Milagro Search for Very High Energy Emission from Gamma-Ray Bursts in the *Swift Era*

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Abstract.
The recently launched *Swift* satellite is providing an unprecedented number of rapid and accurate Gamma-Ray Burst (GRB) localizations, facilitating a flurry of follow-up observations by a large number of telescopes at many different wavelengths. The Very High Energy (VHE, >100 GeV) regime has so far been relatively unexplored. Milagro is a wide field of view (2 sr) and high duty cycle (> 90%) ground-based gamma-ray telescope which employs a water Cherenkov detector to monitor the northern sky almost continuously in the 100 GeV to 100 TeV energy range. We have searched the Milagro data for emission from the most recent GRBs identified within our field of view. These include three *Swift* bursts which also display late-time X-ray flares. We have searched for emission coincident with these flares. No significant detection was made. A 99% confidence upper limit is provided for each of the GRBs, as well as the flares.

INTRODUCTION

Some of the most important contributions to our understanding of gamma-ray bursts have come from observations of afterglows over a wide spectral range [1]. Very little, however, is known about the broadband spectra of GRBs in the prompt phase, due to its short duration. Many GRB production models predict a fluence at TeV comparable to that at MeV scales [2, 3, 4]. Almost all GRBs are detected in the energy range between 20 keV and 1 MeV, though several have been observed above 100 MeV by EGRET, indicating that the spectrum of GRBs extends at least out to 1 GeV [5]. 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 [6]. It is unclear how high in energy this component extends to and whether it is similar to the inverse Compton peak seen in many TeV sources. 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 a significance slightly greater than 3σ [7]. At these high energies, gamma rays suffer from attenuation due to the extra-galactic background light (EBL), which is redshift-

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dependent [8, 9, 10], making GRBs above z>0.5 very difficult to observe. Here, we describe our search for VHE emission from 20 GRBs which have occurred within the field of view of Milagro[2] between December 2004 and December 2005. Recently, *Swift* has also observed bright X-ray flares from GRB afterglows, sometimes of comparable energy to the burst itself [11, 12]. Although the most significant of these flares (from GRB 050502B) was unfortunately outside the field of view of Milagro, six other flares from three different GRBs were observable [13]. We present the upper limits derived from our observations.

DATA ANALYSIS AND RESULTS

A search for an excess of events above those due to the background was made for each of the 20 bursts in our sample, listed in Table 1, as well as for the flares listed in Table 2. The number of events falling within a 1.6 degree bin was summed for the relevant duration (column 2 of Table 1 or column 4 of Table 2). An estimate of the number of background events was made by characterizing the angular distribution of the background using two hours of data surrounding the burst, using a technique known as "direct integration" [14]. For those bursts whose redshift is known, we compute the effect of the absorption, according to the model of [10] and print the upper limits in bold. No significant emission was detected. Our upper limits are given in column seven of Table 1 (for the GRBs) and Table 2 (for the flares).

Some of the more interesting bursts in Table 1 include GRB 050509b, the second *short/hard* burst detected by *Swift*, with a reported duration of 30 ms and a relatively low fluence of 2.3×10^{-8} erg cm^{-2} in the 15–350 keV range [15]. Although Milagro detected no emission from this burst [16], the very favorable zenith angle (10°) and possible low redshift of 0.226 provide the opportunity to set interesting upper limits for TeV emission from this burst. Another burst that deserves mention is GRB 051103, a short burst detected by the IPN, possibly originating from the nearby ($<$ 4 Mpc) galaxy M81 [17]. Although this burst was not at a favorable zenith angle for Milagro ($\theta >$45°), we chose to analyse the data, due to its potential interest. If this burst were associated with M81, as has been suggested, the almost complete absence of absorption would make the Milagro upper limit on the fluence about 20% of the measured fluence in the X-ray band [18]. Finally, GRB 051109 occurred at a zenith angle of less than 10° for Milagro, making it the burst with the best location of our sample. Unfortunately, this burst had a measured redshift of 2.346, making the Milagro limit, once absorption is taken into account, several orders of magnitude larger than the measured fluence in the X-ray band [19].

In Table 2 we list 6 flares detected by *Swift* from 3 GRBs which were in Milagro's field of view [12]. Milagro detected no significant emission from any of these flares. The brightest of these flares, from GRB 050607, had a fluence in the X-ray range of roughly 1.5×10^{-7} erg cm^{-2} [20], placing the Milagro limit about an order of magnitude higher.

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[2] We have included GRB 051103 in our sample, despite being at a relatively large zenith angle, given its potential interest and possible proximity.

TABLE 1. List of GRB in the field of view of Milagro in the Swift Era (December 2004 – December 2005), with preliminary upper limits.

GRB	**T90/Dur.**[*]	$\theta^\dagger$	z^{**}	**Instrument**[‡]	$\sigma^\S$	**UL(fluence)**[¶]
041219a	520	26.9	...	INTEGRAL	+1.7	5.8e-6
050124	4	23.0	...	Swift	-0.8	3.0e-7
050319	15	45.1	3.24	Swift	+0.6	...
050402	8	40.4	...	Swift	+0.6	2.1e-6
050412	26	37.2	...	Swift	-0.6	1.7e-6
050502	20	42.7	3.793	INTEGRAL	+0.6	...
050504	80	27.6	...	INTEGRAL	-0.8	1.3e-6
050505	60	28.9	4.3	Swift	+1.2	...
050509b	0.128	10.0	0.226?	Swift	-0.9	**1.1e-6**
050522	15	22.9	...	INTEGRAL	-0.6	5.1e-7
050607	26.5	29.3	...	Swift	-0.9	8.9e-7
050712	35	38.8	...	Swift	-0.1	2.5e-6
050713b	30	44.2	...	Swift	-0.3	4.0e-6
050715	52	36.9	...	Swift	-1.5	1.7e-6
050716	69	30.3	...	Swift	-0.5	1.6e-6
050820	20	21.9	2.612	Swift	+0.2	...
051103	0.17	49.9[‖]	0.001?	IPN	-0.2	**4.2e-6**
051109	36	9.7	2.346	Swift	-1.1	**4.3e-3**
051111	20	43.7	1.55	Swift	+0.7	**3.8e-2**
051211b	80	33.3	...	INTEGRAL	+0.4	2.6e-6

[*] Duration of burst.
[†] Zenith angle (degrees).
[**] redshift (when known).
[‡] Instrument reporting the first detection.
[§] Significance of the signal.
[¶] 99% upper limit on the fluence (0.2–20 TeV), in ergs cm^{-2}. The numbers in bold take into account absorption by the EBL (using the Primack 05 model). Those with three dots are at redshifts so high that all the emission is expected to be absorbed.
[‖] This burst was analyzed despite its large zenith angle due to its potential interest as a nearby short burst.

TABLE 2. Bright X-ray Flares in Swift GRB Afterglows

GRB	**Burst Time**[*]	**Flare Time**[†]	**Dur.**[**]	$\theta^\ddagger$	$\sigma^\S$	**UL(fluence)**[¶]
050607	33,083	110	120	29.1	-1.3	1.5e-6
050607	33,083	260	340	28.9	-1.3	2.4e-6
050712	50,427.5	170	265	38.5	+1.8	9.7e-6
050712	50,427.5	435	255	38.1	+2.3	1.0e-5
050716	45,364	135	65	30.7	-1.1	1.3e-6
050716	45,364	330	120	31.4	-0.4	2.3e-6

[*] BAT trigger time (UTC second of day).
[†] Time of onset of flare (seconds after BAT trigger time).
[**] Approximate duration of flare (s).
[‡] Zenith angle (degrees).
[§] Significance of the signal.
[¶] 99% upper limit on the fluence (0.2–20 TeV), in ergs cm^{-2}. No absorption is taken into account as the redshift of these bursts is unknown.

CONCLUSION

A search for VHE emission from GRBs was performed with the Milagro observatory in the range of 100 GeV to 100 TeV. A total of 20 satellite-triggered GRBs were well localized and fell within Milagro's field of view in the year since the launch of Swift. In addition, six bright X-ray flares from GRB afterglows were searched for VHE emission. No significant emission was detected from either the bursts or the flares. 99% confidence upper limits on the fluence are presented.

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