A search for GeV-TeV emission from Gamma-ray Bursts using the Milagro detector

P. M. Saz Parkinson for the Milagro Collaboration[1]

Santa Cruz Institute for Particle Physics, University of California, Santa Cruz, CA 95064
e-mail: pablo@scipp.ucsc.edu

Abstract.
The Milagro detector surveyed the sky continuously in the Very High Energy regime from January 2000 through March 2008. During that time, over 130 GRBs were detected and well localized by satellites within its 2sr field of view. We have used Milagro data to search for >1 GeV emission from these bursts. Milagro is a water Cerenkov detector designed primarily for observations in the 0.1-100 TeV energy range. In the standard mode of operation, Milagro data is used to reconstruct the direction of an incoming high energy particle by analyzing the timing information of a large number of photomultiplier tubes that are triggered in coincidence by the air shower generated when such a particle interacts with the Earth's atmosphere. Milagro data, however, can also be analyzed in "scaler mode", where the rates of individual photomultiplier tubes can be used to detect emission above 1 GeV (albeit with no directional information). Here we present results from both techniques for all known GRBs detected by BATSE, BeppoSax, HETE-2, INTEGRAL, Swift, and the IPN, within the field of view of Milagro in its 8 years of operation.

Keywords: gamma-ray sources; gamma-ray bursts; astronomical observations gamma-ray; gamma-ray telescope; Milagro
PACS: 95.55.Ka; 95.85.Pw; 98.70.Rz

INTRODUCTION

Gamma-ray bursts (GRBs) were detected up to GeV energies by the EGRET experiment [1], and many models predict emission all the way into the very high energy (VHE, > 100 GeV) regime (e.g. [2, 3, 4]). More recently, the *Fermi*-LAT detected more than 10 photons above 1 GeV from GRB 080916C [5, 6].

Observations in this regime are limited to sources at relatively low redshifts ($z \leq 0.5$) because VHE gamma rays interact with the extragalactic background light (EBL) producing electron-positron pairs, causing their attenuation. The optical depth for this process increases with redshift and energy, and is roughly unity for 500 GeV (10 TeV) gamma rays from a redshift of 0.2 (0.05), according to one of the leading models [7], although more recent models suggest that this absorption may be overstated [8].

Past VHE detections of GRBs have been marginal (e.g. [9]), although observations

---

[1] A. Abdo, B. T. Allen, T. Aune, D. Berley, E. Blaufuss, S. Casanova, C. Chen, G. E. Christopher, B. L. Dingus, R. W. Ellsworth, M. M. Gonzalez, J. A. Goodman, E. Hays, C. M. Hoffman, B. Hopper, P. H. Hüntemeyer B. E. Kolterman, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, A. I. Mincer, P. Nemethy, D. Noyes, J. R. Pretz, J. M. Ryan, P. M. Saz Parkinson, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, V. Vasileiou, G. P. Walker, D. A. Williams, X. W. Xu and G. B. Yodh

CP1112, *Science with the New Generation of Gamma-Ray Experiments,* edited by D. Bastieri and R. Rando

(and their interpretation) were hampered by the poor localization of GRBs and the small number of measured redshifts. The launch of Swift, in late 2004, has greatly increased the sample of well-localized GRBs available for follow-up observations by instruments such as Milagro, and has thus made possible a much more thorough study of the VHE emission from GRBs.

MILAGRO

Milagro is a TeV gamma-ray observatory located near Los Alamos, New Mexico (35.88° N, 107.68° W and 2630 m above sea level). It employs a water Cherenkov detector instrumented with 723 photomultiplier tubes (PMTs) to observe extensive air showers produced by high-energy particles entering the Earth's atmosphere. The central 60m x 80m pond consists of two layers. The top layer is used to reconstruct the incident direction of the gamma-ray showers, using the time of arrival information from the PMTs, while the bottom layer is used for distinguishing gamma-ray events from background cosmic rays. An additional 175 tanks spread out over an area of roughly 40,000 m^2, known as "outriggers", lined with Tyvek and filled with filtered water and a single 8" PMT, serve to increase the effective area of the detector and improve the angular resolution (from $\sim$0.75 to $\sim$0.5 degrees). Milagro was in operation since 2000 (with otriggers since 2003) until March of 2003. A next generation , more sensitive experiment, HAWC [10, 11], is currently being planned now that Milagro has been decomissioned (see contribution by G. Sinnis in these proceedings). For more details on Milagro, see [12]. As a wide field of view all-sky monitor in the 100 GeV to 100 TeV regime, Milagro is ideally suited for the study of transient phenomena, like GRBs, either in coincidence with satellite detections, or independently, in a blind search [13].

THE STANDARD ANALYSIS

In this analysis, we use the standard reconstructed data generated by the Milagro experiment. The number of reconstructed events falling within a 1.6 degree bin is summed for the relevant duration (e.g. T90). An estimate of the number of background events is made by characterizing the angular distribution of the background using two hours of data surrounding the burst (See [12] for more details). The second-to-last column of Table 1 shows the Milagro upper limits on the fluence in the 0.2–20 TeV energy range, as derived from this technique. For bursts with known redshift (Table 1, right), we compute the effect of the absorption according to the EBL model of [7], and show the numbers in bold. For those with unknown redshift (Table 1, left) we report the limits without any correction for absorption.

THE SCALER ANALYSIS

The single hit rates of the Milagro PMTs are recorded once a second by a CAMAC data acquisition system at two different thresholds: a low threshold of $\sim$0.25 photoelectrons

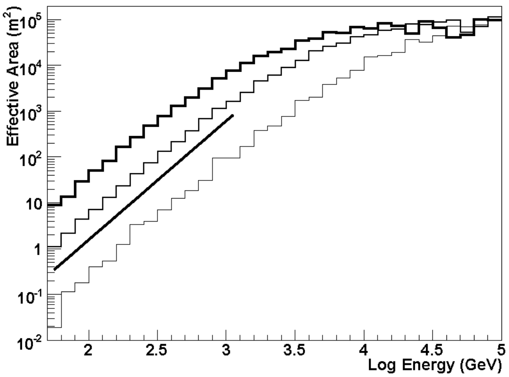

FIGURE 1. Effective area of Milagro with the standard analysis, for zenith angles of 10°, 30°, and 45° (from [14]).

and a high threshold of ~4 photoelectrons. To reduce the number of scalers needed to record these rates, tubes are combined into groups of 8 or 16, and the logical "or" of hits from the individual tubes in the group is recorded. In this analysis, we use the low threshold hits in the PMTs in the Milagro top layer. Those PMTs are in groups of 8 such that the nearest neighbors are in different groups.

The average PMT rate during the GRB is compared to the average rate during a period immediately before and after the burst. By doing the same for many comparable test intervals over an 11 day interval around the burst, a distribution of the fluctuations is obtained which is neither Poisson nor Gaussian. The excess (or deficit) rate during the GRB interval, relative to the background region, is then compared to this distribution to obtain the significance of the excess. This significance is then turned into a 99% upper limit on the scaler rate. Using the effective area of the Milagro scalers (obtained by Monte Carlo simulations) and assuming a power law energy spectrum $dN/dE \sim E^{-2}$ (similar to that seen by EGRET), we obtain upper limits on the fluence in the 1–100 GeV energy range. The last column of Table 1 lists the limits obtained. As in the standard analysis, only the limits for bursts with measured redshifts have been corrected for EBL absorption.

For bursts with measured redshifts (Table 1, right), we use the EBL absorption model of [7] for the corresponding redshift and list the corresponding limits in bold. Those with no measured redshifts (Table 1, left) are computed assuming z=0.

CONCLUSIONS

Two different analysis techniques have been used on the Milagro data to search for emission, in the 1 GeV to 100 TeV energy range, for over 130 GRBs over the last 8 years. The standard analysis on reconstructed events, optimum in the 1–100 TeV range, and the scaler analysis technique carried out on individual PMT counts with no angular

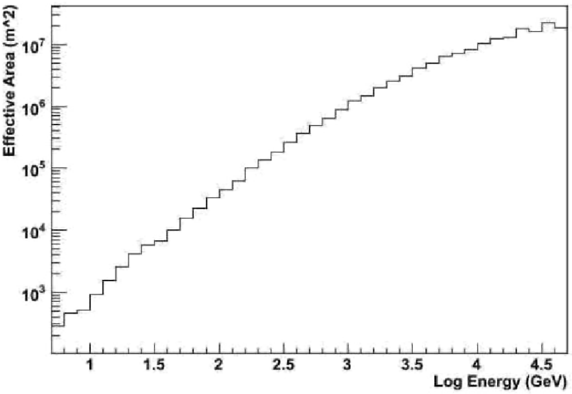

FIGURE 2. Effective area of Milagro using the scaler analysis.

resolution but sensitive to events of energies in the 1–100 GeV range. No emission was detected. Upper limits are presented for both techniques.

ACKNOWLEDGMENTS

I am grateful for the support of the American Astronomical Society and the National Science Foundation in the form of an International Travel Grant, which enabled me to attend this conference. We acknowledge Scott Delay and Michael Schneider for their dedicated efforts in the construction and maintenance of the Milagro experiment. This work has been supported by the National Science Foundation (under grants PHY-0245234, -0302000, -0400424, -0504201, -0601080, and ATM-0002744) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics.

REFERENCES

1. B. L. Dingus, "Observations of the Highest-Energy Gamma Rays from Gamma-ray Bursts," in *American Institute of Physics Conference Series*, edited by F. A. Aharonian, and H. J. Völk, 2001, vol. 558 of *American Institute of Physics Conference Series*, pp. 383–+.
2. R. P. Pilla, and A. Loeb, *ApJL* **494**, L167+ (1998), `arXiv:astro-ph/9710219`.
3. C. D. Dermer, J. Chiang, and K. E. Mitman, *ApJ* **537**, 785–795 (2000).
4. B. Zhang, and P. Mészáros, *ApJ* **559**, 110–122 (2001), `arXiv:astro-ph/0103229`.
5. A. Goldstein, and A. v. d. Horst, *GCN Circular* **8245**, 1–+ (2008).
6. H. Tajima, J. Bregeon, J. Chiang, and G. Thayer, *GCN Circular* **8246**, 1–+ (2008).
7. J. R. Primack, J. S. Bullock, and R. S. Somerville, "Observational Gamma-ray Cosmology," in *High Energy Gamma-Ray Astronomy*, edited by F. A. Aharonian, H. J. Völk, and D. Horns, 2005, vol. 745 of *American Institute of Physics Conference Series*, pp. 23–33.
8. R. C. Gilmore, P. Madau, J. R. Primack, and R. S. Somerville, *ArXiv e-prints* (2008), `0811.1984`.

TABLE 1. Fluence limits for GRBs in the Milagro field of view since the launch of Swift (December 2004). **Left –** Bursts with no measured redshift. Column 1 is the GRB name. Column 2 gives the duration of the burst (in seconds). Column 3 gives the instrument that detected the GRB (S=Swift,I=Integral,P=Interplanetary Network, IPN). Column 4 gives the Milagro 99% confidence upper limit on the 0.2–20 TeV fluence in erg cm^{-2}, using the standard analysis of the data. Column 5 gives the Milagro 99% confidence upper limit on the 1–100 GeV fluence in erg cm^{-2}, using the scaler analysis. **Right –** Bursts with known redshift. Column 1 is the GRB name. Column 2 gives the duration of the burst (in seconds). Column 3 gives the measured redshift. Column 4 gives the instrument that detected the GRB. Columns 5 and 6 give the Milagro 99% confidence upper limits on the 0.2–20 TeV and 1–100 GeV fluences, taking into account absorption by the EBL (using the model by [7]) assuming the redshift given in column 3. Those with three dots imply the redshifts are so high that all the emission is expected to be absorbed.

GRB	Dur.	Inst.	TeV	GeV
041219a	520	I	5.8e-6	7.0e-4
050124	4	S	3.0e-7	2.6e-6
050213	17	P	1.3e-6	6.2e-6
050402	8	S	2.1e-6	8.7e-6
050412	26	S	1.7e-6	2.2e-5
050504	80	I	1.3e-6	8.4e-5
050522	15	I	5.1e-7	7.7e-6
050607	26.5	S	8.9e-7	2.4e-5
050703	26	P	1.2e-6	2.0e-5
050712	35	S	2.5e-6	7.6e-5
050713b	30	S	4.0e-6	1.1e-4
050715	52	S	1.7e-6	1.1e-4
050716	69	S	1.6e-6	1.4e-4
051211b	80	I	2.6e-6	1.6e-4
051221b	61	S	1.8e-6	6.8e-5
060102	20	S	2.0e-6	2.0e-5
060109	10	S	4.1e-7	4.2e-6
060110	15	S	3.0e-6	1.8e-5
060111b	59	S	2.3e-6	1.7e-4
060114	100	I	5.1e-6	8.9e-5
060204b	134	S	2.7e-6	3.3e-4
060306	30	S	7.2e-6	2.1e-4
060312	30	S	3.3e-6	1.4e-4
060313	0.7	S	2.7e-6	1.4e-5
060403	25	S	1.0e-6	1.5e-5
060427b	0.22	P	2.1e-7	2.1e-6
060428b	58	S	1.1e-6	5.2e-5
060507	185	S	1.8e-5	3.2e-3
060515	52	S	9.6e-6	1.8e-4
060712	26	S	3.8e-6	3.2e-5
060814	146	S	2.5e-6	6.0e-4
060904A	80	S	2.4e-6	2.7e-4
061002	20	S	4.0e-6	3.7e-5
061126	191	S	4.3e-6	...
061222a	115	S	5.6e-6	1.9e-4
070103	19	S	1.3e-6	2.3e-5
070129	460	S	1.9e-6	4.0e-4
070311	50	I	2.0e-6	4.4e-5
070402	12	P	4.6e-7	2.2e-6
070612b	20	S	4.7e-6	9.0e-5
070616	402	S	1.1e-6	6.4e-4
071025	109	S	1.9e-6	1.8e-5

GRB	Dur.	z	Inst.	TeV	GeV
050319	15	3.24	S	...	...
050502	20	3.793	I	...	...
050505	60	4.3	S	...	...
050509b	0.128	0.226?	S	**1.1e-6**	**3.3e-6**
050820	20	2.612	S	...	**7.3e-4**
051103	0.17	0.001?	P	**4.2e-6**	**2.1e-5**
051109	36	2.346	S	...	**1.4e-3**
051111	20	1.55	S	...	**2.7e-3**
051221	1.4	0.55	S	**9.8e-4**	**1.2e-4**
060210	5	3.91	S	...	...
060218	10	0.03	S	**3.8e-5**	**9.7e-2**
060510b	330	4.9	S	...	...
060906	43.6	3.685	S	...	...
061210	0.8	0.41?	S	**6.1e-6**	**1.7e-5**
070125	60	1.547	P	**4.5e-4**	**4.9e-4**
070208	50	1.165	S	**4.0e-4**	**3.5e-4**
070521	60	0.55?	S	**1.1e-5**	**7.4e-4**
070529	120	2.5	S	...	**4.2e-6**
071122	68.7	1.14	S	**1.1e-2**	**8.5e-3**
080310	365	2.42	S	...	**1.5e-1**
080319b	50	0.937	S	...	**1.9e-3**
080319c	20	1.95	S	...	**5.3e-4**
080330	60	1.51	S	...	**1.4e-3**

9. R. Atkins, W. Benbow, D. Berley, M. L. Chen, D. G. Coyne, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, D. Evans, A. Falcone, L. Fleysher, R. Fleysher, G. Gisler, J. A. Goodman, T. J. Haines, C. M. Hoffman, S. Hugenberger, L. A. Kelley, I. Leonor, M. McConnell, J. F. McCullough, J. E. McEnery, R. S. Miller, A. I. Mincer, M. F. Morales, P. Nemethy, J. M. Ryan, B. Shen, A. Shoup, C. Sinnis, A. J. Smith, G. W. Sullivan, T. Tumer, K. Wang, M. O. Wascko, S. Westerhoff, D. A. Williams, T. Yang, and G. B. Yodh, *ApJL* **533**, L119–L122 (2000).
10. G. Sinnis, and Hawc Collaboration, "HAWC: A Next Generation VHE All-Sky Telescope," in *High Energy Gamma-Ray Astronomy*, edited by F. A. Aharonian, H. J. Völk, and D. Horns, 2005, vol. 745 of *American Institute of Physics Conference Series*, pp. 234–245.
11. B. L. Dingus, "HAWC (High Altitude Water Cherenkov) Observatory for Surveying the TeV Sky," in *The First GLAST Symposium*, edited by S. Ritz, P. Michelson, and C. A. Meegan, 2007, vol. 921 of *American Institute of Physics Conference Series*, pp. 438–439.
12. R. Atkins, W. Benbow, D. Berley, E. Blaufuss, J. Bussons, D. G. Coyne, R. S. Delay, T. DeYoung, B. L. Dingus, D. E. Dorfan, R. W. Ellsworth, A. Falcone, L. Fleysher, R. Fleysher, G. Gisler, M. M. Gonzalez, J. A. Goodman, T. J. Haines, E. Hays, C. M. Hoffman, L. A. Kelley, R. W. Laird, J. McCullough, J. E. McEnery, R. S. Miller, A. I. Mincer, M. F. Morales, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, M. Schneider, B. Shen, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, O. T. Tumer, K. Wang, M. Wascko, D. A. Williams, S. Westerhoff, M. E. Wilson, X. Xu, and G. B. Yodh, *ApJ* **595**, 803–811 (2003).
13. V. Vasileiou, "Blind Search for Transient Bursts of Very High Energy Gamma-Rays Using Milagro," in *Gamma Ray Bursts 2007*, American Institute of Physics Conference Series, 2008.
14. A. A. Abdo, B. T. Allen, D. Berley, E. Blaufuss, S. Casanova, B. L. Dingus, R. W. Ellsworth, M. M. Gonzalez, J. A. Goodman, E. Hays, C. M. Hoffman, B. E. Kolterman, C. P. Lansdell, J. T. Linnemann, J. E. McEnery, A. I. Mincer, P. Nemethy, D. Noyes, J. M. Ryan, F. W. Samuelson, P. M. S. Parkinson, A. Shoup, G. Sinnis, A. J. Smith, G. W. Sullivan, V. Vasileiou, G. P. Walker, D. A. Williams, X. W. Xu, and G. B. Yodh, *ApJ* **666**, 361–367 (2007), `0705.1554`.