Search for VHE emission from GRB with Milagro

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Abstract. The Milagro gamma-ray observatory employs a water Cherenkov detector to observe extensive air showers produced by high-energy particles impacting in the Earth's atmosphere. Milagro is uniquely capable of searching for very high-energy emission from gamma-ray bursts (GRB) during the prompt emission phase because of its wide field of view and high duty cycle, monitoring the northern sky almost continuously in the 100 GeV to 100 TeV energy range. 33 satellite-triggered GRB have occurred within the field of view of Milagro between January 2000 and December 2003. We have searched for counterparts to these GRB and found no significant emission from any of these burst positions. In the case of GRB 010921, the redshift is low enough (0.45) that our upper limit on the fluence places an observational constraint on potential GRB models.

INTRODUCTION

Some of the most important contributions to our understanding of gamma-ray bursts have come from the observations of afterglows over a wide spectral range [10]. Very little, however, is known about the broadband spectra of GRB in the prompt phase, due to its short duration. Many GRB production models predict a fluence at TeV comparable to that at MeV scales [4, 7, 11]. Almost all GRB 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 GRB extends at least out to 1 GeV [5]. Recently, a second component was found in one burst [6] which extended up to at least 200 MeV and had a much slower temporal decay than the main burst. It is unclear how high in energy this component extends and whether it is similar to the inverse Compton peak seen in TeV sources. At very high energies (VHE), above 100 GeV, 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 3 σ [1]. Here we describe our search for VHE emission from the 33 well-localized GRB[2] which have occurred within the field of

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[2] A great resource for well localized GRB is Jochen Greiner's web page `http://www.mpe.mpg.de/~jcg/grbgen.html`.

view of Milagro between January 2000 and December 2003.

THE MILAGRO OBSERVATORY

Milagro is a TeV gamma-ray detector which uses the water Cherenkov technique to detect extensive air-showers produced by very high-energy gamma-rays as they traverse the Earth's atmosphere. Milagro is located at an altitude of 2600 m, has a field of view of $\sim$2 sr and a duty cycle of approximately 90%, making it an ideal all-sky monitor of transient phenomena at very high energies, such as gamma-ray bursts. The effective area of Milagro is a strong function of zenith angle (see Figure 1) and ranges from $\sim$10 m^2 at 100 GeV to $\sim 10^5$ m^2 at 10 TeV. The right part of Figure 1 shows the cumulative fraction of total effective area of Milagro below a given energy for different zenith angles. The angular resolution is approximately 0.7 degrees.

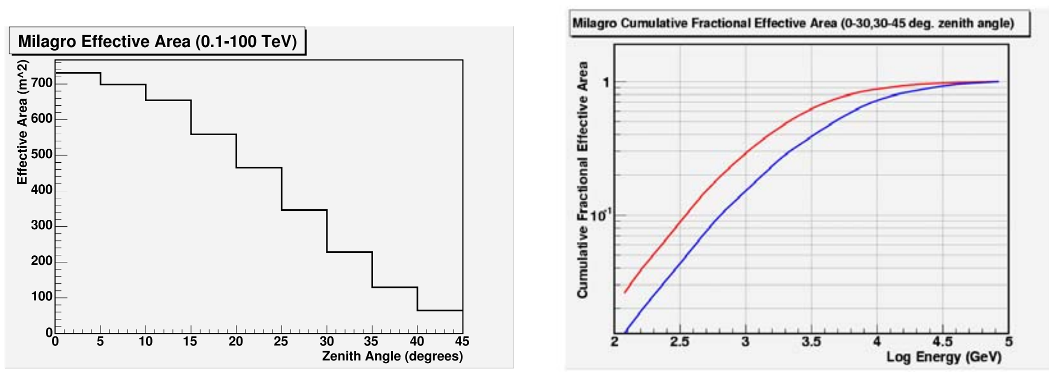

FIGURE 1. **Left** – Milagro Effective Area as a function of zenith angle (2000-01). **Right** – Cumulative fraction of total effective area of Milagro below a given energy for different zenith angles: 0-30 degrees (top curve) and 30-45 degrees (bottom curve).

DATA ANALYSIS

A search for an excess of events above those which are background was made for each of the 33 bursts in our sample. The number of events falling within a 1.6 degree bin was summed for the duration of the burst (N_{ON}). For bursts with an uncertainty in the position greater than 0.5 degree, we searched the entire region given by this uncertainty by tiling it with an array of overlapping 1.6 degree radius bins, spaced 0.1 degree apart in right ascension and declination. We then report the maximum significance. An estimate of the number of background events was made by characterizing the angular distribution of the background using 2 hours of data surrounding the burst, using a technique known as "direct integration" [2]. Figure 2 shows an example of our analysis, as applied to GRB 010921. The top left panel shows the number of events in successive time bins of duration equal to the duration (T_{90}) of the burst, centered at the location of the burst. Time 0 represents the GRB trigger time.

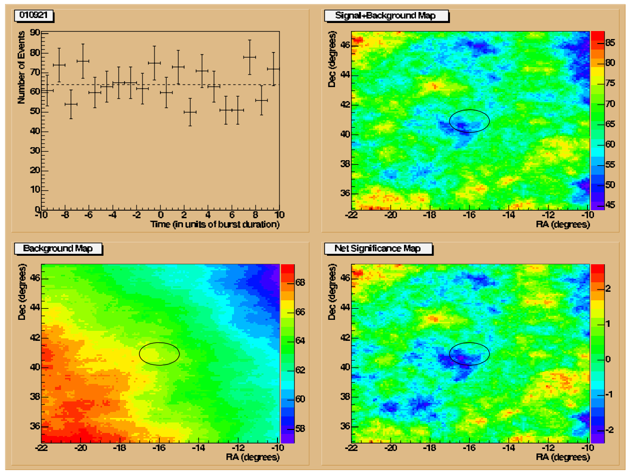

FIGURE 2. Milagro analysis for GRB 010921.

The top right panel shows the total number of events in 1.6 degree bins around the region of the burst. The ellipse represents Milagro's angular resolution of $\sim$0.7 degrees, and is centered at the burst location. The bottom left panel is an estimate of the background at the same location, and the bottom right panel shows the net signal ($N_{ON} - N_{OFF}$) in units of standard deviations (in this case, the signal has negative significance).

RESULTS

Table 1 shows a summary of GRB analyzed with Milagro between the years of 2000 and 2003. Two major changes occurred in the detector beginning in 2002. One was the deployment of an additional 175 PMTs in external water tanks known as "outriggers," surrounding the main pond. The second major change involved the modification in the trigger, significantly changing Milagro's effective area at lower energies[3]. Because of these changes to the instrument, GRB that occurred in 2002 and 2003 were treated separately. None of the bursts searched showed any significant emission. The left part of Figure 3 shows a histogram with the significances, at the central 1.6 degree bin, of the 33 observed GRB. This distribution is consistent with random fluctuations of the background, as can be seen by the superimposed normal distribution centered around zero.

In addition to searching at the duration of the burst (T_{90}), we also searched all the bursts furing the first 5 minutes after the trigger. The 99.9% confidence upper limits on the fluence for both durations are listed in columns 8 and 9 of Table 1 respectively. The right part of Figure 3 compares our upper limits with the measured quantities for several BATSE and HETE bursts. The quantity plotted is E^2dN/dE, where we chose an E^{-2} spectrum at the lower energies and an $E^{-2.4}$ spectrum for Milagro's energy range, and evaluated it at 2 TeV. Circles represent HETE bursts while squares are BATSE bursts.

TABLE 1. List of GRB in the field of view of Milagro from 2000 to 2003, together with preliminary upper limits.

GRB	T90/Dur.*	$\theta^{\dagger}$	N_{ON}**	N_{OFF}‡	σ§	UL(cts)¶	UL(fluence)‖	UL(5 min)††
000113	370	20.9	471	423.2	2.22	111.5	8.01e-06	2.91e-06
000212	8	2.21	32	17.7	3.04	35.9	1.71e-06	3.07e-06
000226	10	31.5	25	11.4	3.48	33.3	4.93e-06	6.75e-06
000301C	14	37.6	11	10.3	0.22	16.0	4.21e-06	3.90e-06
000302	120	31.9	143	113.1	2.68	71.1	1.09e-05	6.92e-06
000317	550	6.39	1740	1625.9	2.69	238.7	1.16e-05	3.32e-06
000330	0.2	30.0	3	0.3	2.91	12.8	1.67e-06	7.26e-06
000331	55	38.3	94	66.2	3.20	61.8	1.75e-05	1.21e-05
000408	2.5	31.1	4	3.4	0.33	11.8	1.68e-06	3.97e-06
000508	30	34.1	25	15.3	2.26	29.4	5.46e-06	5.59e-06
000615	10	39.0	3	7.2	-1.78	9.1	2.79e-06	4.67e-06
000630	20	33.2	23	22.6	0.08	20.5	3.53e-06	3.98e-06
000727	10	40.8	5	6.2	-0.49	11.5	4.32e-06	7.17e-06
000730	7	19.2	8	13.9	-1.72	11.3	7.53e-07	1.65e-06
000926	25	15.9	60	56.8	0.43	32.3	1.89e-06	2.07e-06
001017	10	42.1	2	4.6	-1.35	8.83	3.85e-06	6.00e-06
001018	31	31.8	31	31.5	-0.09	22.90	3.41e-06	4.07e-06
001019	10	19.5	27	21.1	1.23	26.69	1.77e-06	6.86e-07
001105	30	8.5	87	76.2	1.21	45.95	2.18e-06	1.24e-06
010104	2	19.8	3	3.3	-0.19	11.91	7.01e-07	1.69e-06
010220	150	27.0	155	168.8	-1.06	23.95	3.82e-06	1.80e-06
010613	152	24.7	277	280.5	-0.20	52.5	4.68e-06	3.08e-06
010921	24.6	10.4	61	65.4	-0.55	27.1	1.37e-06	1.33e-06
011130	83.2	33.7	93	100.9	-0.79	31.0	5.54e-06	4.95e-06
011212	84.4	33.0	132	113.1	1.72	58.7	9.87e-06	6.82e-06
021104	19.7	13.3	67	62.3	0.59	34.98	1.66e-06	1.75e-06
021112	7.1	33.6	12	6.9	1.77	20.20	3.51e-06	4.41e-06
021113	20	17.7	53	54.7	-0.23	27.14	1.44e-06	1.38e-06
021211	6	34.8	11	4.7	2.48	20.91	4.15e-06	9.15e-06
030413	15	27.1	29	24.87	0.81	25.38	1.81e-06	1.40e-06
030823	56	33.4	61	53.25	1.03	36.43	4.71e-06	4.52e-06
031026	114.2	33.0	156	146.90	0.74	52.96	6.56e-06	2.03e-06
031220	23.7	43.4	11	10.50	0.15	15.84	6.96e-06	3.02e-06

* Duration of burst
† Zenith angle (degrees)
** Number of events "on source"
‡ Estimate of number of "background" events
§ Significance of the signal
¶ 99.9% upper limit on number of counts
‖ 99.9% upper limit on the fluence (0.2–20 TeV), in ergs cm^{-2};
†† 99.9% upper limit on the fluence for a duration of 5 minutes

No absorption is taken into account.

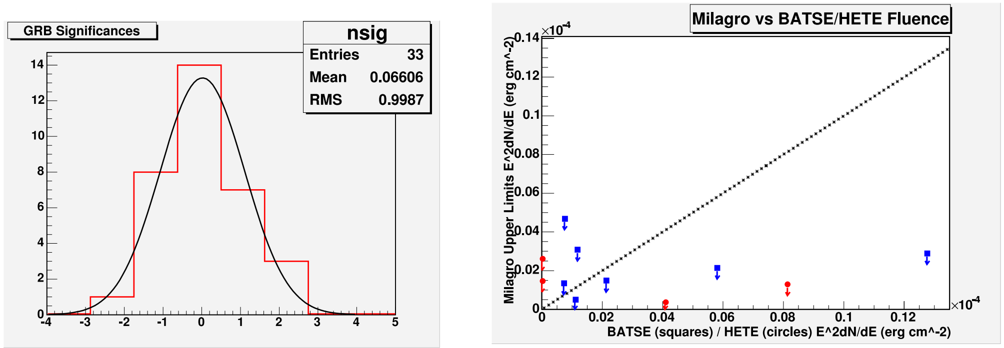

FIGURE 3. **Left** – Significances of the excess observed in Milagro for 33 GRB analyzed. **Right** – Comparison of Fluences from HETE/BATSE and Milagro upper limits.

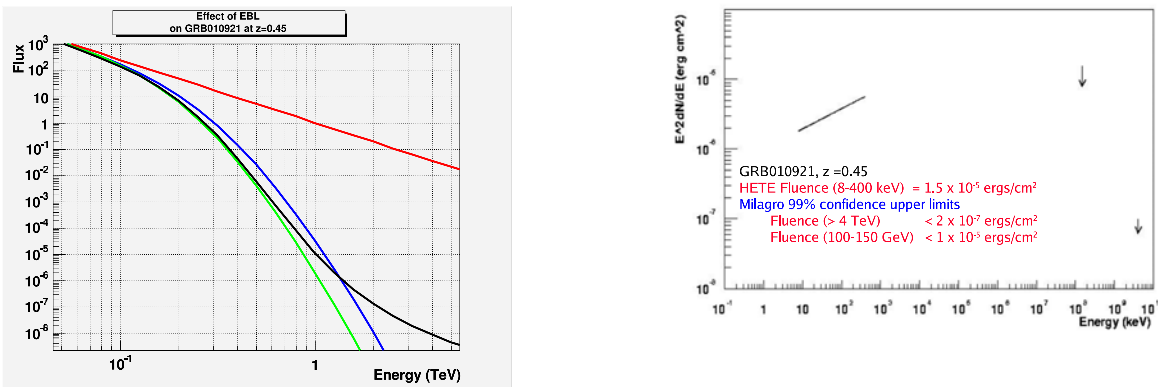

FIGURE 4. **Left** – Effect of the EBL on an $E^{-2.4}$ Spectrum. **Right** – Spectrum of GRB 010921 as seen by HETE, with upper limits from Milagro.

GRB 010921

The most interesting burst in our sample is GRB010921, with a measured redshift of z=0.45. Because of the attenuation of TeV photons by the extragalactic background, we expect the spectrum to cut off sharply at a few hundred GeV [8, 9]. In the left portion of Figure 4 we show the effect of the EBL on an $E^{-2.4}$ spectrum (shown, unabsorbed, as a straight line) at a redshift of 0.45, according to different models (the two parallel curves are from [9], while the third curve is from [8]). From Figure 1, we can see that Milagro's effective area up to 150 GeV is only a few percent of the effective area from 0.1 to 100 TeV. The right part of Figure 4 shows the spectrum measured by HETE for GRB010921, along with our upper limits derived by assuming a hard cut-off at 150 GeV, and a limit assuming no such cut-off.

CONCLUSION

A search for VHE emission from GRB was performed with the Milagro observatory in the range of 100 GeV to 100 TeV. A total of 33 satellite-triggered GRB were well localized and fell within Milagro's field of view in the four year period between January 2000 and December 2003, including GRB 010921 with a known redshift of z=0.45. No significant emission was detected for any of these bursts. 99.9% confidence upper limits on the fluence are presented. After the launch of Swift, in October of 2004, we expect to observe $\sim$25 well-localized GRB per year.

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