Search for GeV Emission from Gamma-Ray Bursts Using Milagro Scaler Data

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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. We have used the counting rate (scaler) data to search for high energy emission from a sample of 98 gamma-ray bursts (GRB) detected from January 2000 through June 2006 by BATSE, BeppoSax, HETE-2, INTEGRAL, Swift or the IPN. No evidence for emission from any of the bursts has been found, and we present fluence upper limits from these bursts.

Keywords: gamma-ray sources; gamma-ray bursts; astronomical observations: gamma-ray
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Air shower detectors such as Milagro are normally sensitive to particles which produce showers large enough to fire many detector elements (photomultiplier tubes, PMTs, in the case of Milagro) in coincidence. Nevertheless, a change in the flux of particles with lower energy, which changes the flux of secondary cosmic ray particles reaching the ground, can manifest itself as a change in the counting rates of the individual detector elements [1]. Monitoring these rates is therefore a way to detect transient fluxes of particles with less energy than those which the detector normally records. This idea, applied to the counting rates of the Milagro PMTs, has been used to search for transient gamma-ray emission around 10 GeV from gamma-ray bursts (GRBs) occurring in the Milagro field of view.

Milagro [2] is located about 35 miles west of Los Alamos, New Mexico at 2630 m above sea level. The central detector consists of a 80 m by 60 m light-tight, water-filled reservoir, and it is surrounded by 175 smaller water tanks. There are two layers of photomultiplier tubes in the central detector, 450 in the top layer about 1.5 m below the surface, and 273 in bottom layer at about 6 m depth. Milagro has been in operation >90% of the time since the start of 2000.

The single hit rates of all of the Milagro PMTs are recorded at two different thresholds (a low threshold of $\sim$0.25 photoelectrons and a high threshold of $\sim$4 photoelectrons) once a second by a CAMAC data acquisition system. To reduce the number of scalers needed to record the 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 nearest neighbors are in different groups. The RMS of the rate for each PMT group is calculated over the 11 day interval centered on the day of each burst. Noisy channels with an RMS which degrades the signal to noise of the sum are excluded from the analysis for that burst, yielding a "cleaned" rate from the remaining groups of 8. The PMT rates vary as the outside temperature and pressure change the profile of the atmospheric overburden. Linear corrections for temperature and pressure which minimize the overall RMS of the rate (while keeping the average rate unchanged) are calculated for the 11 day interval around each burst and applied to the rates before searching for a burst.

The average PMT rate during the GRB is compared to the average rate during a background period immediately before and after the burst. The background region is 10 times the burst duration, consisting of 5 times the burst duration before the burst and 5 times the burst duration after the burst. By doing the same for many comparable test intervals over an 11 day interval around each burst, it is seen that the fluctuations are neither Poisson nor Gaussian. The excess (or deficit) rate during the GRB interval, relative to the background region, is compared to the distribution of excesses from the test intervals to obtain the significance of the excess — by computing the Gaussian sigma which corresponds

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TABLE 1. Upper limits for the 5–50 GeV fluence, in erg cm^{-2}, for a selection of bursts visible to Milagro. **Left:** The ten bursts with measured or candidate redshift less than 3. The limits for those bursts have been corrected for EBL absorption using the redshift. For bursts with redshift >3, we need a more complete model of the EBL absorption below 10 GeV to obtain meaningful limits. **Right:** The ten bursts with the lowest limits from among those with no redshift determination. Limits are given taking into account the effect of EBL absorption for 4 possible redshifts, z. T90 for each burst has been rounded up to an integral number of seconds. θ is the zenith angle of the burst at Milagro, in degrees.

GRB	T90	θ	z	Limit
000301c	14	38	2.03	2.7e-3
000926	25	16	2.04	5.6e-4
010921	25	10	0.45	6.4e-4
050509b	1	10	0.226?	6.9e-6
050820	20	22	2.612	1.3e-3
051103	1	50	0.001?	4.4e-5
051109	36	10	2.346	2.9e-3
051111	20	44	1.55	5.0e-3
051221	2	42	0.55	2.6e-4
060218	2000	44	0.03	2.1e-1

GRB	T90	θ	z=0.1	z=0.5	z=1.0	z=2.0
000330	1	30	7.5e-6	3.2e-5	6.5e-5	1.6e-4
000408	3	31	7.0e-6	3.0e-5	6.2e-5	1.5e-4
000730	7	19	1.2e-5	4.3e-5	8.6e-5	2.1e-4
001019	10	20	9.6e-6	3.5e-5	7.0e-5	1.7e-4
001204	1	48	1.1e-5	6.6e-5	1.4e-4	3.7e-4
020914	9	6	1.0e-5	3.4e-5	6.8e-5	1.7e-4
030413	15	27	1.8e-5	7.2e-5	1.5e-4	3.6e-4
050124	4	23	9.6e-6	3.7e-5	7.4e-5	1.8e-4
060109	10	22	1.5e-5	5.8e-5	1.2e-4	2.8e-4
060427b	1	16	7.1e-6	2.5e-5	5.0e-5	1.2e-4

to the probability that the excess is a background fluctuation — and to obtain the 99% confidence level upper limit on the rate — by computing the amount of signal which must be added to the test intervals so that 99% of them have a larger excess than the GRB interval. The resulting distribution of significances of the excess is consistent with expectations from background fluctuations alone, having a mean of -0.02 and an RMS of 1.04 for 98 entries. The most significant excess is 3.5 standard deviations, with a 2% probability of occurring in a sample of 98; we don't interpret that as evidence for emission and report upper limits for all the bursts.

The effective area of the Milagro scalers for gamma rays is calculated using the standard Milagro detector simulation as described in [3], including accounting for any PMTs excluded at the cleaning step. We assume a power law energy spectrum $dN/dE \sim E^{-2}$, absorbed by collisions with the extragalactic background light (EBL) according to the model of Ref. [4]. For bursts with measured or tentative redshifts, we report limits using EBL absorption for that redshift. For the remaining bursts, we calculate limits for 4 possible redshifts: 0.1, 0.5, 1.0 and 2.0. The preliminary fluence limits between 5 and 50 GeV for the unabsorbed power law spectrum are given for a selection of bursts in Table 1. We have corrected an error in the normalization of the limits shown at the symposium: the limits are now higher by a factor of 1.6. The limits are generally comparable to or better than those obtained by this method for other bursts by the ARGO-YBJ [5] group and to the sensitivity expected using this method at Auger [6].

Additional work is underway which may improve these limits, including extending the effective area calculation below 5 GeV and considering the counting rates of the bottom layer of PMTs in the Milagro reservoir.

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