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A Search for Prompt Very High Energy Emission from Satellite-detected Gamma-ray Bursts using Milagro

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Abstract: Gamma-ray bursts (GRBs) have been detected up to GeV energies and are predicted by many models to emit in the very high energy (VHE, $>$ 100 GeV) regime too. Detection of such emission would allow us to constrain GRB models. Since its launch, in late 2004, the Swift satellite has been locating GRBs at a rate of approximately 100 per year. The rapid localization and follow-up in many wavelengths has revealed new and unexpected phenomena, such as delayed emission in the form of bright X-ray flares. The Milagro gamma-ray observatory is a wide field of view (2 sr) instrument employing a water Cherenkov detector to continuously ($>$ 90% duty cycle) observe the overhead sky in the 100 GeV to 100 TeV energy range. Over 100 GRBs are known to have been in the field of view of Milagro since January 2000, including 57 since the launch of Swift (through May 2007). We discuss the results of the searches for prompt emission from these bursts, as well as for delayed emission from the X-ray flares observed in some of the Swift bursts.

Introduction

Almost 40 years after the detection of the first gamma-ray burst (GRB), many questions remain about these powerful explosions. Progress in the field has accelerated in the decade since the detection of the first X-ray afterglow [1]. The launch of Swift [2], in late 2004, has resulted in the rapid and accurate localization of $\sim$100 GRBs per year. This has enabled an unprecedented number of multiwavelength follow-up observations in every band of the electromagnetic spectrum, from radio to the highest energy gamma rays, paving the way for a more complete understanding of these phenomena.

The highest energy emission to be detected conclusively from GRBs was seen by the EGRET instrument. EGRET detected several bursts above 100 MeV, with no evidence for a cut-off in the spectrum [3]. One burst in particular, GRB 940217, emitted an 18 GeV photon over 90 minutes after the start of the burst [4]. Another burst, GRB 941017, was found to display a second, higher energy, spectral component which extended up to at least 200 MeV and decayed more slowly than the lower energy component [5]. On this evidence alone, the expectations are that the upcoming launch of GLAST, with its much higher sensitivity than EGRET, will result in a large number of detections at high energies, leading to a better understanding of the GeV properties of GRBs.

At very high energy (VHE, >100 GeV), there have been no conclusive detections of GRBs, although there have been several tantalizing hints of emission. Milagrito, a prototype of Milagro, searched for emission coincident with 54 BATSE bursts and reported evidence for emission above 650 GeV from GRB 970417a, at the 3σ level [6, 7]. The HEGRA group reported evidence at the 3 sigma level for emission above 20 TeV from GRB 920925c [8]. Follow-up observations above 250 GeV by the Whipple atmospheric Cherenkov telescope [9] failed to find any high energy afterglow for 9 bursts studied, though the delay in slewing to observe these bursts ranged from 2 minutes to almost an hour. More recent efforts by the MAGIC [10], Whipple [11], and Milagro [12] telescopes have resulted only in upper limits.

There is no shortage of models predicting (or explaining) very high energy emission from GRBs (e.g. [13, 14, 15, 16, 17]). Many of the proposed emission mechanisms predict a fluence at TeV energies comparable to that at keV-MeV energies. One such mechanism involves the inverse Compton upscattering of lower energy (synchrotron) photons by the energetic electrons which emitted them. The strong magnetic fields and large bulk Lorentz factors present in GRB jets can result in a high energy component peaked at TeV energies. The strength of such a component is highly dependent on the environments of the particle acceleration and the gamma ray production.

Milagro[18, 19] is a TeV gamma-ray detector, located at an altitude of 2630 m in northern New Mexico. Milagro uses the water Cherenkov technique to detect extensive air-showers produced by VHE gamma rays as they interact with the Earth's atmosphere. The Milagro field of view is $\sim$2 sr and duty cycle is $>$90%. The effective area is a function of zenith angle and ranges from ~ 50 m^2 at 100 GeV to $\sim 10^5$ m^2 at 10 TeV. A sparse array of 175 4000-l water tanks, each with a PMT, was added in 2002. These "outriggers," extend the physical area of Milagro to 40000 m^2. The combination of large field of view and high duty cycle make Milagro the best instrument currently available for conducting a search for prompt VHE emission from GRBs. Milagro is also able to operate in "scaler" mode, where individual tube rates can be monitored to search for GRB emission in the 1–100 GeV energy range coincident in time with known satellite bursts (see [20, 21]). In addition to conducting a search for emission from satellite-detected GRBs, Milagro is capable of performing a blind search for emission at all locations in its field of view and many different durations (see [22]).

The GRB Sample

Twenty-five satellite-triggered GRBs occurred within the field of view of Milagro between January 2000 and December 2001. No significant emission was detected from any of these bursts [23]. In the period from January 2002 to December 2004 (post-BATSE and pre-Swift), there were only 11 well-localized GRBs within the Milagro field of view. Since the launch of Swift (through the end of May 2007), however, there have been a total of 57 bursts in the field of view of Milagro [1], many of them with measured redshift. Table 1 lists the 57 GRBs in this sample, along with some of their properties. Due to the absorption of high-energy gamma rays by the extragalactic background light (EBL), detections at VHE energies are only expected for redshifts less than $\sim$0.5. The degree of gamma-ray extinction from this effect is uncertain, because the amount of EBL is not well known. In this work we use the model of [24], which predicts an optical depth of roughly unity for 500 GeV (10 TeV) gamma rays from a redshift of 0.2 (0.05).

Bright X-ray Flares

One of the highlights of the Swift mission has been the detection of bright X-ray flares in the afterglow phase of many GRBs [25]. These flares can sometimes be as bright as the prompt component of the GRB itself. While the exact nature of the flares is not clear, with various different proposals for what may be causing them (e.g. [26, 27, 28]), there are reasonable expectations that these flares will result in the emission of delayed very high energy photons [29]. The first survey of X-ray flares from GRBs observed by Swift in the first year of operations [30] shows that approximately one third of GRBs show significant flaring activity. Table 2 lists the 10 flares from the flare catalog of [30, 31] which were in the field of view of Milagro.

Data Analysis and Results

A search for an excess of events above those due to the background was made for each of the 57 bursts in Table 1, as well as for the 10 flares listed in Table 2. The number of events falling within a 1.6 degree bin was summed for the relevant duration. 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 (or flare), as described in [32]. No significant emission was detected. The upper limits are given in the final column of Table 1 and Table 2. For those bursts with known redshift, we

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[1] A good source of information on well-localized GRBs is J. Greiner's web page http://www.mpe.mpg.de/$\sim$jcg/grbgen.html

compute the effect of the absorption, according to the model of [24] and print the upper limits in bold.

Among the most interesting limits presented here is the one for GRB 070521, recently detected by Swift. Assuming a redshift of 0.55 for the possible host [33], the Milagro upper limit [34] on the fluence is lower than the $\sim 1.8\times10^{-5}$ erg cm^{-2} measured by the Konus-Wind experiment [35] in the 20 keV – 1 MeV energy range. It should be noted, however, that [36] have calculated a "pseudo-redshift" for this burst of pz= 2.28±0.45, and on these grounds, claim it is incompatible with the spectroscopic redshift of 0.55.

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GRB	Dur.	θ	z	Inst.	UL
041219a	520	27	...	INT.	5.8e-6
050124	4	23	...	Swift	3.0e-7
050213	17	23	...	IPN	1.3e-6
050319	15	45	3.24	Swift	...
050402	8	40	...	Swift	2.1e-6
050412	26	37	...	Swift	1.7e-6
050502	20	43	3.793	INT.	...
050504	80	28	...	INT.	1.3e-6
050505	60	29	4.3	Swift	...
050509b	0.128	10	0.226?	Swift	**1.1e-6**
050522	15	23	...	INT.	5.1e-7
050607	26.5	29	...	Swift	8.9e-7
050703	26	26	...	IPN	1.2e-6
050712	35	39	...	Swift	2.5e-6
050713b	30	44	...	Swift	4.0e-6
050715	52	37	...	Swift	1.7e-6
050716	69	30	...	Swift	1.6e-6
050820	20	22	2.612	Swift	...
051103	0.17	50	0.001?	IPN	**4.2e-6**
051109	36	9.7	2.346	Swift	...
051111	20	44	1.55	Swift	...
051211b	80	33	...	INT.	2.6e-6
051221	1.4	42	0.55	Swift	**9.8e-4**
051221b	61	26	...	Swift	1.8e-6
060102	20	40	...	Swift	2.0e-6
060109	10	22	...	Swift	4.1e-7
060110	15	43	...	Swift	3.0e-6
060111b	59	37	...	Swift	2.3e-6
060114	100	41	...	INT.	5.1e-6
060204b	134	31	...	Swift	2.7e-6
060210	5	43	3.91	Swift	...
060218	10	45	0.03	Swift	**3.8e-5**
060306	30	46	...	Swift	7.2e-6
060312	30	44	...	Swift	3.3e-6
060313	0.7	47	...	Swift	2.7e-6
060403	25	28	...	Swift	1.0e-6
060427b	0.22	16	...	IPN	2.1e-7
060428b	58	27	...	Swift	1.1e-6
060507	185	47	...	Swift	1.8e-5
060510b	330	43	4.9	Swift	...
060515	52	42	...	Swift	9.6e-6
060712	26	35	...	Swift	3.8e-6
060814	146	23	...	Swift	2.5e-6
060904A	80	14	...	Swift	2.4e-6
060906	43.6	29	3.685	Swift	...
061002	20	45	...	Swift	4.0e-6
061126	191	28	...	Swift	4.3e-6
061210	0.8	23	0.41?	Swift	**6.1e-6**
061222a	115	30.	...	Swift	5.6e-6
070103	19	39	...	Swift	1.3e-6
070125	60	9.5	1.547	IPN	**4.5e-4**
070129	460	31	...	Swift	1.9e-6
070208	50	32	1.165	Swift	**4.0e-4**
070311	50	33	...	INT.	2.0e-6
070402	12	12	...	IPN	4.6e-7
070521	60	8.7	0.55?	Swift	**1.1e-5**
070529	120	45	2.5	Swift	...

Table 1: Recent GRBs in the Milagro field of view. Column 1 is the GRB name. Column 2 gives the duration of the burst (in seconds), column 3 the zenith angle for Milagro (in degrees), column 4 the measured redshift, when it exists, 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 take into account absorption by the EBL (using the Primack 05 model) for a redshift given in column 4. Those with three dots in column 6 imply the redshifts are so high that all the emission is expected to be absorbed.

GRB	UTC	T_i	T_f	θ	UL
050607	33082.8	94	255	29	2.7e-6
050607	33082.8	255	640	29	3.2e-6
050712	50427.5	88	564	38	8.8e-6
050712	50427.5	302	435	38	4.1e-6
050712	50427.5	415	590	30.	2.9e-6
050712	50427.5	788	952	37	2.3e-6
050716	45363.6	155	211	31	1.2e-6
050716	45363.6	315	483	32	1.8e-6
050820	23693.1	200	382	21	...
060109	60881.2	4305	6740	6.6	4.8e-6

Table 2: List of X-ray Flares. Column 1 gives the Swift GRB name during which they occurred. Column 2 gives the trigger time in UTC second of the day. Columns 3 and 4 give the start and end times of the flare relative to the trigger time given in Column 2. Column 5 gives the zenith angle for Milagro. Column 6 gives the Milagro 99% upper limit on the 0.2–20 TeV fluence in erg cm^{-2}. As in Table 1, three dots implies the redshift is so high that all emission is expected to be absorbed.