Search for Ultra High Energy (UHE) γ-Ray Counterparts of BATSE 3B Catalog Events

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We search for a Ultra High Energy ($E > 10^{14}$ eV) counterpart source to cosmic γ-ray bursts detected with the BATSE detectors. Using the 3B catalog positions, we examine 115 candidate bursts with the CASA-MIA detector for UHE γ-ray emission at or near the time of the observed γ-ray burst. No statistically significant excess of γ-rays is found from any of the candidate event regions. Based upon these results, we calculate the flux limits for UHE emission from these candidate event regions. Typical 95% confidence level flux limits are about 6×10^{-12} γ cm^{-2} sec^{-1} at a γ-ray detection threshold of 160 TeV.

INTRODUCTION

The unknown nature of the source of cosmic γ-ray bursts (GRBs) has led observational astrophysicists to search in substantially higher and lower energy bands than the observed keV to GeV GRB energies. Observation of a burst of $10^{12} - 10^{15}$ eV (1-1000 TeV) γ-rays in coincidence with a GRB measured with BATSE would provide strong constraints on the maximum distance scale to the GRB source, as TeV γ-rays should be attenuated by extragalactic IR and 2.7° microwave backgrounds if the GRB sources are cosmological (1–5). Recent theoretical considerations have also suggested the possibility of γ-ray production up to the TeV energy range (6) and particle acceleration up to 10^{20} eV (7–9). In recent measurements of GRB spectra by the EGRET experiment (10), γ-rays with energies approaching 20 GeV were observed in coincidence with a strong GRB detected with the BATSE detectors. In this paper, we use the CASA-MIA UHE γ-ray observatory to search for such coincident γ-rays in the 100 TeV energy regime.

DETECTOR DESCRIPTION

The CASA-MIA cosmic ray observatory (11) is the world's most sensitive detector for γ-rays above 100 TeV. The observatory is located at the Dugway Proving Grounds, Utah, USA (40.2° N, 112.8° W) at an altitude of 1480 meters above sea level. The CASA detector consists of 1089 scintillation detectors arranged in a square grid of 15m spacing. The scintillation detectors measure the properties of the electromagnetic component of extensive air showers (EAS) generated by cosmic ray primaries in the atmosphere. The detection area of the CASA experiment is approximately 0.23 km^2.

Event direction is reconstructed by fitting a wavefront to the arrival times of the EAS wavefront at each detector in an event. For events at the detection threshold of CASA, the detector angular resolution for optimal searches with circular bins is $\sigma_{72} = 2.46°$. The primary energy of the original cosmic ray is estimated from the size of the fitted electromagnetic component of the EAS. The detector has a γ-ray detection efficiency of 75% at 63 TeV for vertical showers and nearly 100% efficiency at 100 TeV. The array provides continuous UHE γ-ray observation with "all-sky" monitoring over the visible sky.

The MIA detector consists of 1024 scintillation counters buried 3 meters below the surface array. The MIA counters are grouped into 16 patches, with total scintillator area of 2500 m^2. These buried counters measure the muon content of the EAS; the muon content measurement can enhance the significance of a γ-ray source signal. An EAS generated by a cosmic ray nucleus is expected to have substantially larger muon content in the EAS than a γ-ray induced EAS of the same energy. By selecting EAS with muon content of approximately 1/10 of the measured muon content for a similar size EAS induced by a cosmic ray nucleus, we reject 95% of the hadronic background and keep 70% of the γ-ray signal.

The full CASA-MIA array began operation in 1990, and has been observing with better than 90% on-time since January 1992.

COUNTERPART SEARCH ANALYSIS

About 15% of the BATSE 3B catalog events are within the field of view of the CASA-MIA detector for short time intervals around the BATSE burst time. Of the 1122 BATSE events in the 3B catalog, 94 bursts are visible to the operating CASA-MIA detector with elevation $> 45°$. We also selected an additional 21 BATSE bursts with $30° <$ elevation $< 45°$ to provide a γ-ray flux measurement at higher median energies. The CASA-MIA data set was examined for the existence of UHE γ-ray counterparts of these 115 GRBs.

CASA-MIA events from the BATSE 3B direction were selected using a fixed time window extending from -10 seconds to +110 seconds around the BATSE burst time. An angular acceptance radius σ_θ about the BATSE event ecliptic coordinates was calculated from the combined CASA-MIA and BATSE angular resolutions:

$$\sigma_\theta^2 = \sigma_{\mathrm{CASA}}^2 + \sigma_{\mathrm{BATSE,sys}}^2 + \sigma_{\mathrm{BATSE,stat}}^2$$

where $\sigma_{\mathrm{BATSE,sys}} = 1.6^{\circ}$, as specified by the BATSE 3B catalog, and $\sigma_{\mathrm{BATSE,stat}}$ is the statistical BATSE direction uncertainty specified on an event-by-event basis in the 3B catalog. The expected background event rate in each angular acceptance bin was calculated from bins of the same acceptance radius and the same local azimuth-elevation as the true burst direction, but at times occurring well before and after the BATSE burst time.

For each visible BATSE burst, the CASA-MIA data set was examined with two different muon content requirements. The first analysis required no cuts on muon content; this is known as the All Data sample. Source events with this muon content could be any type of neutral particle emitted by the GRB source. The second analysis imposed a muon-poor requirement; this is known as the γ-Ray sample. The γ-Ray sample consists of EAS from the All Data sample which have less than 1/10 of the muon content expected for a cosmic ray nuclear induced EAS of the same shower size.

RESULTS AND FLUX LIMITS

Statistical significances of excess event rate from the source bin over the background rate is calculated using the method of Li and Ma (12). No evidence is seen for a statistically significant signal in either the All Data sample or the γ-Ray sample. Figure 1 plots the integral number distribution as a function of burst probability for the γ-Ray (muon poor) sample. No statistically significant excesses are seen at the 95% confidence level.

Table 1 lists bright burst flux limits calculated for both the All Data and the γ-Ray samples. These integral flux limits are calculated in the standard manner (13,14). We assume both background and signal obey Poisson statistics, and normalize the flux limits to the known all particle cosmic ray energy spectrum. Typical 95% confidence level integral flux limits are about 6×10^{-12} γ cm^{-2} sec^{-1} for γ-rays above 160 TeV. This is about a factor of 3 lower flux limit than presented by other UHE observatories (15). A search for delayed emission (on the order of several hours) has been performed for the BATSE GRBs from the 2B catalog. No excess emission has been observed from these burst positions. Typical integral flux limits are 5×10^{-10} cm^{-2} sec^{-1}.

DISCUSSION

We find no statistically significant evidence for the emission of UHE γ-rays or neutral particles near the time and location of the BATSE 3B coordinates. A simple power law extrapolation to UHE energies of several bright GRB burst spectra measured by EGRET and COMPTEL can be performed. Using the CASA detection threshold and detector size, one expects CASA to detect a burst of 10-50 γ-ray events. This would be an extremely significant observation as the number of signal events expected in the γ-Ray sample due to background alone is usually less than one.

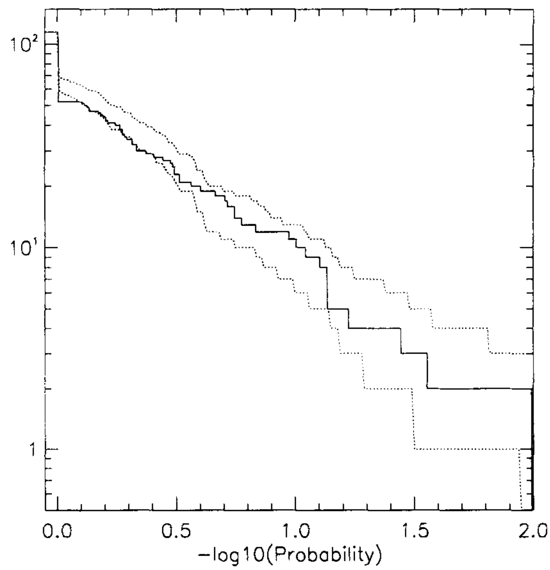

FIG. 1. Integral number distribution of the 115 bursts in the γ-Ray data sample as a function of the burst probability. Vertical Axis: Number of events; Horizontal Axis: $-log_{10}$(Probability); Solid Line: CASA DATA distribution. Dotted Lines: Expected distribution for 95% confidence level excess (upper dotted) and 50% confidence level excess (lower dotted) based upon Monte Carlo simulation of background.

3B Catalog GRB Name	Median Energy (TeV)	CASA-MIA Array Flux Limit ($\times 10^{-12}$ cm^{-2} sec^{-1}) Φ_γ	Φ_{All}
920210	120	11.3	14.5
920308	260	10.8	14.8
920524	160	5.5	14.4
920720	150	8.6	9.6
920801	370	12.7	13.9
930720	160	17.0	22.0
931031	150	6.5	11.2
940129	360	7.4	7.8
940503	250	6.5	14.1
940623	310	6.9	7.8

TABLE 1. CASA-MIA Flux limits for UHE Counterparts to Bright BATSE 3B Bursts

Although we have yet to have a very strong GRB occurring directly overhead CASA-MIA when the observatory is operational, the analysis of weaker bursts reveals that the measured UHE γ-ray flux is smaller than the expected flux extrapolated from lower energies, for many of the observed GRB. A natural interpretation is that a change in spectral index of the GRB spectrum must occur somewhere in the GeV to TeV energy range. Such a cutoff could be a source effect for bursts occurring at any distance scale, or may be due to a modification of a cosmological distance source spectrum by pair production off the extragalactic IR and microwave backgrounds.

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