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Search for Very High Energy Emission from Satellite-triggered GRBs with the Milagro Observatory

P. M. Saz Parkinson[a] for the Milagro Collaboration

(a) Santa Cruz Institute for Particle Physics, University of California, 1156 High Street, Santa Cruz, CA 95064

Presenter: P. M. Saz Parkinson (pablo@scipp.ucsc.edu), usa-saz-parkinson-P-abs1-og24-oral

The Milagro gamma-ray observatory employs a water Cherenkov detector to observe extensive air showers produced by high energy particles interacting in the Earth's atmosphere. Milagro has a wide field of view (2 sr) and high duty cycle (> 90%) making it an ideal all-sky monitor of the northern hemisphere in the 100 GeV to 100 TeV energy range. More than 45 satellite-triggered gamma-ray bursts (GRBs) have occurred in the field of view of Milagro since January 2000, with the rate of bursts increasing significantly with the launch of *Swift*. We discuss the most recent results of a search for very high energy (VHE) emission from these GRBs.

1. Introduction

The search for prompt VHE emission (>100 GeV) from GRBs is motivated by experimental observations and theoretical predictions, and its detection could allow us to constrain GRB emission models. Although VHE emission from GRBs has not been conclusively demonstrated, there are several hints of emission at these high energies. Milagrito, a prototype of Milagro, searched for emission coincident with 54 BATSE bursts and reported evidence for emission above 650 GeV from GRB 970417a, with a (post-trials) probability of 1.5×10^{-3} of being a background fluctuation [1, 2]. The HEGRA group reported evidence at the 3 sigma level for emission above 20 TeV from GRB 920925c [3]. Follow-up observations above 250 GeV by the Whipple atmospheric Cherenkov telescope [4] 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. EGRET detected emission above 100 MeV from several bursts, including an 18 GeV photon from GRB 940217, over 90 minutes after the start of the burst [5], indicating both that the spectra of some GRBs extend to at least GeV energies and that this emission may be delayed [6, 7]. More recently, a second spectral component was discovered in GRB 941017 [8] which extended up to at least 200 MeV and decayed more slowly than the lower energy component.

While VHE emission from GRBs has been elusive, many GRB production models predict a fluence at TeV energies comparable to that at MeV energies [9, 10, 11]. This is because MeV emission from GRBs is likely synchrotron radiation produced by energetic electrons within the strong magnetic field of a jet with bulk Lorentz factors exceeding 100. In such an environment, the inverse Compton mechanism for transferring energy from electrons to gamma rays is likely to produce a second higher energy component of GRB emission with fluence possibly peaked at 1 TeV or above. The relative strengths of the synchrotron and inverse Compton emission depend on the environments of the particle acceleration and the gamma ray production.

Milagro[12, 13] is a TeV gamma-ray detector, located at an altitude of 2630 m in northern New Mexico, which uses the water Cherenkov technique to detect extensive air-showers produced by VHE gamma rays as they interact with the Earth's atmosphere. Its field of view is $\sim$2 sr and duty cycle >90%. The effective area is a function of zenith angle and ranges from $\sim$ 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, substantially increasing its sensitivity. The angular resolution is approximately $0.75°$. The combination of large field of view and high duty cycle make Milagro the best instrument available for conducting a search for VHE emission from GRBs.

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 [14]. Between January 2002 and mid-December 2004 only 11 well-localized GRBs were within 45° of zenith at Milagro, due to the demise of BATSE. However, in the six months since the launch of *Swift* [15], an additional 11 bursts have fallen in Milagro's field of view [1], several of them with measured redshift. Due to the absorption of high-energy gamma rays by the extragalactic background light, 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. There are different models of the extinction [16, 17, 18], which are similar in their general features because of the constraints from the available data. The most recent model now predicts a somewhat smaller absorption than was previously expected [19], with an optical depth predicted to be roughly unity for 500 GeV (10 TeV) gamma rays from a redshift of 0.2 (0.05).

In addition to searching for VHE emission from satellite-localized GRBs, an independent real-time search for VHE bursts in the Milagro data has been conducted for many different durations [20].

2. The GRB sample

Table 1 shows a summary of the sample of satellite-triggered GRBs within the field of view (up to zenith angles of 45°) of Milagro between January 2002 and June 2005. The first column lists the GRB name, following the usual convention (UTC date YYMMDD). The second column gives the instrument that first reported the burst. The third column gives the trigger time (UTC second of the day). Column four gives the coordinates, right ascension (RA) and declination (Dec.), in degrees, of the burst. The fifth column gives the duration of the burst. Although this duration is derived from observations made at much lower energies than Milagro detects, EGRET showed that the T90 duration obtained in the keV regime is relevant at higher energies too. Four GRBs observed by EGRET were among the five brightest BATSE bursts, and the significance of the EGRET detections in the T90 interval ranged from 6 to 12 sigma, leading to the speculation that all GRBs might have high energy emission during their respective T90 time intervals, and EGRET simply did not have the sensitivity to detect most of them [7]. Column six of Table 1 lists the zenith angle of the burst at Milagro, in degrees. We include only bursts for which the zenith angle was less than 45° since the effective area of Milagro at zenith angles greater than 45° becomes small in the energy range where we expect GRB emission to be detectable (e.g. < 1 TeV). Column 7 gives the redshift (if measured) of the burst.

3. Data Analysis and Results

A search for an excess of events above the expected background was carried out for the 22 bursts listed in Table 1. The total number of events within a circular bin of radius 1.6° at the location of the burst was summed for the duration of the burst and the number of background events was extimated by characterizing the angular distribution of the background using two hours of data surrounding the burst [2]. The significance of the excess (or deficit) for each burst was evaluated using equation 17 of [21] and is shown in column 8 of Table 1.

No significant excess was found from any burst in the sample. The 99% confidence upper limit on the number of signal events detected given the observed events and the predicted background is computed for each of the bursts following the method described by [22], except for those bursts where the number of events is small ($<$ 10), where we use the prescription by [23]. Finally, we convert the upper limit on the counts into an upper limit on the fluence (in the 0.25 to 25 TeV range) by using knowledge of the effective area of Milagro, and assuming a differential power-law photon spectrum of the form $dN/dE = KE^{-2.4}$ photons/TeV/m^2. The power-law

[1] For information about well-localized GRBs see J. Greiner's web page http://www.mpe.mpg.de/∼jcg/grbgen.html

GRB	Instrument	UTC	RA,Dec. (deg.)	T90 Dur(s)	θ (deg.)	z	Li-MAσ	99% UL fluence (erg cm^2)
020625b	HETE	41149.3	310.9,+7.1	125	38.1	...	1.4	5.7e-6
021104	HETE	25262.9	58.5,+38.0	19.7	13.3	...	0.9	7.5e-7
021112	HETE	12495.9	39.3,+48.9	7.1	33.6	...	-0.1	9.4e-7
021113	HETE	23936.9	23.5,+40.5	20	17.7	...	0.1	6.4e-7
021211	HETE	40714.0	122.3,+6.7	6	34.8	1.01	2.0	1.7e-06*
030413	IPN	27277.0	198.6,+62.4	15	27.1	...	0.8	1.0e-6
030823	HETE	31960.6	322.7,+22.0	56	33.4	...	1.0	2.8e-6
031026	HETE	20143.3	49.7,+28.4	114.2	33.0	...	0.7	3.8e-6
031220	HETE	12596.7	69.9,+7.4	23.7	43.4	...	0.2	4.0e-6
040924	HETE	42731.4	31.6,+16.0	0.6	43.3	0.859	-0.6	1.5e-06*
041211	HETE	41507.0	101.0,+20.3	30.2	42.8	...	0.9	4.8e-6
041219	INTEGRAL	6400.0	6.1,+62.8	520	26.9	...	1.7	5.8e-6
050124	Swift	41403.0	192.9,+13.0	4	23.0	...	-0.8	3.0e-7
050319	Swift	34278.4	154.2,+43.5	15	45.1	3.24	0.6	4.4e-06*
050402	Swift	22194.6	136.5,+16.6	8	40.4	...	0.6	2.1e-6
050412	Swift	20642.9	181.1,-1.3	26	37.1	...	-0.6	1.7e-6
050502	INTEGRAL	8057.7	202.4,+42.7	20	42.7	3.793	0.6	3.8e-06*
050504	INTEGRAL	28859.1	201.0,+40.7	80	27.6	...	-0.8	1.3e-6
050505	Swift	84141.1	141.8,+30.3	60	28.9	4.3	1.2	2.3e-06*
050509b	Swift	14419.2	189.1,+29.0	0.03	10.0	0.225	-0.9	9.2e-08*
050522	INTEGRAL	21621.0	200.1,+24.8	15	22.8	...	-0.6	5.1e-7
050607	Swift	33082.7	300.2,+9.1	26.5	29.3	...	-0.9	8.9e-7

Table 1. GRBs in the field of view of Milagro in 2002–2005. The upper limits assume the burst was nearby (z=0). Those with a (*) next to them have a measured redshift, making this assumption invalid (See text).

index of 2.4 was chosen as a conservative value for the spectrum. The upper limits listed in column 9 of Table 1 assume the bursts occured nearby (z=0), ignoring the effects of the EBL absorption. This assumption is invalid for the six bursts with measured redshifts. For those with redshifts > 1, all TeV emission would be absorbed. Only two bursts in our sample have redshifts less than 1. For GRB 040924, taking into account the absorption, the upper limits on the fluence are 1.6×10^{-3} erg cm^{-2} and 3.1×10^{-3} erg cm^{-2}, using the absorption models of Primack et al. [19] and Stecker et al. [16] respectively. We describe the most interesting GRB of our sample in the next section.

3.1 GRB 050509b

GRB 050509b [24] is so far only the second *short/hard* burst detected by *Swift*. It had 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 [25]. This bursts represents the first clear detection of an afterglow from a short burst [26]. Although Milagro detected no emission from this burst [27], the very favorable zenith angle (10°) and relatively low redshift of 0.225 [28][2] provide the opportunity to set interesting upper limits for TeV emission from this burst. Assuming a differential photon spectral index of -2.4, the derived 99% upper limit on E^{2}dN/dE at 2.5 TeV is 5.4×10^{-8} erg cm^{-2}, assuming

[2] Some observers still question whether this is the true redshift of the burst [29].

no EBL absorption. Taking into account the attenuation of TeV photons expected at a redshift of 0.225, the 99% upper limits for E^2dN/dE are 5.5×10^{-7} erg cm^{-2} at 150 GeV, using the model of Stecker et al. [16], and 2.0×10^{-7} erg cm^{-2} at 300 GeV, using the model of Primack et al. [19]. The energies quoted represent the median energy of the events that would be detected from a power-law spectrum with index -2.4 convolved with each absorption model.

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