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Search for Ultra-High-Energy Radiation from γ-ray Bursts

The CYGNUS Collaboration

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Presented by Richard W. Schnee

Abstract

Using data from the CYGNUS extensive air shower array, we have searched for evidence of emission of ultra-high-energy radiation coincident with γ-ray bursts observed by the BATSE instrument on the Compton Gamma-Ray Observatory. No statistically significant excess was found for any point in the sky within 4σ of BATSE's best location coordinates for any of the 56 bursts examined. Furthermore, no events were seen in the 2.2° radius circular bin surrounding γ-ray burst GRB 920720, whose location was determined accurately by the Compton/Ulysses/PVO Interplanetary Network of satellites. Flux upper limits depend greatly on the actual zenith angle of the burst. Typical fluence upper limits above 100 TeV are $\sim 10^{-6}$ erg cm^{-2}. The fluence upper limit for GRB 920720 is 2×10^{-5} erg cm^{-2}.

Introduction. The Burst and Transient Source Experiment (BATSE)[1] has been detecting γ-ray bursts at a rate of about one per day since it began operating in 1991 April[2]. BATSE has a flux threshold of $\sim 10^{-7}$ erg cm^{-2} s^{-1} and a sensitivity to γ-rays in the energy range of 20 keV to 2 MeV[2].

The CYGNUS-I extensive air shower array[3] has been operating since 1986 April, at a trigger rate of about 3.5 s^{-1} since upgrades in summer 1989. The energy threshold depends strongly on the zenith angle of the incident particle. The median energy of detected γ-rays is about 50 TeV for showers overhead, about 100 TeV for showers with zenith angle $\theta = 30^\circ$, and about 1000 TeV for showers with $\theta = 60^\circ$.

We have examined the CYGNUS data set for evidence of ultra-high energy (UHE) emission coincident with bursts detected by BATSE. We considered the 260 bursts detected by BATSE in its first year of operation[4]; 56 of these

bursts had $\theta < 60°$ and so were visible to the CYGNUS array. In addition, we included one burst (GRB 920720) whose location was well determined by the Ulysses/Compton/PVO Interplanetary Network[5]. We searched for UHE emission during the time BATSE received 90% of the burst flux, rounded up to the nearest second (burst durations vary from hundredths to hundreds of seconds).

Method of Search The 56 bursts from the BATSE catalog[4] have 1σ location errors ranging from 4° to ~20°. However, the BATSE group does not expect the errors to be Gaussian, particularly for weaker bursts. An area 4 times as large as the 1σ area may be needed for a 95% confidence level[4]. The angular resolution of the CYGNUS array is 0.7°[3]. For the small number of background events expected during the bursts, the optimally sized square bin[6] is 2.6° on a side, much smaller than the BATSE error box. Therefore, we divide an area of sky 4 times the quoted 1σ error box around each burst into a non-overlapping grid of square bins with dimensions 2.6° in declination (δ) by $2.6°/\cos\delta$ in right ascension (α). We test whether any of these (~150 to ~1000) bins contains more events during the burst period than would be expected from background fluctuations. 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.

The expected number of background events in a bin with declination δ and hour angle HA is computed from

$$N_{exp}(\delta, HA) = \frac{N_{in}(\delta, HA)}{N_{tot}} R_{2min} \frac{T}{120sec}. \quad (1)$$

Here $N_{in}(\delta, HA)$ is the number of events falling in the bin during the rest of the run containing the burst (a run varies in duration from 3 to 10 hours), while N_{tot} is the total number of events observed during the rest of the run, R_{2min} is the total number of events detected during the two minutes around the burst, and T is the burst duration in seconds. This formula is used because the overall event rate varies over the course of a run, but the efficiency as a function of local coordinates does not.

The probability of background yielding at least the number of observed events is determined for each bin in each of the four large grids, taking into account the uncertainties in the expected background. For each burst, the smallest probability, P_{min}, is designated the *pre-trial* probability of the burst. We then determine the probability P_f of background fluctuations yielding at least one pre-trial probability as small as P_{min}. To test the distribution of final burst probabilities P_f, we determine whether the distribution's most significant excess is consistent with no signal. The probabilities P_f are sorted into ascending order $P_1, P_2, \ldots, P_{56}$, where P_i is the ith smallest probability of any burst in the sample. For each P_i we calculate the probability that i or more bursts would have probabilities less than or equal to P_i.

Results Figure 1 shows the integral distribution of the final burst probabilities P_f. The most significant excess in the distribution corresponds to 33 bursts with $P_f = 0.42$. The probability of so many bursts having P_f this low is 0.6%. After including a trials factor (determined from Monte Carlo simulation[7] to be 13.6)

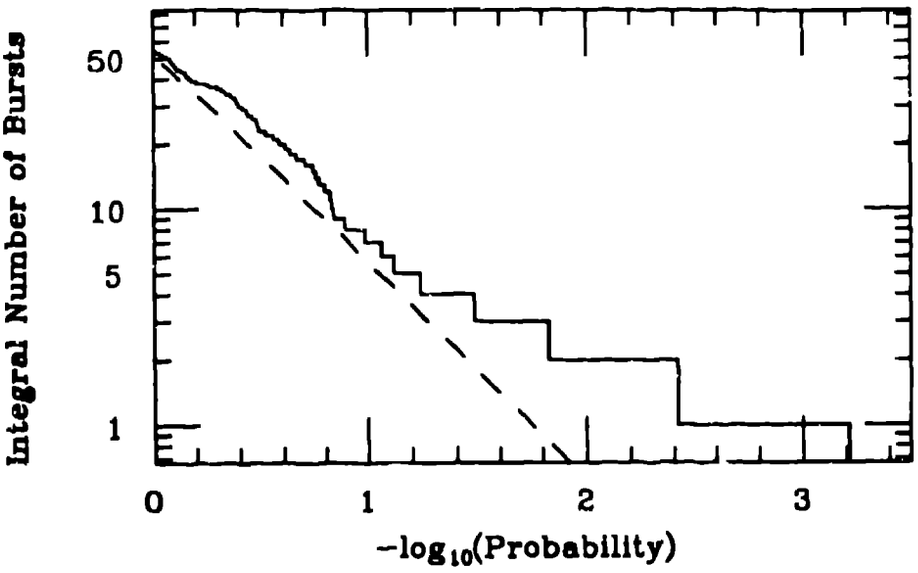

Figure 1. Integral number distribution of the 56 BATSE catalog bursts as a function of post-trial burst probability P_f. The dashed line shows the expected distribution, which exhibits a discontinuous jump at $-\log_{10} P = 0.0$ due to the finite number of bursts expected to have no events in the entire area searched.

to account for searching the distribution for the most significant deviation, the probability is 8%, consistent with the hypothesis of no signal.

Flux Limits The (90% CL) upper limit on the flux of photons above an energy E is given by

$$F_{ul}(>E) = \frac{N_{ul}}{N_{exp}} \frac{f_{cr}(>E)\Omega}{R_\gamma \beta} \tag{2}$$

where N_{ul} is the (90% CL) upper limit on the number of source events, $f_{cr}(>E)$ is the all-particle cosmic ray flux (above the energy E), Ω is the angular size of the bin used, β is the fraction of source events expected to fall in this bin, and R_γ is the ratio of the efficiency of detecting source photons to that of detecting cosmic rays. We take f_{cr} from the measured values of the cosmic ray proton flux and the ratio of of the all-particle flux to the proton flux[8]:

$$f_{cr}(>E) = 1.8 \times 10^{-5} \left(\frac{E}{1\ \mathrm{TeV}}\right)^{-1.70} cm^{-2} s^{-1} sr^{-1}. \tag{3}$$

A Monte Carlo simulation that takes into account uncertainties in the source position within a bin predicts $\beta = 0.77$. The value of R_γ depends on the source zenith angle, the source spectrum at earth, and the assumed cosmic-ray composition. For extragalactic sources, absorption[9] by the microwave background[10,11] and the infrared background[12] drastically reduces R_γ (see ref. 13 for quantitative results). Here we assume no absorption and a source spectrum the same as the cosmic ray spectrum. We use a cosmic ray composition of 4 parts H, 4 parts He, 2 parts N, 2 parts Mg, 1 part Cl, and 1 part Fe (based on ref. 8). Flux limits for sources with small zenith angles and moderate durations are typically

$$F_{ul}(>100\ \mathrm{TeV}) = 2 \times 10^{-10} cm^{-2} s^{-1}. \tag{4}$$

The fluence upper limit ϕ_{ul} depends strongly on the assumed spectrum. For a differential power-law spectrum $dN/dE \propto E^{-\alpha}$,

$$\phi_{ul}(>E) = F_{ul}(>E)TE\frac{\alpha}{\alpha-\frac{1}{2}}, \tag{5}$$

where T is the burst duration. For a spectrum the same as background cosmic rays, typical fluence limits $\phi_{ul}(>100\ \mathrm{TeV}) \approx 10^{-6}$ erg cm^{-2}.

GRB 920720 The accurately located burst GRB 920720 (BATSE trigger #1711) occurred at (1950 coordinates) $\alpha = 194.94°$, and $\delta = 37.01°$, which yield a zenith angle of 35.5°. The burst lasted 7 seconds, during which time we observed no events within 2.2° of it. The flux upper limit for this burst $f_{ul}(>100\ \mathrm{TeV}) = 8 \times 10^{-10}$ cm^{-2} sec^{-1}; the fluence upper limit $\phi_{ul}(>100\ \mathrm{TeV}) = 2 \times 10^{-6}$ erg cm^{-2}.

Conclusion For the 57 visible bursts, we saw no evidence of emission of ultra-high-energy radiation.

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