VHE Observations of GRB with Milagro

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Abstract.
The Milagro gamma-ray observatory employs a novel water Cherenkov detector to observe extended air showers produced by high energy particles impacting the earth's atmosphere. The detector consists of a large pond instrumented with an array of 723 photomultiplier tubes. The instrument operates 24 hours a day and continuously observes the entire overhead sky (∼2 sr). Because of its wide field of view and high duty cycle Milagro is uniquely capable of searching for gamma-ray bursts. Milagro can play a role in the extension of the measured spectrum of prompt and afterglow emission to VHE energies (>500 GeV). Detection of VHE counterparts would place powerful constraints on GRB mechanisms, and because of their attenuation from pair production on background IR fields, provide an additional estimate of the source redshift when optical lines cannot be detected. More than 20 GRB have occured within the field of view of Milagro since observations began in January 2000. We describe the results of a search for VHE counterparts to these GRB.

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. This has allowed detailed modeling of gamma-ray burst afterglow properties both as a function of time and a function of wavelength. However, because of the very short duration, far less is known about the broadband spectra during the prompt phase of gamma-ray bursts. Almost all gamma-ray bursts are detected in the energy range between 20 keV and 1 MeV. A few gamma-ray bursts have been observed at energies above 100 MeV by EGRET indicating that the spectra of gamma-ray bursts extends out to at least 100s of MeV. However, it is unknown how far in energy gamma-ray burst spectra extend, or indeed, whether there may be a second higher energy component of emission, similar to that seen in other objects observed at TeV energies.

THE MILAGRO DETECTOR

Milagro is a ground-based gamma-ray observatory sensitive at energies around a few TeV. With a large field of view of >2 steradians, high duty cycle ($>$90%) and large effective area, Milagro is ideally suited to making VHE observations of gamma-ray bursts. Milagro consists of 723 photomultiplier tubes (PMTs), submerged below the surface of a large, covered pool of water. The PMTs are placed on a grid with 2.8 m spacing in each of two layers, at 1.5 m and 7 m below the surface. A VHE gamma-ray interacts with the Earth's atmosphere to produce an extensive air-shower. The relativistic charged particles in the shower which reach ground level radiate Cherenkov light in the water. An event is recorded when ∼60 PMTs sense light within a ∼200ns of one another. The resulting trigger rate is around 1500 Hz. The relative arrival times of the shower front at photomultiplier tubes on the top layer are used to determine the origin (on the sky) of the particle or gamma ray initiating the shower to within $\sim 0.75^{\circ}$. The lower layer of photomultiplier tubes is used to identify and reject hadron-induced showers which dominate the data.

The expected performance of the Milagro detector has been simulated using CORSIKA [1] to model air-shower development in the atmosphere, and GEANT [2] to model the detector response. The sensitivity and energy threshold of Milagro are strong functions of zenith angle. This is because showers which originate closer to the horizon pass through more atmosphere and are attenuated. We have investigated the sensitivity and energy response of Milagro for a rudimentary binned analysis in direction with no background rejection due to gamma-hadron differentiation. Figure 1 shows the median energy for gamma-rays detected in Milagro as a function of zenith angle assuming an $E^{-2.4}$ differential photon spectrum. Also shown is the sensitivity to bursts on timescales of 1, 10 and 100 seconds as a function of zenith angle. Due to the rapidly falling sensitivity and in-

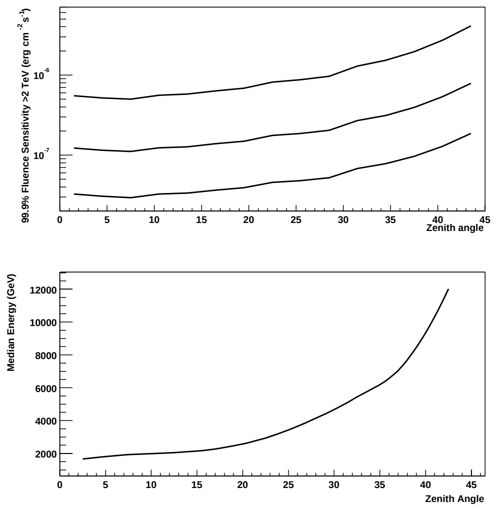

FIGURE 1. (top) The sensitivity of Milagro as a function of zenith angle for 1, 10 and 100 second bursts. (bottom) the median energy of gamma-rays which trigger Milagro as a function of zenith angle

creasing energy threshold we restrict our search for VHE counterparts to bursts that are within 45° of the zenith at Milagro. While the peak sensitivity of Milagro to a typical VHE spectrum of $E^{-2.4}$ is at energies around a few TeV, it is important to note that there is significant sensitivity at lower energies, and thus to spectra with cutoffs at lower energies. This is illustrated in Figure 2 which shows the distribution of energies for gamma-rays which trigger Milagro.

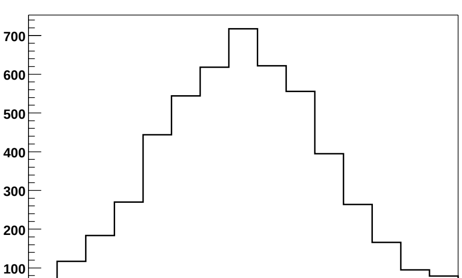

FIGURE 2. Distribution of energies of gamma-rays, from an $E^{-2.4}$ differential photon spectrum, which trigger Milagro

THE GAMMA-RAY BURST SAMPLE

The very high data rate in Milagro makes it prohibitively expensive to archive all raw data. Instead the data are processed online and only the reconstructed arrival times and directions of the showers are archived. The quality of the reduced data being stored will improve as analysis techniques are refined. It is advantageous to store the complete data for interesting regions of the sky and/or interesting periods of time. This allows more sensitive analyses to be carried out at a later date.

We respond to a GRB notification from the Gamma-ray burst Coordinated Network (GCN) by storing complete data on all events from 30 minutes before the GRB trigger to 2 hours after the trigger. Since Milagro began full operation in January 2000, there have been 26 GRB detected by satellite experiments within its field of view.

We have searched for an VHE excess from each of these bursts during the duration reported by BATSE, HETE, IPN or BeppoSAX. In cases where more than one duration was reported, we searched over the longest duration. For some bursts the position was not well known. In these cases we tiled the GRB error region with an array of 1.2 degree bins centered on a 0.1x0.1 degree grid. The bin with largest positive fluctuation from background was used to calculate a VHE upper limit or flux. No significant VHE excesses were found. In table 1 we list the 99% fluence upper limit above 2 TeV for each burst assuming a differential photon spectral index of $E^{-2.4}$. This energy was chosen as it is close to the me-

TABLE 1. Limits on VHE fluence (above 2 TeV) on 26 bursts which were within the field of view of Milagro.

	Dur(s)	Zenith ang.	99% fluence limit (erg cm^{-2})
GRB000113	370	20.8	6.89e-06
GRB000212	8	2.21	1.12e-06
GRB000226	10	31.5	2.39e-06
GRB000301c	14	37.5	1.9e-06
GRB000302	120	31.9	2.3e-06
GRB000317	550	6.39	1.6e-06
GRB000330	0.2	30.0	8.5e-07
GRB000331	55	38.3	6.6e-06
GRB000408	2.5	31.1	2.8e-06
GRB000508	30	34.1	3.0e-06
GRB000615	10	39.0	8.9e-07
GRB000630	20	33.2	1.5e-06
GRB000727	10	40.8	2.6e-06
GRB000730	7	19.2	4.1e-07
GRB000926	25	15.9	1.2e-06
GRB001017	10	42.1	2.1e-06
GRB001018	31	31.8	1.4e-06
GRB001019	10	19.5	8.45e-07
GRB001105	30	8.6	9.5e-07
GRB010104	2	19	3.2e-07
GRB010115	5	41	2.9e-06
GRB010220	150	26.9	1.489e-06
GRB010613	150	24	2.9e-06
GRB010921	12	10.3	5.9e-07
GRB011130	30	33.6	1.7e-06
GRB011212	80	33.0	3.3e-06

dian energy, so the quoted fluence limit is relatively insensitive to the assumed spectral index.

GRB010921

TeV photons are absorbed by pair production with infrared background photons. The importance of this process depends on the energy of the TeV photon and the distance to the GRB. The limits on VHE emission presented in this paper, while interesting, do not constrain the emission spectrum of the bursts in a straightforward way. Without knowing the distance to the burst we cannot distinguish whether the upper limit is telling us that the emitted TeV flux was low, or if it has simply been absorbed in intergalactic space.

An interesting exception to this is GRB010921. This burst has a measured redshift of 0.45 [3]. The upper energy cutoff due to absorption on the IR background is uncertain, but is likely to be somewhere between about 100 GeV and 300 GeV [4]. We have crudely approximated the effect of IR absorption as a sharp cutoff at 150 GeV. In this case, we find a upper limit on the fluence at the 99% confidence level of 5.6×10^{-5} erg cm^{-2}.

CONCLUSIONS AND FUTURE PROSPECTS

In the two years since Milagro began full operation, observations have been made of 26 gamma-ray bursts. No evidence for a prompt VHE counterpart was found for any of these bursts. High energy gamma-rays are attenuated by interactions with the intergalactic infrared background. Thus the limits presented in this paper can constrain either the distance to the burst or the level of VHE flux. Our observations of GRB010921 represent, for the first time, a limit on the VHE flux which constrains emission from the GRB and not simply its distance from us.

The sensitivity of Milagro compares favorably to that of other instruments which make prompt observations of GRB. Figure 3 shows the sensitivity of Milagro (>1 TeV), GLAST (>100 MeV) and EGRET (>100 MeV). The data points show the distribution of fluence and duration seen by the BATSE instrument.

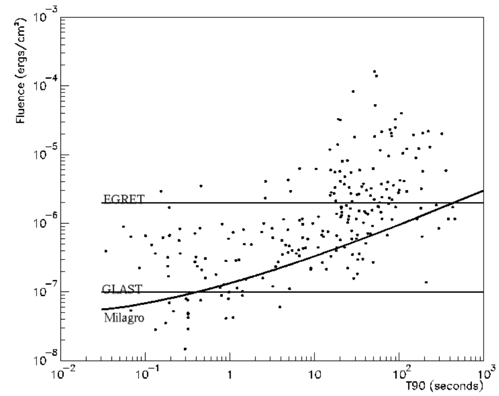

FIGURE 3. Sensitivity of Milagro, EGRET and GLAST superimposed on the distribution (black dots) of fluence and duration seen by BATSE.

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REFERENCES

1. Heck, D., et al., *CORSIKA: A Monte Carlo Code to Simulate Extensive Air Showers*, FZKA 6019, Forschungszentrum Karlsruhe, 1998.
2. CERN-Application-Software-Group, *CERN W*, 5013, version 3.21, 1994.
3. Ricker, G., et al., GCN 1096, Tech. rep., GCN 1096 (2001).
4. Primack, J., *Frascati Physics Series* (2002), in press (astro-ph/0201119).