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Search for 1-100 GeV Emission from Gamma-Ray Bursts Using Milagro

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Abstract: Milagro is a wide field (2 sr) high duty cycle (>90%) ground-based water Cherenkov detector built to observe extensive air showers produced by high energy particles interacting in the Earth's atmosphere. Milagro records extensive air showers in the energy range 100 GeV to 100 TeV, as well as the counting rates of the individual photomultiplier tubes in the detector. The individual tube counting rates can be used to detect transient emission above $\sim$1 GeV by the temporary increase in secondary shower particles reaching the ground. We have used the counting rate data to search for high energy emission from a sample of approximately one hundred gamma-ray bursts (GRBs) detected since the beginning of 2000 by BATSE, BeppoSax, HETE-2, INTEGRAL, Swift or the IPN. No evidence for emission from the GRBs was found. Considering absorption by the extragalactic background light, upper limits on the fluence at four redshifts are determined for bursts at unknown distances. For bursts with known redshifts, fluence upper limits in the energy range 1–100 GeV as low as 3.3×10^{-6} ergs/cm^2 are obtained.

Introduction

Milagro is a ground-based gamma-ray observatory located in the Jemez mountains (2630 m a.s.l.) outside Los Alamos, New Mexico. Ground-based gamma-ray observatories are, by necessity, most sensitive to photons in the TeV energy range and above. Generation of a shower core and/or Cherenkov ring bright enough to be analyzed and reconstructed by detectors on the ground requires a highly energetic primary particle which produces a large number of secondary shower particles. Space-based pair-production gamma-ray telescopes such as EGRET and GLAST are able to detect photons in the GeV energy range, with the latter expected to be sensitive up to a few hundred GeV. Ground-based extended air shower (EAS) arrays such as Milagro also have the ability to probe the GeV spectrum, using a method known as the "single particle" or "scaler" technique [1, 2, 3, 4]. The number of shower particles reaching the ground due to a primary with an energy of a few GeV is too small to allow for reconstruction of the event, but an increase in counting rates due to these particles may be large enough so as to give a considerable excess compared to the background counting rate.

Though the energy spectra of gamma-ray bursts peak around a few hundred keV, EGRET has observed photons in the GeV energy range from GRBs [5]. When operated in scaler mode, Milagro is sensitive in this energy range and can be used to look for small increases in particle flux coincident with gamma-ray bursts observed at lower energies by various satellite-based instruments such as BATSE and the BAT instrument on board Swift. Due to its high duty cycle and large field of view, prompt emission from GRBs should be observable provided the burst is located within the 2 sr view of Milagro. In this paper, we present the fluence upper limits of GRBs in the field of view of Milagro since January 2000 in the 1–100 GeV energy range. Milagro is also being used to look for GRB emission at higher energies, both in satellite-detected [6] and blind [7] searches.

The Milagro Detector

Milagro is a large (60m wide, 80m long, 8m deep) pool of highly purified water, fitted with a light-tight cover, and instrumented with 723 photomultiplier tubes (PMTs). The PMTs are individually housed in water-tight enclosures, anchored to a weighted grid and submerged in the pond. They are organized into two horizontal layers. The "air-shower layer" consists of 450 PMTs located 1.5 m below the surface of the water. This layer is used to reconstruct air showers based on PMT timing. The remaining 273 PMTs (the "muon layer") are located 6 m below the surface and are used for rejection of background from cosmic rays. Furthermore, an array of 175, 4000-liter water tanks, each instrumented with a single PMT, is distributed around the pond, and serves to increase the effective area of the detector. In addition to being used to reconstruct air showers from high energy events, Milagro can be operated in scaler mode, as described in the following section.

Scaler Analysis

In parallel with normal data-taking, Milagro is operated in scaler mode, where the single hit rates of all of the Milagro PMTs are recorded once a second. The rates are recorded at both low (~0.25 photoelectrons) and high (~4 photoelectrons) thresholds. In order to reduce the amount of scaler data, the photomultiplier tubes (PMTs) are grouped into sets of eight (air-shower layer) or sixteen (muon layer) and the logical "or" for this set is recorded. For this particular analysis, the rate used is that of the low-threshold of the upper (air-shower) layer. A discussion of the sensitivity of the scaler system is also presented in [8].

The first step in the analysis of the raw scaler data is the exclusion of noisy channels. This is done by calculating the RMS of each logical "or" group over the ± 5 day time period surrounding the burst. Channels with an RMS that degrades the signal to noise ratio of the sum of all the "or" groups are considered noisy, and are excluded from the analysis. The next step is the correction of the variation in the rates due to pressure and temperature fluctuations. Linear corrections for both temperature and pressure which minimize the RMS of the rate, while leaving the average rate unchanged, are calculated for the same ± 5 day time period.

Finally, the average PMT rate during the GRB is compared to the average background rate immediately before and after the burst itself. This is done for many comparable test intervals over the 11 day period surrounding the burst, and it is observed that the fluctuations are neither Poisson nor Gaussian. The difference in the counting rate between the burst region and the background region is compared to the rate differences in the test intervals to obtain the significance of the counting rate difference and the 99% confidence upper limit on the rate. The former is accomplished by computing the Gaussian σ which corresponds to the probability that the counting rate is a background fluctuation, while the latter is determined by computing the amount of signal that must be added to the test intervals so that 99% of them have a larger excess than the GRB interval.

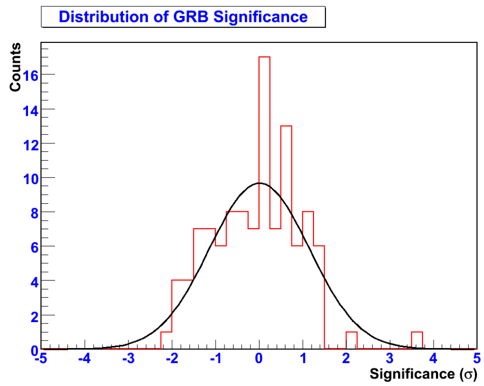

Figure 1: Distribution of GRB significances seen by Milagro when operated in scaler mode. With a mean of zero and RMS of one, the distribution is consistent with background fluctuations.

Results

The distribution of GRB significances for the 111 bursts in the catalog is shown in Figure 1. It is evident that the distribution is consistent with fluctuations of the background. The greatest significance (~3.5σ), has a 2.5% chance of appearing in a randomly sampled group of 111. We don't consider this evidence for emission, and we report upper limits for all of the bursts.

The effective area of Milagro when operated in scaler mode is calculated using the standard Milagro detector simulation as described in [9, 10, 11]. In addition, the PMTs excluded due to excessive

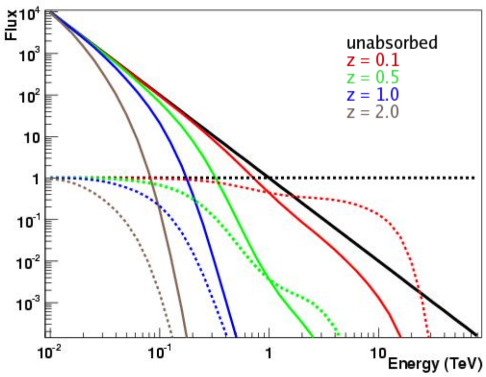

Figure 2: The effect of the EBL absorption [12] on the shape of the spectrum. The solid curves show the spectrum (with arbitrary normalization) and the dashed curves show the absorption factor.

noise or other instrumental problems are taken into account. A power law source spectrum of $\frac{dN}{dE} \sim E^{-2}$ is assumed. The spectrum is then attenuated by interaction with the extragalactic background light (EBL) according to the model of [12] as shown in Figure 2. Although we quote the fluence limits in the 1–100 GeV band, for setting the limit on the normalization of the spectrum we include the contribution to the Milagro sensitivity from photons >100 GeV. For low redshifts, where the power-law spectrum is not much attenuated above 100 GeV, this contribution is substantial, and results in lower fluence limits than if all the emission were restricted to the 1–100 GeV energy interval, as assumed in the sensitivity calculations reported in [8].

For the 21 gamma-ray bursts with measured (or tentatively measured) redshift in the field of view of Milagro since January 2000, we report limits using that redshift in Table 1. The fluence upper limits on gamma-ray bursts with $z > 3$ are omitted due to the fact that a more complete model of the EBL is needed to provide meaningful results. For the remaining 90 bursts with unknown redshift we calculate the limits for four possible redshifts: 0.1, 0.5, 1, and 2. The fluence upper limits (at the 99% confidence level) for the 15 bursts with the lowest limits are given in Table 2. The limits are given in terms of the fluence for the intrinsic power law

Table 1: Fluence upper limits on the 1–100 GeV energy band on GRBs with known redshift in the Milagro field of view since January 2000. Dur. is the duration of the burst (seconds), θ is the zenith angle (degrees), z is the redshift, and Limit is the fluence upper limit (ergs/cm^2).

GRB	Dur.	θ	z	Limit
000301C	14	37.6	2.03	1.3e-3
000926	25	15.9	2.04	2.7e-4
010921	25	10.4	0.45	3.0e-4
021211	6	34.8	1.01	7.0e-5
040924	1	43.3	0.859	1.2e-4
050319	15	45.1	3.24	–
050502	20	42.7	3.793	–
050505	60	28.9	4.3	–
050509b	1	10.0	0.226?	3.3e-6
050820	20	21.9	2.612	7.3e-4
051103	1	49.9	0.001?	2.1e-5
051109	36	9.6	2.346	1.4e-3
051111	20	43.7	1.55	2.7e-3
051221	2	41.8	0.55	1.2e-4
060210	5	43.4	3.91	–
060218	2000	43.7	0.03	9.7e-2
061210	1	23.4	0.41?	1.7e-5
060510b	300	42.8	4.9	–
060906	43	28.8	3.685	–
070125	60	9.5	1.55	4.9e-4
070208	48	31.7	1.165	3.6e-4

spectrum assumed for the bursts, before absorption by the EBL. The upper limits we calculate are comparable to those obtained by the ARGO-YBJ collaboration [13], as well as to those expected at the Pierre Auger Observatory, using the scaler method [14].

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Table 2: The fifteen gamma-ray bursts with the lowest 1–100 GeV fluence upper limits of those with unknown redshift. Dur. is the duration of the burst (seconds), and θ the zenith angle (degrees). The upper limits in ergs/cm^2 are given for assumed redshifts of 0.1, 0.5, 1.0, and 2.0.

GRB	Dur.	θ	$z = 0.1$	$z = 0.5$	$z = 1.0$	$z = 2.0$
000330	1	30.0	3.6e-6	1.5e-5	3.1e-5	7.7e-5
000408	3	31.1	3.4e-6	1.4e-5	3.0e-5	7.3e-5
000424	5	36.2	9.3e-6	4.4e-5	9.3e-5	2.3e-4
000615	10	39.0	8.5e-6	4.3e-5	9.4e-5	2.5e-4
000730	7	19.2	5.7e-6	2.1e-5	4.1e-5	1.0e-4
001019	10	19.5	4.6e-6	1.7e-5	3.4e-5	8.1e-5
001204	1	47.8	5.1e-6	3.1e-5	6.6e-5	1.7e-4
020914	9	5.7	4.9e-6	1.6e-5	3.2e-5	8.1e-5
030413	15	27.1	8.5e-6	3.4e-5	7.1e-5	1.7e-4
050124	4	23.0	4.6e-6	1.8e-5	3.6e-5	8.6e-5
050213	17	22.6	1.1e-5	4.1e-5	8.3e-5	2.0e-4
050522	15	22.8	1.3e-5	5.2e-5	1.0e-4	2.5e-4
060109	10	22.4	7.3e-6	2.8e-5	5.6e-5	1.4e-4
060427b	1	16.4	3.5e-6	1.2e-5	2.4e-5	5.8e-5
070402	12	11.9	3.7e-6	1.3e-5	2.4e-5	5.7e-5

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