# Search for Very High Energy Emission from Gamma-Ray Bursts using Milagro

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**Abstract.** Gamma-Ray Bursts (GRBs) have been detected at GeV energies by EGRET and models predict emission at $> 100$ GeV. Milagro is a wide field (2 sr) high duty cycle ($> 90\%$) ground based water Cherenkov detector that records extensive air showers in the energy range 100 GeV to 100 TeV. We have searched for very high energy emission from a sample of 106 gamma-ray bursts (GRB) detected since the beginning of 2000 by BATSE, BeppoSax, HETE-2, INTEGRAL, Swift or the IPN. No evidence for emission from any of the bursts has been found and we present upper limits from these bursts.

**Keywords:** gamma-ray sources; gamma-ray bursts; astronomical observations: gamma-ray
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Some of the most important contributions to understanding gamma-ray bursts (GRBs) have come from observations of afterglows over a wide spectral range [1]. Many GRB models predict very high energy (VHE, $> 100$ GeV) emission from GRBs at a level comparable to that at MeV energies (e.g. [2, 3]). EGRET detected several GRBs at energies above 100 MeV, indicating that the spectrum of GRBs extends at least out to 1 GeV, with no evidence for a spectral cut-off [4]. A second component was also found in one burst which extended up to at least 200 MeV and had a much slower temporal decay than the main burst [5]. At very high energies, there has been no conclusive emission detected for any single GRB, though a search for counterparts to 54 BATSE bursts with Milagrito, a prototype of Milagro, found evidence for emission from one burst, with an after trials significance slightly greater than $3\sigma$ [6]. At these high energies, gamma rays are attenuated by the redshift-dependent extra-galactic background light (EBL) [7], making the detection of VHE emission from GRBs very challenging.

A search for an excess of events above those due to the background was carried out for each of the 106 satellite-detected GRBs in our sample (see Table 1). These represent all the GRBs known to have occurred within the field of view of Milagro during its first seven years of operations (2000-2006)[2]. Milagro detected no significant emission from any of these bursts, and fluence upper limits are given in Table 1.

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[2] GRB 060218, due to its long duration of more than 2000 s moved out of Milagro's field of view after the start of the burst. The limit presented here is for the initial 10 s hard spike reported by the instrument team.

**TABLE 1.** GRBs in the Milagro field of view (2000-2006). Column 1 is the GRB name. A superscript refers to the number of IPN error regions in the Milagro field of view. A superscript of one implies only one of two error regions fell in the Milagro field of view, while a two implies that both did, and they are listed one after the other. Column 2 gives the duration of the burst (in seconds), column 3 the zenith angle (in degrees), column 4 the measured redshift, column 5 the satellite(s) detecting the GRB, and column 6 gives the Milagro 99% confidence upper limit on the 0.2–20 TeV fluence in erg cm$^{-2}$. Numbers in bold (also labelled with a [#]) take into account absorption by the EBL (using the Primack 05 model) for a redshift given in column 4. Those with three dots imply the redshifts are so high that all the emission is expected to be absorbed.

| GRB | Dur. | $\theta$ | z | Inst. | 99% UL | GRB | Dur. | $\theta$ | z | Inst. | 99% UL |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 000113 | 370 | 21 | ... | BATSE | 5.5e-6 | 031026 | 0.24 | 45 | ... | IPN | 1.1e-6 |
| 000131[1] | 12 | 41 | ... | IPN | 6.5e-7 | 031220 | 23.7 | 43 | ... | HETE | 4.0e-6 |
| 000205 | 23 | 25 | ... | BSAX | 6.9e-7 | 040506 | 175 | 49 | ... | IPN | 6.0e-6 |
| 000206 | 10 | 39 | ... | BSAX | 9.3e-7 | 040924 | 0.6 | 43 | 0.859 | HETE | **1.4e-3**[#] |
| 000212 | 8 | 2.2 | ... | BATSE | 1.1e-6 | 041211 | 30.2 | 43 | ... | HETE | 4.8e-6 |
| 000220 | 2.4 | 49 | ... | BATSE | 1.1e-5 | 041219a | 520 | 27 | ... | INTGR. | 5.8e-6 |
| 000226 | 10 | 32 | ... | BATSE | 3.4e-6 | 050124 | 4 | 23 | ... | Swift | 3.0e-7 |
| 000226b[1] | 94.5 | 32 | ... | IPN | 7.8e-7 | 050213 | 17 | 23 | ... | IPN | 1.3e-6 |
| 000301C | 14 | 38 | 2.03 | BATSE | ... | 050319 | 15 | 45 | 3.24 | Swift | ... |
| 000302 | 120 | 32 | ... | BATSE | 6.8e-6 | 050402 | 8 | 40 | ... | Swift | 2.1e-6 |
| 000314 | 12.8 | 45 | ... | BSAX | 3.6e-5 | 050412 | 26 | 37 | ... | Swift | 1.7e-6 |
| 000317 | 550 | 6.4 | ... | BATSE | 7.9e-6 | 050502 | 20 | 43 | 3.793 | INTGR. | ... |
| 000330 | 0.2* | 30 | ... | BATSE | 1.0e-6 | 050504 | 80 | 28 | ... | INTGR. | 1.3e-6 |
| 000331 | 55 | 38 | ... | BATSE | 1.2e-5 | 050505 | 60 | 29 | 4.3 | Swift | ... |
| 000402 | 120 | 48 | ... | BSAX | 4.5e-5 | 050509b | 0.128 | 10 | 0.226? | Swift | **1.1e-6**[#] |
| 000408 | 2.5 | 31 | ... | BATSE | 1.0e-6 | 050522 | 15 | 23 | ... | INTGR. | 5.1e-7 |
| 000424 | 5 | 36 | ... | BATSE | 7.6e-7 | 050607 | 26.5 | 29 | ... | Swift | 8.9e-7 |
| 000508 | 30 | 34 | ... | BATSE | 3.7e-6 | 050703 | 26 | 26 | ... | IPN | 1.2e-6 |
| 000607[1] | 0.12 | 42 | ... | IPN | 4.6e-7 | 050712 | 35 | 39 | ... | Swift | 2.5e-6 |
| 000615 | 10 | 39 | ... | BSAX | 1.6e-6 | 050713b | 30 | 44 | ... | Swift | 4.0e-6 |
| 000630 | 20 | 32 | ... | IPN | 2.2e-6 | 050715 | 52 | 37 | ... | Swift | 1.7e-6 |
| 000707[2] | 18 | 43 | ... | IPN | 1.9e-6 | 050716 | 69 | 30 | ... | Swift | 1.6e-6 |
| 000707[2] | 18 | 41 | ... | IPN | 1.0e-6 | 050820 | 20 | 22 | 2.612 | Swift | ... |
| 000727 | 10 | 41 | ... | IPN | 2.6e-6 | 051103 | 0.17 | 50 | 0.001? | IPN | **4.2e-6**[#] |
| 000730 | 7 | 19 | ... | IPN | 4.2e-7 | 051109 | 36 | 9.7 | 2.346 | Swift | ... |
| 000821[1] | 8 | 27 | ... | IPN | 6.9e-7 | 051111 | 20 | 44 | 1.55 | Swift | ... |
| 000830[1] | 8 | 35 | ... | IPN | 9.1e-7 | 051211b | 80 | 33 | ... | INTGR. | 2.6e-6 |
| 000926 | 25 | 16 | 2.04 | IPN | ... | 051221 | 1.4 | 42 | 0.55 | Swift | **9.8e-4**[#] |
| 001017 | 10 | 42 | ... | IPN | 2.2e-6 | 051221b | 61 | 26 | ... | Swift | 1.8e-6 |
| 001018 | 31 | 32 | ... | IPN | 2.1e-6 | 060102 | 20 | 40 | ... | Swift | 2.0e-6 |
| 001019 | 10 | 20 | ... | IPN | 1.1e-6 | 060109 | 10 | 22 | ... | Swift | 4.1e-7 |
| 001105 | 30 | 8.5 | ... | IPN | 1.4e-6 | 060110 | 15 | 43 | ... | Swift | 3.0e-6 |
| 001204 | 0.44 | 48 | ... | BSAX | 1.2e-5 | 060111b | 59 | 37 | ... | Swift | 2.3e-6 |
| 010104 | 2 | 20 | ... | IPN | 4.0e-7 | 060114 | 100 | 41 | ... | INTGR. | 5.1e-6 |
| 010220 | 150 | 27 | ... | BSAX | 2.1e-6 | 060204b | 134 | 31 | ... | Swift | 2.7e-6 |
| 010613 | 152 | 25 | ... | IPN | 2.9e-6 | 060210 | 5 | 43 | 3.91 | Swift | ... |
| 010706 | 48 | 37 | ... | IPN | 2.6e-6 | 060218 | 10 | 44.6 | 0.03 | Swift | **3.8e-5**[#] |
| 010903 | 41 | 49 | ... | IPN | 2.9e-5 | 060306 | 30 | 46 | ... | Swift | 7.2e-6 |
| 010921 | 24.6 | 10 | 0.45 | HETE | **2.9e-5**[#] | 060312 | 30 | 44 | ... | Swift | 3.3e-6 |
| 011130 | 83.2 | 34 | ... | HETE | 3.4e-6 | 060313 | 0.7 | 47 | ... | Swift | 2.7e-6 |
| 011212 | 84.4 | 33 | ... | HETE | 6.7e-6 | 060403 | 25 | 28 | ... | Swift | 1.0e-6 |
| 020311 | 11.5 | 27 | ... | IPN | 1.7e-7 | 060427b | 0.22 | 16 | ... | IPN | 2.1e-7 |
| 020429[2] | 16 | 39 | ... | IPN | 4.6e-7 | 060428b | 58 | 27 | ... | Swift | 1.1e-6 |
| 020429[2] | 16 | 30 | ... | IPN | 3.0e-7 | 060507 | 185 | 47 | ... | Swift | 1.8e-5 |
| 020625b | 125 | 38 | ... | HETE | 5.7e-6 | 060510b | 330 | 43 | 4.9 | Swift | ... |
| 020702 | 26 | 34 | ... | IPN | 1.4e-6 | 060515 | 52 | 42 | ... | Swift | 9.6e-6 |
| 020908[1] | 17 | 19 | ... | IPN | 7.3e-7 | 060712 | 26 | 35 | ... | Swift | 3.8e-6 |
| 020914 | 9 | 5.7 | ... | IPN | 4.2e-7 | 060814 | 146 | 23 | ... | Swift | 2.5e-6 |
| 021104 | 19.7 | 13 | ... | HETE | 7.5e-7 | 060904A | 80 | 14 | ... | Swift | 2.4e-6 |
| 021112 | 7.1 | 34 | ... | HETE | 9.4e-7 | 060906 | 43.6 | 29 | 3.685 | Swift | ... |
| 021113 | 20 | 18 | ... | HETE | 6.4e-7 | 061002 | 20 | 45 | ... | Swift | 4.0e-6 |
| 021211 | 6 | 35 | 1.01 | HETE | ... | 061126 | 191 | 28 | ... | Swift | 4.3e-6 |
| 030413 | 15 | 27 | ... | IPN | 1.0e-6 | 061210 | 0.8 | 23 | 0.41? | Swift | **6.1e-6**[#] |
| 030823 | 56 | 33 | ... | HETE | 2.8e-6 | 061222a | 115 | 30 | ... | Swift | 5.6e-6 |