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# MILAGRO CONSTRAINTS ON VERY HIGH ENERGY EMISSION FROM SHORT-DURATION GAMMA-RAY BURSTS

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## ABSTRACT

Recent rapid localizations of short, hard gamma-ray bursts (GRBs) by the *Swift* and *HETE* satellites have led to the observation of the first afterglows and the measurement of the first redshifts from this type of burst (Fox et al. 2005; Gehrels et al. 2005; Villasenor et al. 2005; Berger et al. 2005; Barthelmy et al. 2005). Detection of >100 GeV counterparts would place powerful constraints on GRB mechanisms. Seventeen short-duration (<5 s) GRBs detected by satellites occurred within the field of view of the Milagro gamma-ray observatory between 2000 January and 2006 December. We have searched the Milagro data for >100 GeV counterparts to these GRBs and find no significant emission correlated with these bursts. Due to the absorption of high-energy gamma rays by the extragalactic background light (EBL), detections are only expected for redshifts less than ~0.5. While most long-duration GRBs occur at redshifts higher than 0.5, the opposite is thought to be true of short GRBs. Lack of a detected VHE signal thus allows setting meaningful fluence limits. One GRB in the sample (050509b) has a likely association with a galaxy at a redshift of 0.225, while another (051103) has been tentatively linked to the nearby galaxy M81. Fluence limits are corrected for EBL absorption, either using the known measured redshift, or computing the corresponding absorption for a redshift of 0.1 and 0.5, as well as for the case of $z = 0$.

*Subject headings:* gamma rays: bursts — gamma rays: observations

Gamma-ray bursts (GRBs) have long been classified by their durations into long and short bursts (Mazets & Golenetskii 1981; Norris et al. 1984). Later classification schemes took into account the combination of both the temporal and spectral properties (Kouveliotou et al. 1993) leading to what are currently known as short, hard bursts and long, soft bursts. Recent classification schemes list as many as 10 different criteria to try and distinguish between these two populations (Donaghy et al. 2006). The fraction of bursts that fall in each category is instrument dependent, with BATSE finding approximately 25% of bursts to be "short" (Paciesas et al. 1999), while the equivalent fraction for *Swift* is closer to 10% (Gehrels & *Swift* Team 2006). The discovery of the first X-ray afterglow from a long-duration GRB (Costa et al. 1997) led to a rapid string of observations validating the fireball shock model of GRBs (Rees & Meszaros 1992; Meszaros & Rees 1993), culminating in the observation of a GRB-supernova association (Hjorth et al. 2003; Stanek et al. 2003) confirming that at least some GRBs are related to the deaths of massive stars, as predicted by the "collapsar" model (Woosley 1993).

Until recently, however, all the observations of afterglows (and therefore, most of the information about GRBs) came from long-duration GRBs. The first detection of the afterglow of a short, hard burst—for GRB 050509b (Gehrels et al. 2005)—was followed by others (Fox et al. 2005; Villasenor et al. 2005; Berger et al. 2005), and there are now approximately half a dozen measured redshifts for short, hard bursts (Hurley 2006). Although some of these redshifts are less secure than others, their average (~0.3–0.5) is significantly lower than the typical redshift of long-duration bursts. The location of several of these short bursts in old galaxies with little star formation, unlike the association of long GRBs with active star-forming regions, seems to rule out the collapsar model for these bursts and favors instead merger models involving binary neutron stars or black hole–neutron star systems as the progenitors for these bursts. One predicted consequence of these models (Razzaque & Mészáros 2006) is that the neutron-rich outflows expected from these mergers would lead to pion decay photons at ~60 GeV, which could be detected by Milagro.

The detection of gamma rays in the GeV–TeV regime is affected by the extragalactic infrared background light (EBL; Nikishov 1961). The amount of gamma-ray absorption due to the EBL is not well determined, although it is a strong function of redshift

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and energy. One model (Primack et al. 2005), recently validated by H.E.S.S. observations (Aharonian et al. 2006), predicts an optical depth of roughly unity to 500 GeV (10 TeV) gamma rays from a redshift of 0.2 (0.05). The significantly lower redshift of short-duration GRBs compared to long-duration ones makes them particularly suitable candidates for very high-energy (VHE) emission studies, such as possible with the Milagro detector. On the other hand, their much lower luminosity means their possible emission at higher energies is also expected to be substantially lower than the brighter, long-duration bursts.

Previous searches for VHE emission from GRBs, both long and short, have produced no conclusive detection to date. Milagrito, a prototype of Milagro, reported evidence for emission above 650 GeV from GRB 970417a, with a (posttrials) probability of $1.5 \times 10^{-3}$ of being a background fluctuation (Atkins et al. 2000a, 2003a). More recent Milagro searches have yielded no conclusive detection (Atkins et al. 2005; Saz Parkinson 2007). Evidence at about the 3 $\sigma$ level from the HEGRA AIROBICC array has been published for emission above 20 TeV from GRB 920925c (Padilla et al. 1998). Follow-up observations above 200 GeV by the Whipple atmospheric Cerenkov telescope (Connaughton et al. 1997; Horan et al. 2007) did not find any high energy afterglow from the GRBs observed. Recently, the MAGIC group have reported upper limits on the gamma-ray flux in the 85–1000 GeV energy range from the 9 GRBs[15] they observed in their first year of operations, including the afterglow of the short-duration *HETE* burst 060121 (Albert et al. 2007). The MAGIC list includes GRB 050713a, for which they had the fastest response so far, beginning their observations 40 s after the burst onset (Albert et al. 2006). Because searches carried out with atmospheric Cerenkov telescopes, like MAGIC or Whipple, involve slewing a telescope to the right location in the sky and are limited by their relatively small fields of view and duty cycles, Milagro is the best-suited instrument for observing the shortest GRBs at very high energies.

In this paper we place limits on the VHE emission from short-duration[16] GRBs, which might help constrain models of their progenitors. We selected all known bursts detected by satellites that occurred in the Milagro field of view and had a duration of 5 s or less. This duration was chosen, rather than 2 s, in part due to the recent work of Donaghy et al. (2006), but also in order to be more inclusive. In § 1 we describe the detector, Milagro, which was used to perform the search. We describe in some detail the new low-energy-threshold trigger, which was especially designed to increase Milagro's sensitivity to GRB detections. In § 2, the sample of short-duration GRBs analyzed in the paper is presented, with a special emphasis on GRB 050509b, the most promising candidate in the sample. Section 3 describes the analysis carried out to search for emission, both prompt and delayed. Finally, in § 4 we discuss the main results and summarize our conclusions.

## 1. THE MILAGRO OBSERVATORY

Milagro is a TeV gamma-ray detector, which uses the water Cerenkov technique to detect extensive air showers produced by VHE gamma rays as they traverse the Earth's atmosphere (Atkins et al. 2000b). Milagro is located in the Jemez Mountains of northern New Mexico (35.9° north, 106.7° west) at an altitude of 2630 m above sea level, and has a field of view of ~2 sr and a duty cycle of over 90%, making it an ideal all-sky monitor of transient phenomena at very high energies, such as GRBs. The effective area and energy threshold of Milagro are a function of zenith angle, due to the increased atmospheric overburden at larger zenith angles, which tends to attenuate the particles in the air shower before they reach the ground. The sensitivity of Milagro varies slowly with zenith angle from 0° to ~30° and then decreases more rapidly (Atkins et al. 2005).

For the data sample used in this analysis, the typical single shower angular resolution is approximately 0.7°; however, at lower energies there are fewer photomultiplier tubes hit, so the angular resolution is about 1°. The energy response of Milagro is rather broad, with no clear point to define as an instrument threshold. To obtain a rough guide of the range of energies to which Milagro is sensitive, we consider a power-law spectrum with a differential photon index, $\alpha$, of −2.4. The energy ($E_5$) above which 95% of the triggered events from such a spectrum are obtained is approximately 350 GeV, the energy ($E_{95}$) below which 95% of the triggered events occur is 30 TeV, and the median energy is 3 TeV. This illustrates the breadth of the energy response of Milagro, showing that the Milagro detector has significant sensitivity below energies of several hundred GeV.

The Milagro sensitivity as a function of energy can be understood as a simple consequence of one-dimensional cascade shower theory. The fluctuations in the amount of energy reaching a certain detector level from a gamma-ray shower arise primarily because of variations in the depth of the first interaction, which follows a probability distribution $P \sim e^{-(9/7)X}$, where $X$ is the depth of the interaction in radiation lengths. According to "Approximation B" (Rossi & Greisen 1941), after shower maximum (>10 km above sea level for the energy range of Milagro, well above the altitude of the Milagro detector), the average number of particles in a gamma-ray shower, as well as the amount of energy, decreases exponentially as shower particles are absorbed by the atmosphere. From the longitudinal shower profile obtained in Approximation B, the number of radiation lengths deeper in the atmosphere, $X$, which a gamma-ray of energy $E$ must penetrate in order to deposit energy at the ground equivalent to that of a typical shower of higher energy $E_{\rm thr}$ is given by $X \simeq 2 \ln (E_{\rm thr}/E)$. So the probability that a gamma-ray shower of energy $E$ has a certain minimum amount of energy reaching the ground is given approximately by $P(E) \sim (E/E_{\rm thr})^{2.6}$. In other words, the low-energy effective area scales like a power law in energy. Figure 1 shows that the effective area of Milagro does, indeed, follow this power law. As seen from Figure 1, the ratio of the effective area at 100 GeV to that at 1 TeV is ~0.005, roughly what is predicted by the previous formula. The effective area of Milagro at a median energy of ~4 TeV has been confirmed by the measurement of the flux from the Crab, in agreement with atmospheric Cerenkov telescope measurements. For more details on Milagro see Atkins et al. (2003b).

During the period covered by these observations, the Milagro trigger underwent a significant upgrade. Until 2002, the Milagro trigger consisted of a simple multiplicity count of the number of photomultiplier tubes hit out of the 450 in the top layer of the pond. This threshold was set to between 50 and 70 tubes hit within a 200 ns time window to maintain the trigger rate at ~1400–1600 Hz, the maximum sustained rate that can be handled by the Milagro data acquisition system with a reasonable deadtime (~5%).[17] A lower trigger threshold would lower the energy threshold of

[15] Unfortunately, four out of the nine GRBs that MAGIC observed had measured redshifts in excess of 3.5, making it virtually impossible for any VHE gamma rays to reach Earth.

[16] The term "short duration" is used in the paper to refer only to the duration of the burst being less than 5 s, while the term "short, hard" burst is used in the usual more narrow sense found in the literature, based on the timing and spectral properties of the burst, as introduced by Kouveliotou et al. (1993).

[17] The deadtime to record single triggers depends instead on the digitization time, which scales with the number of hit PMTs, and is <50 $\mu$s. Triggers separated by as little as 30 $\mu$s are routinely recorded.

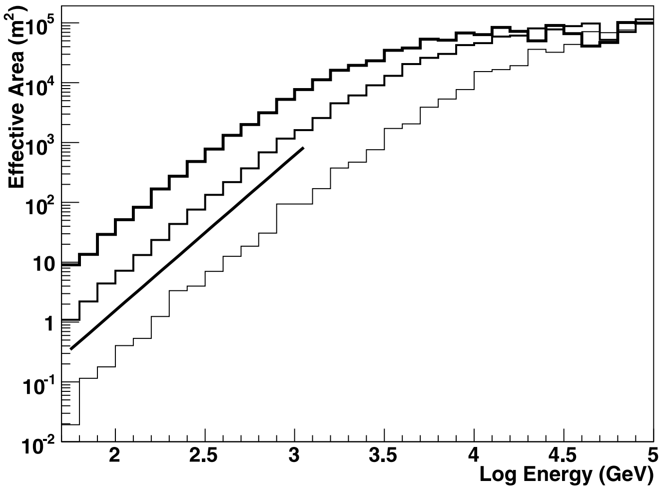


FIG. 1.—Effective area of Milagro for gamma rays as a function of energy for three different zenith angles. The straight line is a power law $E^{2.6}$ (with arbitrary normalization). The different curves (in decreasing order of thickness) reflect the effective area for zenith angles of 10°, 30°, and 45° (roughly corresponding to GRBs 050509b, 050505, and 040924). The figure illustrates the decrease in effective area with zenith angle. The limited number of simulated showers at the highest energies results in fluctuations in the curves above $10^4$ GeV.

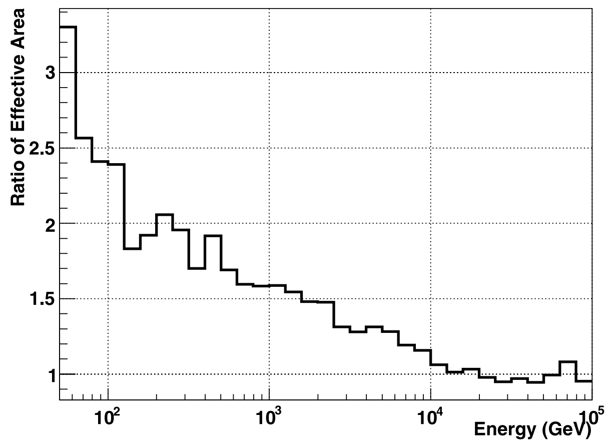


FIG. 2.—Relative increase in effective area between the simple (55 tube) multiplicity trigger and the VME programmable trigger, as applied to GRB 050509b. The figure shows an increase in effective area using the new trigger of more than 50% at 1 TeV and around 150% at 100 GeV, relative to the old trigger.

Milagro, thus making it more sensitive to GRBs. Based on the knowledge that most of the increase in the rate as the multiplicity requirement is lowered comes from single muon events, which produce enough light to trigger the instrument but cannot be fit to a shower plane, a new programmable trigger was custom-designed for Milagro. It is known from Monte Carlo simulations that gamma-ray events can be reconstructed with as few as 20 tubes hit. A high-angle muon traveling across the pond nearly horizontally produces light that arrives over a longer time period than the shower particles, so by making a cut on the time development of the event, it is possible to eliminate these muon events. A custom VME trigger module was built, allowing the use of multiple trigger conditions and including the rise time of the pulse representing the number of struck tubes in the top layer as one of the triggering criteria. The new trigger greatly increased the number of low-energy showers detected, while maintaining a manageable overall trigger rate and dead time. Figure 1 shows the effective area of Milagro to gamma rays as a function of energy for three different zenith angles. Figure 2 shows the significant increase in sensitivity gained from the new trigger, relative to the old simple multiplicity trigger, especially at energies below 100 GeV, where detection of GRBs is most likely. The VME trigger was installed in 2002 January and became fully operational on 2002 March 19. The "Notes" column in Table 1 identifies the bursts in our sample for which the VME trigger was in operation.

## 2. THE GRB SAMPLE

There is no sharp cutoff point between long-duration and short-duration bursts; these two populations of GRBs have overlapping distributions in duration. Although earlier studies determined that an effective $T_{90}$ (duration over which the cumulative counts over the background increase from 5% to 95% of the total) cut for separating short from long bursts should be approximately 2 s (Kouveliotou et al. 1993), more recent work (Donaghy et al. 2006) suggests that bursts shorter than 5 s have a higher probability of belonging to the short-duration class than the long-duration one, so we have chosen to include GRBs with durations up to 5 s in this list of "short-duration" bursts.

In the seven years since Milagro began operations (2000 January to 2006 December), there have been approximately 100 known GRBs detected by satellites, which have been in the Milagro field of view. Of these, 17 had measured durations of 5 s or shorter. Many of the bursts in this study were detected by the Interplanetary Network (IPN),[18] and their locations were not immediately known to experiments on the ground, making it very unlikely that a redshift could be determined. More recent bursts detected by *Swift* and *HETE* have benefited from extensive multiwavelength observations from the ground and are therefore far better studied. One burst in our sample (GRB 001204) was obtained from the *BeppoSAX* GRBM catalog (Guidorzi 2001).

Table 1 lists the sample of 17 bursts that we analyzed for this paper. Four of the bursts in the sample (000330, 000408, 000424, and 010104) were presented in an earlier paper summarizing the first 2 years of Milagro observations of GRBs (Atkins et al. 2005) and are included here for completeness. One of these bursts (GRB 010104) has recently been found to have occurred at a significantly different location than previously thought (K. Hurley 2007, private communication), so we take this opportunity to present our results on this burst at the new location. The first column of the table gives the GRB name, which, following the usual convention, represents the UTC date (YYMMDD) on which the burst took place. The second column gives the instrument(s) that detected the burst. We list the IPN as an instrument, although it consists of a network of many satellites, a different set of which may detect any given burst. The third column gives the time of the burst, represented by the UTC second of the day. Column (4) gives the coordinates (right ascension and declination, in degrees) of the burst. All the bursts listed in the table except for one (GRB 000330) were localized to an error region significantly smaller than the Milagro angular resolution. For GRB 000330, the position error was approximately 5°, so the upper limit was computed using the most significant bin within that region, as described in Atkins et al. (2005). For one burst, GRB 000607, the coordinates are not known unambiguously; the IPN sometimes determines two possible error regions, and in this case only one of them was in the field of view of Milagro. The fifth column gives the duration of the burst, as reported by the different instrument teams. Column (6) lists the zenith angle of the burst at Milagro, in degrees. We include only bursts for which the zenith angle was less than approximately 50°. The effective area of Milagro at zenith angles greater

[18] See http://www.ssl.berkeley.edu/ipn3/.

TABLE 1

List of Short-Duration GRBs in the Field of View of Milagro

| GRB (1) | Instrument (2) | Time[a] (3) | R.A., Decl. (deg) (4) | $T_{90}$/Duration (5) | $\theta$[b] (6) | $z$[c] (7) | keV Fluence[d] (8) | TeV Fluence UL[e] (9) | 312s TeV Fluence UL[f] (10) | Notes (11) |
|---|---|---|---|---|---|---|---|---|---|---|
| 000220............ | BATSE | 17083.78 | 182.0, +66.0 | 2.4 | 48.8 *R* | ... | 3.7E−7 (25–300) | 4.1E−3, 1.5E−4, 1.8E−5 | 1.8E−2, 6.6E−4, 7.9E−5 | $T_{90} > 2$ s. High zenith angle |
| 000330............ | BATSE | 75449.40 | 358.3, +39.3[g] | 0.2 | 30.0 *S* | ... | ... | 3.0E−5, 2.1E−6, 7.5E−7 | 1.6E−4, 1.1E−5, 4.0E−6 | ... |
| 000408............ | BATSE, IPN | 9348.43 | 137.3, +66.6 | 2.5 | 31.1 *R* | ... | 7.4E−6 (25–100) | 2.7E−5, 2.1E−6, 7.2E−7 | 1.8E−4, 1.4E−5, 4.8E−6 | $T_{90} > 2$ s |
| 000424............ | BATSE | 32666.36 | 233.1, +71.8 | 5.0 | 36.2 *S* | ... | 1.3E−6 (25–300) | 6.4E−5, 4.7E−6, 1.4E−6 | 1.9E−4, 1.4E−5, 4.2E−6 | $T_{90} > 2$ s |
| 000607............ | IPN | 8690.4 | 224.7, +13.5[h] | 0.12 | 41.8 *R* | ... | 5.3E−6 (15–5000) | 7.6E−5, 4.1E−6, 1.1E−6 | 5.6E−4, 3.0E−5, 8.4E−6 | One of two error regions |
| 001204............ | *BeppoSAX*, IPN | 28870.25 | 40.3, +12.9 | 0.25 | 47.8 *S* | ... | 3.7E−7 (25–100) | 1.8E−3, 1.6E−4, 2.0E−5 | 1.0E−2, 8.9E−4, 1.1E−4 | High zenith angle |
| 010104............ | IPN | 62490.327 | 317.4, +63.5 | 2.0 | 44.8 *R* | ... | 4.3E−7 (25–100) | 6.6E−5, 3.5E−6, 9.9E−7 | 5.8E−4, 3.1E−5, 8.7E−6 | Revised location |
| 031026............ | IPN | 5189.02 | 338.8, +0.02 | 0.24 | 45.3 *R* | ... | ... | 1.1E−4, 7.6E−6, 2.0E−6 | 7.6E−4, 5.3E−5, 1.4E−5 | High zenith angle, VME trigger |
| 040924............ | *HETE* | 42731.36 | 31.6, +16.0 | 0.6 | 43.3 *S* | 0.859 | 4.2E−6 (7–400) | 1.4E−3 | 2.1E−2 | VME trigger |
| 050124............ | | 41402.87 | 192.9, +13.0 | 4.1 | 23.0 *R* | ... | 2.1E−6 (15–350) | 1.3E−5, 9.0E−7, 3.1E−7 | 1.2E−4, 8.4E−6, 2.9E−6 | $T_{90} > 2$ s, VME trigger |
| 050509b........... | *Swift* | 14419.23 | 189.1, +29.0 | 0.128 | 10.0 *R* | 0.225? | 9.5E−9 (15–350) | 9.6E−7 | 2.1E−5 | VME trigger |
| 051103............ | IPN | 33942.186 | 148.1, 68.8 | 0.17 | 49.9 *R* | 0.0? | 2.3E−5 (20–2000) | 1.9E−5 | 9.2E−5 | High zenith angle, VME trigger |
| 051221a........... | *Swift*, *Suzaku* | 6675.61 | 328.7, +16.9 | 1.4 | 41.8 *S* | 0.5465 | 3.2E−6 (20–2000) | 1.3E−4 | 8.4E−4 | VME trigger |
| 060210............ | *Swift* | 17929.8 | 57.7, +27.0 | 5 | 43.4 *S* | 3.91 | 7.7E−6 (15–150) | ... | ... | $T_{90} > 2$ s, High z, VME trigger |
| 060313............ | *Swift* | 726.29 | 66.6, −10.9 | 0.8 | 46.7 *S* | ... | 7E−5 (20–2000) | 1.4E−3, 2.1E−4, 1.9E−5 | 9.9E−3, 1.5E−3, 1.4E−4 | High zenith angle, VME trigger |
| 060427b........... | IPN | 85915.32 | 98.5, +21.3 | 0.22 | 16.4 *S* | ... | 5.0E−6 (20–2000) | 1.8E−5, 1.1E−6, 3.6E−7 | 1.3E−4, 7.6E−6, 2.6E−6 | ... |
| 061210............ | *Swift*, *Suzaku* | 44439.33 | 144.5, +15.6 | 0.8[i] | 23.4 *S* | 0.41? | 3.0E−7 (15–150)[i] | 8.6E−6 | 1.7E−4 | ... |

[a] Time of burst, UTC second of the day.
[b] Zenith angle, in degrees; $R$ = rising, $S$ = setting.
[c] Redshift. A redshift of 0.5, 0.1, or 0 is assumed for those bursts where it is unknown.
[d] Measured fluence in the keV energy range (given in parentheses) in erg $cm^{-2}$.
[e] 99% upper limit on the fluence (0.05–5 TeV) in erg $cm^{-2}$ for the GRB duration, using the Primack et al. (2005) EBL absorption model. When no redshift is given in the table, the limits are calculated assuming three different redshifts: $z = 0.5$, $z = 0.1$, $z = 0.0$.
[f] 99% upper limit on the fluence (0.05–5 TeV), in erg $cm^{-2}$ over a duration of 312 s from the burst trigger. The same assumptions as in the previous column apply.
[g] This GRB is the only one from this sample whose error region is larger than the Milagro bin size. (See Atkins et al. 2005) .
[h] This location represents one of two possible error regions (the other is outside the field of view of Milagro).
[i] These quantities apply only to the initial hard spike, not the entire burst.

than 50° becomes negligible in the energy range, where we expect GRB emission to be detectable (e.g., <1 TeV). Column (7) gives the value of the redshift, if measured.

For those bursts with no measured redshift, we take into account the effect of absorption in computing the upper limits by considering two different redshifts, $z = 0.5$ and $z = 0.1$. We also give limits for the case $z = 0$ (i.e., nearby bursts). By their very nature, short-duration bursts are much more difficult to localize than long-duration bursts. In addition to being very brief events, they also tend to be much less luminous than long-duration GRBs, making it much more challenging to obtain redshifts from these bursts than from long GRBs. GRB 040924, detected by *HETE* (Fenimore et al. 2004), was the first short-duration burst to have a measured redshift (Wiersema et al. 2004), although its spectrum was considered too soft to be part of the short, hard population, and it has been speculated that it may belong to the short-duration tail of the long-duration GRB population (Huang et al. 2005). GRB 050509b was the first short, hard burst for which an afterglow was detected. As it is the most interesting burst in the sample, we describe it in more detail in the following paragraph. The remaining columns of Table 1 present the Milagro results, which we describe later.

The detection of an X-ray afterglow from GRB 050509b by *Swift* (Gehrels et al. 2005) represented the first time such an event had been observed from a short, hard burst. A low probability ($\sim 5 \times 10^{-3}$) of chance alignment suggests that this burst may be associated with a bright elliptical galaxy at a redshift of 0.225 (Bloom et al. 2006). Subsequent detections of short, hard bursts (Barthelmy et al. 2005) have made this association more plausible and point to an origin of these bursts in regions of low star formation, thus disfavoring the collapsar model invoked for explaining the long-duration bursts. At 10°, the zenith angle of this burst is the most favorable in the list of 17 short bursts, and one of the most favorable of all bursts to have occurred in the Milagro field of view. Its redshift of 0.225 is the second or third lowest of those GRBs with known redshift in the Milagro field of view (depending on whether or not one believes GRB 051103 is associated with the nearby satellite galaxy M81), again, making it a very promising candidate. The 15–150 keV fluence of this burst, however, was measured by *Swift* to be $(9.5 \pm 2.5) \times 10^{-9}$ erg cm$^{-2}$, making it one of the dimmest bursts detected by *Swift* (Gehrels et al. 2005) and about 40 times dimmer than the next dimmest short-duration burst in this sample. If the VHE emission of GRBs scales with the fluence measured at the lower energies, this would dampen significantly the expectations of detecting such emission from this burst.

## 3. DATA ANALYSIS

A search for an excess of events above those expected from the background was made for each of the 17 bursts in the sample. The total number of events falling within a circular bin of radius 1.6° at the location of the burst was summed for the duration of the burst. An estimate of the number of background events was then made by characterizing the angular distribution of the background using 2 hours of data surrounding the burst, as described in Atkins et al. (2003b). Figure 3 shows the rate of background events detected by Milagro in a 1.6° bin as a function of zenith angle. This background rate is a function of the trigger settings and the particular conditions of the detector on the given day and varies slightly from burst to burst. The significance of the excess (or deficit) for each burst was evaluated using equation (17) of Li & Ma (1983). The 99% confidence upper limits on the number of signal events detected, $N_{\rm UL}$, given the observed $N_{\rm ON}$ and the predicted background $N_{\rm OFF}$, is computed using the Feldman-Cousins

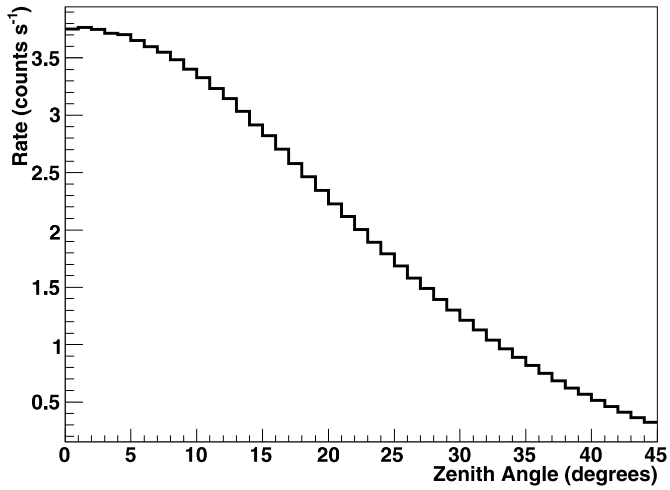


FIG. 3.—Number of background events per second detected in a circular bin of radius 1.6°, as a function of zenith angle. The background rate depends on the analysis cuts used as well as the detector configuration and atmospheric conditions on a particular day. The figure was made with data taken within one hour of GRB 050509b.

prescription (Feldman & Cousins 1998). This upper limit on the number of gamma-ray events is then converted into an upper limit on the fluence. Using the effective area of Milagro, $A_{\rm eff}$, and assuming a differential power-law photon spectrum, we integrate in the appropriate energy range and solve for the normalization constant. We chose a spectrum of the form $dN/dE = KE^{-2.4}$ photons TeV$^{-1}$ m$^{-2}$. The spectrum of a GRB has never been measured above 100 GeV, so we must make an assumption of a suitable spectrum for evaluating the limits. The average spectrum of the four brightest bursts observed by EGRET has a differential power-law spectrum with index $1.95 \pm 0.25$ over the energy range of 30 MeV to 10 GeV, showing no sign of a cutoff, although only four gamma rays were detected above 1 GeV (Dingus 2001). The choice of 2.4 as the spectral index in the Milagro energy range allows for some softening of the spectrum at higher energy.

The normalization factor $K$ can be calculated by solving the equation $N_{\rm UL} = \int A_{\rm eff}(dN/dE)e^{-\tau_{\rm EBL}}\, dE$, where $\tau_{\rm EBL}$ represents the optical depth due to the EBL. Finally, we integrate the photon spectrum multiplied by the energy to obtain the corresponding value for the total fluence: $F = \int E(dN/dE)\, dE$, integrating from 0.05 to 5 TeV. For bursts of known (albeit uncertain) redshift (040924, 050509b, 051103, and 051221a), we use the optical depths predicted by Primack et al. (2005) and take these into account in computing the preceding integrals, thus obtaining a more realistic upper limit that factors in the correct absorption due to the EBL. For the remaining bursts, we compute the upper limits assuming three possible values of the redshift: 0.5, 0.1, and 0.0.

In addition to searching for prompt emission from these bursts, we also searched for extended emission over a period of 312 s following the reported trigger time. This timescale is motivated both by the observations of late-time (several hundred seconds after the GRB trigger) X-ray flares during some GRB afterglows (Falcone et al. 2006; Burrows et al. 2005), which are predicted by some to emit in the GeV–TeV regime (e.g., Wang et al. 2006), as well as by the discovery of a second higher energy component in GRB 941017. While the $T_{90}$ for that burst was 77 s, the second higher energy component (which has a fluence more than three times greater than the fluence in the BATSE energy range alone) had a duration of approximately 211 s (Gonzalez et al. 2003).

## 4. RESULTS AND DISCUSSION

None of the bursts in the sample showed significant VHE emission, either prompt or delayed. Column (9) of Table 1 gives the 99% upper limits on the fluence, computed as described in § 3 over the duration (given in col. [5]) of the burst. For comparison, we give the measured fluence in the keV band in column (8). Most models of VHE emission predict it should be correlated to the lower energy emission. In column (10), we give the 99% upper limits on the fluence computed over a duration of 312 s from the trigger time.

The localization of several short, hard bursts to old, low–star-forming galaxies has led to the speculation that their origins may be related to binary mergers, possibly double neutron star systems or black hole–neutron star binaries. Razzaque & Mészáros (2006) propose that in such a scenario, the accretion of neutron star material would lead to the emission of a neutron-rich jet, which would emit $\pi^0$ decay photons in the 100 GeV range. Several parameters and assumptions are important in this model, including the total isotropic-equivalent energy outflow of the burst, the total energy to mass flow ratio, $\eta$, and the initial neutron to proton number density ratio, $\xi_0$.

Of the bursts considered in the sample, GRB 050509b is the most promising candidate, given its known low redshift and its optimal zenith angle at Milagro. The attenuation due to the IR background in this case is not very significant. Using the Primack et al. (2005) model, the corresponding optical depth for the resulting 60 GeV photons at $z = 0.225$ would be $\sim$0.04, leading to an attenuation of less than 5%. Using the Razzaque & Mészáros (2006) model with their standard parameters, $\eta = 316$, and $\xi_0 = 10$, and using the measured isotropic luminosity in gamma rays, $E_{\rm iso}$, the predicted flux from this GRB would be $2.3 \times 10^{-7}$ cm$^{-2}$ s$^{-1}$ gamma rays of energy $\sim$60 GeV (S. Razzaque 2006, private communication). The effective area of Milagro is approximately 90,000 cm$^2$ at 60 GeV for the given zenith angle of this burst, yielding approximately 0.02 s$^{-1}$, or less than $3 \times 10^{-3}$ events for the duration (0.128 s) of the burst, making this burst clearly undetectable. The next best candidate is GRB 061210. Despite having a much larger $E_{\rm iso}$ than 050509b (about 20 times larger), this burst, assuming a redshift of 0.41, has a predicted flux of pion-decay photons comparable to 050509b (Razzaque & Mészáros 2006). Given the less favorable zenith angle of this burst and the fact that the VME trigger was not operating at the time this burst took place, the effective area of Milagro for these events is approximately an order of magnitude lower than for the case of 050509b. As discussed below, GRB 051103 might have been an SGR outburst in M81. If it is not an SGR outburst, but a binary merger at very low redshift, the model by Razzaque & Mészáros (2006) would predict a significant detection of this burst in Milagro, had it occurred at a zenith angle $\leq 20^\circ$, instead of at $50^\circ$. This is despite having a very low $E_{\rm iso}$, more than an order of magnitude less than GRB 050509b.

It has been suggested that a fraction of short-duration GRBs could be due to soft gamma-ray repeaters (SGRs) in nearby galaxies. There is some debate as to the exact fraction such objects could represent, with estimates ranging from <40% (Nakar et al. 2006) to <4% (Lazzati et al. 2005), or between 1%–16% (Ofek 2007), depending on various different assumptions. We have presented upper limits at three different redshifts, including the case of $z = 0$, which would be appropriate for bursts happening nearby. Indeed, the bright GRB 051103 detected by the IPN has been found to be consistent with an SGR flare originating in the nearby M81 galaxy group (Ofek et al. 2006). Assuming this to be the location of the burst, we obtain a Milagro TeV upper limit ($1.9 \times 10^{-5}$ erg cm$^{-2}$), which is lower than the IPN measured fluence of $2.3 \times 10^{-5}$ erg cm$^{-2}$.

In conclusion, we have searched the Milagro data for prompt and delayed GeV–TeV emission from a collection of 17 short-duration (<5 s) GRBs that occurred in Milagro's field of view in the seven years since Milagro began operations in 2000. This represents the most comprehensive search for very high energy emission from short GRBs ever performed. Due to the short duration and low rate of short bursts, such observations must carried out by an experiment like Milagro with its large field of view of $\sim$2 sr and high duty cycle. While no emission was detected from any of these short bursts, HAWC (Dingus 2007), a next-generation version of Milagro, would have more than 15 times the sensitivity. The GLAST Gamma-ray Burst Monitor with its BATSE-like field of view of over $2\pi$ sr will detect many bright, short GRBs and simultaneous observations of the GLAST Large Area Telescope and HAWC will provide prompt spectra from keV–TeV energies to further our understanding of short GRBs.

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