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SEARCH FOR ULTRA HIGH ENERGY RADIATION FROM GAMMA-RAY BURSTS

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representing

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ABSTRACT

A recent model suggests that some gamma-ray bursts may have photon energies as high as 10 TeV. Extensive air shower arrays could detect strong bursts with hard spectra extending above such energies. Using data from the CYGNUS array, we have searched for evidence of emission of ultra high energy (≥ 100 TeV) radiation coincident with gamma-ray bursts observed either by BATSE or by the third Interplanetary Network. No statistically significant excess was found for the six bursts whose locations were accurately determined by the IPN, or for any point in the sky within 2σ of the BATSE location coordinates of an additional 52 bursts. Flux upper limits depend greatly on the zenith angle of the burst, but typical limits above 100 TeV are $\sim 4 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}$. The flux upper limits for three bursts imply that the observed spectrum softens between 2 MeV and ~ 100 TeV.

INTRODUCTION

The origin of gamma-ray bursts (GRB's) remains a mystery in part due to the lack of observed counterparts at other wavelengths. Although detecting

lower energy counterparts seems more likely, searches at ultra high energies are also important. At least one recent theory¹ suggests that some GRB's may have photon energies as high as 10 TeV. Furthermore, the EGRET instrument² has detected bursts with hard power-law spectra, no evidence of softening, and photons with energies as high as 10 GeV.

The CYGNUS array could detect the hardest observed GRB's if the bursts' energy spectra continue to ultra high energies. For example, the differential flux measured with EGRET³ at ~ 10 MeV during the 7-second burst 1B910503 has a differential spectral index of about $\gamma = -2.2$. Extrapolating this flux to ultra high energies results in about 7 detected source events expected in a bin with 0.1 expected background events for a source overhead; for a zenith angle $\theta \approx 30^\circ$, about 2.5 detected source events and 0.02 background events are expected. Unfortunately, this GRB and the very strong "superbowl" burst⁴⁻⁷ detected on 31 January 1993 were not in the CYGNUS field of view.

Many bursts detected at lower energies (20 keV to 2 MeV) by BATSE⁸ were in the CYGNUS field of view. Some of these bursts also would be detectable if their spectra continued to ultra high energies. Extrapolating the $\gamma = -1.7$ spectrum⁹ measured by BATSE for burst 1B911104 results in about 2500 expected source events in a bin with fewer than 0.01 expected background events.

We have examined the CYGNUS data set for evidence of ultra high energy (UHE) emission coincident with bursts detected by BATSE and/or the third Interplanetary Network¹⁰ (IPN). BATSE has been detecting GRB's at a rate of about one per day since it began operation in April 1991.¹¹ BATSE has a flux threshold of $\sim 10^{-7}$ erg cm⁻² s⁻¹ and is sensitive to γ -rays in the energy range of 20 keV to 2 MeV.¹¹ The IPN, which has consisted of Ulysses, the Pioneer Venus Orbiter, the Compton Gamma-Ray Observatory, and other satellites, accurately localized about 30 GRB's by triangulation from three spacecraft.

We have considered the 260 bursts in the first BATSE catalog,¹² as well as 18 bursts whose locations were well determined by the IPN¹³ between April 1991 and July 1992. Six of the IPN bursts and 52 of the BATSE bursts (according to BATSE's best location coordinates) had $\theta \leq 60^\circ$ and so were in the CYGNUS field of view.

THE CYGNUS EXPERIMENT

The CYGNUS-I extensive air shower array,¹⁴ located in Los Alamos, New Mexico, has been operating since April 1986. The trigger rate has been about 3.5 s⁻¹ since the summer of 1989. The angular resolution is 0.7°.¹⁵ The energy threshold depends strongly on the zenith angle of the incident particle. The median energy of detected γ -rays (E_{med}) is about 50 TeV for showers from zenith, about 90 TeV for showers with zenith angle $\theta \approx 30^\circ$, and about 1000 TeV for showers with $\theta \approx 60^\circ$.

METHOD OF SEARCH

We search for UHE emission during T_{90} , the time BATSE received 90% of the burst flux, rounded up to at least a second (burst durations vary from hundredths to hundreds of seconds). The observed number of events from the direction of the burst is compared to the expected number of background events,

as calculated using data within a few hours of the burst. For each of five well located IPN bursts a single circular bin of 1.5° is used. This bin size maximizes the sensitivity of the search.¹⁶ For one IPN burst, the source locus is a short arc, so three overlapping such bins are used.

The remaining 52 bursts from the BATSE catalog have 1σ location errors ranging from 4° to 19° (much larger than the angular resolution of the CYGNUS array). There is a 92% probability that a burst is within 2σ of the reported location.¹² Therefore, an angular area with radius twice that of the quoted BATSE 1σ error around each burst and with $\theta < 60^\circ$ is searched by dividing it into a non-overlapping grid of (44 to 665) square bins with dimensions 2.6° in declination (δ) by $2.6^\circ/\cos\delta$ in right ascension (α). The number of observed events in each of the bins is compared with the number expected from the cosmic ray background. To ensure sensitivity to a source near the edge of a bin on this grid, the process is repeated with the grid shifted $1/2$ of a bin width in α , then $1/2$ of a bin width in δ , then $1/2$ of a bin width in both.

For each of the five well localized IPN bursts, the probability P_i of background fluctuations yielding at least the number of observed events is determined, including the uncertainties in the background calculation. For these bursts, the burst probability P_{burst} is simply P_i . For each BATSE burst, and for the remaining IPN burst, P_i is found for each bin, and the smallest probability is called P_{min} . Then P_{burst} is the probability of background fluctuations yielding at least one P_i as small as P_{min} . Figure 1 shows the integral distribution of the burst probabilities P_{burst} .

Figure 1. Integral number distribution of the 58 bursts as a function of post-trials burst probability P_{burst} . The dotted line shows the expected distribution, which exhibits a discontinuous jump at $-\log_{10} P_{\text{burst}} = 0.0$ due to the finite number of bursts expected to have no events in the entire area searched. The dashed line indicates the excess needed to yield a 1% confidence level for the sample.

To test this distribution, we determine whether the most significant excess is consistent with no signal. Final burst probabilities P_{burst} are sorted into ascending order $P_1, P_2, \dots, P_{58}$, where P_i is the i^{th} smallest probability of any burst in the sample. For each P_i we calculate the probability that i or more bursts have probabilities less than or equal to P_i .

RESULTS

The most significant excess in the distribution corresponds to four bursts with $P_{\text{burst}} \leq 0.015$. The probability of background fluctuations causing so unlikely an excess at some point in the distribution is 10%, consistent with the hypothesis of no signal.

The 90% CL upper limit on the flux of photons above an energy E is obtained by normalizing the upper limit on the number of excess events to the background cosmic ray flux (see ref. 15 for details). The upper limits depend on the source zenith angle, the source spectrum at earth, and the assumed cosmic-ray composition. For extragalactic sources, absorption¹⁷ by intergalactic radiation fields^{18–20} may drastically reduce the flux above the detector's energy threshold (for quantitative results, see ref. 21). Here we assume no absorption and a source spectrum matching the $E^{-2.7}$ cosmic ray spectrum, but the upper limits change by $\lesssim 10\%$ for spectra as hard as E^{-2} . Flux upper limits for sources with small zenith angles ($\sim 30^\circ$) and moderate durations (~ 10 s) are typically

$$F_{\text{ul}}(> 100 \text{ TeV}) \sim 4 \times 10^{-10} \text{ cm}^{-2} \text{ s}^{-1}. \quad (1)$$

Table I shows the flux upper limits for the six IPN bursts. Also given are the number of source events N_{extrap} expected from a direct extrapolation using the BATSE high-energy spectral index β ,⁹ which was unavailable for bursts 1B910421 and 920720. Although the CYGNUS array would have easily detected three of the bursts if their spectra continued to ultra high energies, there is no significant excess in the number of observed events N_{obs} . The 90% CL upper limit β_{ul} on the spectral index above an assumed break at 2 MeV is smaller if the spectrum softens at a higher energy.

Table I. Flux Limits for IPN bursts.							
Burst	θ_{zen} (deg.)	E_{med} (TeV)	$F_{\text{ul}}(> E_{\text{med}})$ ($\text{cm}^{-2} \text{ s}^{-1}$)	BATSE index β	N_{extrap}	CYGNUS β_{ul}	N_{obs}
1B 910421	27	80	9.5×10^{-10}				0
1B 910627	51	600	3.6×10^{-10}	-2.03 ± 0.02	1		0
1B 911104	40	100	3.4×10^{-9}	-1.67 ± 0.03	2500	-2.03	1
1B 911126	31	90	1.0×10^{-10}	-2.02 ± 0.05	29	-2.16	0
920325	26	70	2.2×10^{-9}	-2.04 ± 0.02	8	-2.12	0
920720	30	90	5.8×10^{-10}				0

CONCLUSIONS

For the 58 visible bursts, we saw no evidence for emission of UHE radiation. The results for three bursts clearly indicate either a softening of the production spectrum at high energies or the presence of UHE γ -ray absorption. Such absorption would imply a cosmological origin for the bursts.

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