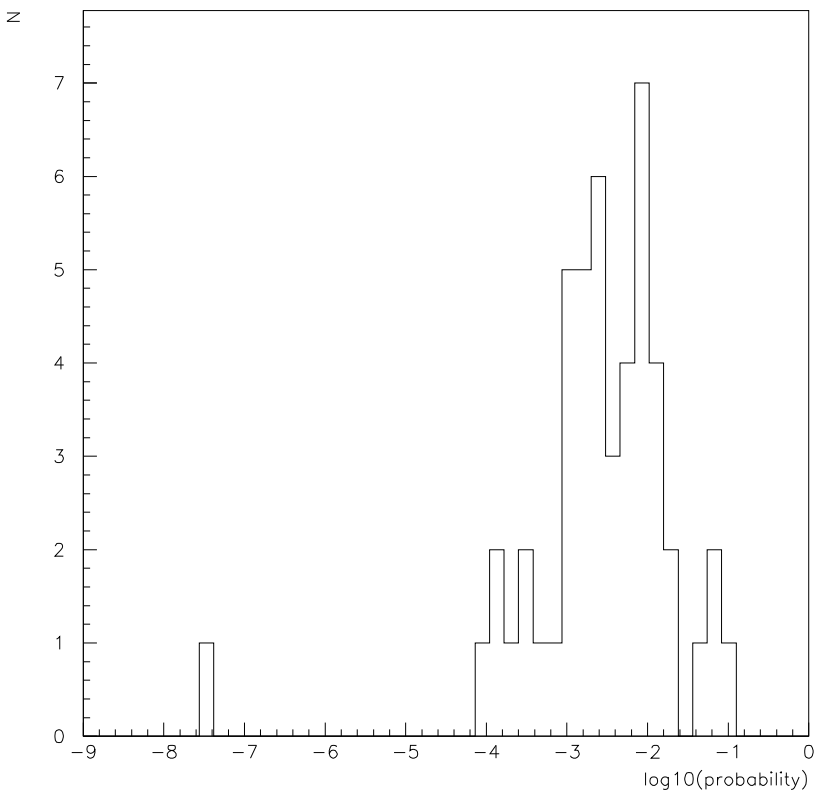

Fig. 4.— The distribution of probabilities, for all 54 bursts, that the observed signal at the candidate TeV postions was a fluctuation from background

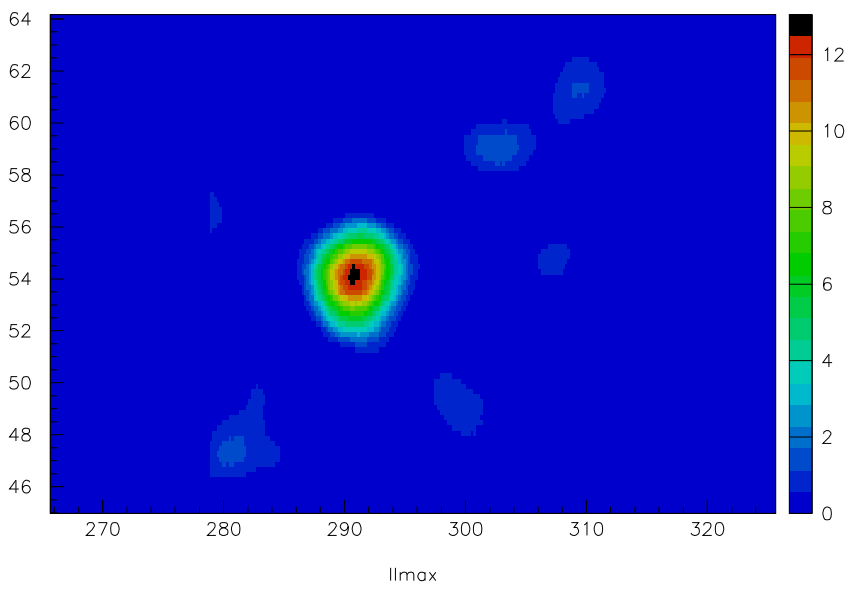

Fig. 5.— The a map of the likelihood ratio, optimised for signal strength, in the search region for GRB 970417a