Search for GeV-TeV emission from GRB 080319B using the Milagro Observatory

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***Abstract*. On March 19, 2008 NASA's Swift satellite discovered one of the brightest gamma-ray bursts ever recorded. With a peak visual magnitude of 5.3, GRB 080319B was dubbed the "naked-eye" gamma-ray burst, as an observer under dark skies could have seen the burst without the aid of an instrument. Due to the proximity in both time and space to GRB 080319A, prompt emission from GRB 080319B was detected in both the optical and γ-ray bands by several wide-field instruments. Follow-up observations spanned 11.5 orders of magnitude in wavelength, making GRB 080319B one of the most well-studied gamma-ray bursts to date. The Milagro observatory was an extended air shower array located near Los Alamos, NM, that operated from January 2000 to May 2008. GRB 080319B was fortuitously located in the field of view of Milagro, and a search for prompt emission in the GeV-TeV energy range is presented here. No evidence for emission is found and constraining upper limits on VHE emission from GRB 080319B are obtained.**

***Keywords*: gamma-ray burst 080319B**

I. Introduction

Milagro was a ground-based gamma-ray observatory located in the Jemez mountains (2630 m a.s.l.) outside Los Alamos, New Mexico. The central part of the detector consisted of a large pool of highly purified water, fit with a light-tight cover, and instrumented with 723 photomultiplier tubes (PMTs). These 723 PMTs were distributed in two layers, a top layer ~ 1.5 m below the surface of the pond known as the air-shower layer, and a bottom layer commonly called the muon layer, located ~ 6 m below the surface. This lower layer is primarily used in the standard analysis to discriminate gamma-ray events from muon-induced events. An array of 175, 4000 liter water tanks known as "outriggers," each instrumented with a single PMT, was distributed around the central pond, and served to increase the effective area of the detector as well as improve gamma/hadron separation. Milagro was a member of the extensive air shower class of particle detectors, and as such, was primarily sensitive to photons in the TeV energy range. In addition to being analyzed in the standard fashion, in which every air shower event is reconstructed (see Section II), Milagro data can also be analyzed using the "scaler" or "single-particle" technique [1], [2], [3], [4] in which statistically significant excesses in the PMT count rates, temporally coincident with satellite-detected GRBs, are searched for (see Section III). These combined analyses allow for energy coverage ranging from 1 GeV to over 100 TeV.

Many GRB afterglow models (e.g. [5], [6], [7]) predict production of photons in the GeV-TeV energy range and GeV emission has indeed been detected by both previous and current generation space-based γ-ray detectors [8], [9]. GRB 080319B is a particularly interesting burst, in part due to its gamma-ray brightness, but also because of the exceptionally strong optical emission during the prompt phase of the event [10]. Furthermore, the gamma-ray and optical emission are seen to be correlated in GRB 080319B, like a relatively small number of earlier gamma-ray bursts [12], [13], [14], [15]. This correlation appears to favor the models of prompt emission in which the optical emission is synchrotron radiation and the gamma rays are created through inverse Compton (IC) scattering. It has been suggested that the seed photons involved in the IC scattering arise from synchrotron field itself (the synchrotron self-Compton model) [16], [17] or from an external photon field (the external Compton model)[11], [18]. While the synchrotron self-Compton (SSC) model provides a natural explanation of the optical and gamma ray correlation seen in GRB 080319B, it also implies that a relatively strong second-order inverse Compton component of the GRB spectrum should peak in the tens of GeV [10]. Observations by the Milagro detector of GRB 080319B set constraining limits on the strength of this second IC peak.

II. Standard Analysis

For energies > 50 GeV, the Milagro standard analysis is used to search for an excess of events above the expected background, temporally and positionally coincident with satellite-detected GRBs. An estimate of the number of background events is made by characterizing the angular distribution of the background using 2 hours of data surrounding the burst, as described in [19]. The total number of events falling within a circular bin of radius $1.6°$ centered on the burst is summed over the duration of the burst. The significance of the excess (or deficit) of each burst is evaluated using eq. (17) of Li & Ma [21]. Given the observed on-source counts and the predicted background, the 99% and 99.9% confidence upper limits on signal counts are computed using the Helene prescription [29].

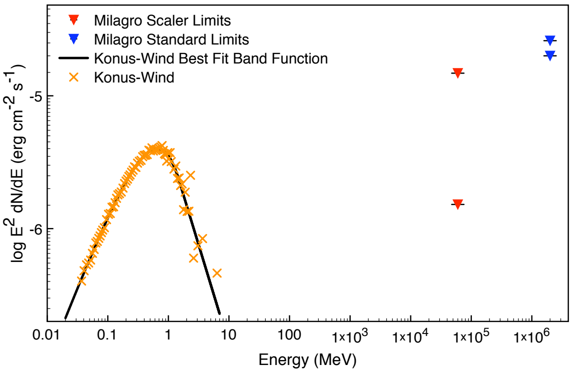

Fig. 1. Konus-Wind data and Milagro upper limits on the prompt phase ($T_0 < t < T_0 + 60$s) of GRB 080319B. The Konus-Wind data fully covers the first order inverse-Compton peak associated with the SSC model. The Milagro upper limits are given for both the standard and scaler analyses at the 99% and 99.9% confidence levels.

The upper limits on the counts are then converted to an upper limit on the fluence, using the effective area of Milagro and assuming a differential power-law photon spectrum. The effective area of Milagro for gamma rays, is calculated using the standard Milagro detector simulation as described in [19], [20] while also accounting for any PMTs excluded due to excessive noise or other instrumental problems. An intrinsic GRB power law energy spectrum $\frac{dN}{dE} \sim E^{-2}$ for both the scaler and standard analyses is assumed. This spectrum is then softened due to the gamma rays being absorbed by interactions with the extragalactic background light (EBL) according to the model of [23], [24].

III. Scaler Analysis

In parallel with normal data-taking, Milagro was operated in scaler mode, where the single hit rates of all of the Milagro PMTs were recorded once a second. The rates were recorded at both low ($\sim$0.25 photoelectrons) and high ($\sim$4 photoelectrons) thresholds. In order to reduce the amount of scaler data, the photomultiplier tubes (PMTs) were 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, as it has the lowest energy threshold of the Milagro arrays (air-shower, muon, and outrigger).

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 $\pm$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 $\pm$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% and 99.9% confidence upper limits on the rate. Determining the significance of the counting rate is accomplished by computing the Gaussian σ which corresponds to the probability that the counting rate is a background fluctuation, while the upper limit is determined by computing the amount of signal that must be added to the test intervals so that 99% (or 99.9%) of them have a larger excess than the GRB interval.

IV. GRB 080319B

On March 19, 2008 one of the most energetic gamma-ray bursts to date was detected by the Konus-Wind and Swift BAT instruments. Due to the proximity (10° separation) of the burst to GRB 080319A, which was detected $<$ 30 minutes earlier, the prompt phase of GRB 080319B ($z = 0.937$) was recorded in the optical band by both the "Pi of the Sky" and "TORTORA" wide field robotic telescopes. This fortuitous coincidence allows for contemporaneous and detailed comparisons of the gamma-ray and optical emission from GRB 080319B. The similarities of the optical and gamma-ray light curves [10] appear to suggest that both the optical and gamma-ray emission is produced in the same physical region [25], [26]. Perhaps the most natural explanation of the observed emission of GRB 080319B comes from the SSC model [16], [17]. The SSC interpretation in the context of correlated optical and gamma-ray emission and a relatively strong first order inverse Compton (IC) peak, as observed in the case of GRB 080319B, predicts a second order IC peak in the tens of GeV [26], [31], within the energy range of the Milagro detector. Furthermore, this second order IC peak is expected to carry an order of magnitude more energy than the observed gamma-rays [10].

For Milagro, GRB 080319B was located at an angle of $\sim$ 43° from zenith. Assuming an intrinsic GRB spectrum of $dN/dE \sim E^{-2}$ softened through interactions with the EBL as described in [23], [24], the upper limits on the prompt gamma-ray fluence obtained with Milagro are listed in Table I. In this case, prompt emission is defined as the emission associated with the main pulse as detected by the Konus-Wind (25 keV - 7 MeV) instrument. In the case of GRB 080319B, this was $\sim$ 60 seconds. In Figure 1, the Milagro fluence limits are displayed along with the Konus-Wind data, which cover much of the first order inverse Compton peak. These limits, particularly the limit obtained using the scaler analysis, put strong constraints on the emission associated with the second order inverse Compton process in

TABLE I
FLUENCE UPPER LIMITS ON PROMPT GAMMA-RAY EMISSION FROM GRB 080319B OBTAINED WITH THE MILAGRO DETECTOR

Analysis	Energy Range (GeV)	Median Energy (GeV)	99% conf. U. L. (erg cm^{-2})	99.9% conf. U. L. (erg cm^{-2})
Standard	$50 - 100000$	2000	9.3×10^{-3}	1.2×10^{-2}
Scaler	$1 - 100$	60	4.2×10^{-4}	4.1×10^{-3}

the SSC model. The standard single zone SSC model faces some difficulty[26] in describing completely the behavior of GRB 080319B and modifications to the standard SSC model e.g. [27] or alternative models [28] have been invoked to explain the observed properties of GRB 080319B. In addition to the prompt emission, it has been suggested [30] that delayed GeV-TeV emission from the external forward shock could peak in the TeV energy range and thus be detectable by ground-based gamma-ray experiments. Evidence for emission during $60\,\mathrm{s} < \mathrm{t} < 2\,\mathrm{ks}$ is not found in either the scaler or standard Milagro analyses and the resulting upper limits on the fluence are not constraining.

V. CONCLUSION

GRB 080319B was one of the most spectacular cosmic events ever recorded. Aside from being one of the most energetic gamma-ray bursts detected, the extremely bright optical component and proximity to GRB 080319A led to GRB 080319B being the most well-studied gamma-ray burst to date. The extreme qualities of GRB 080319B, particularly the intensity of optical emission associated with the prompt phase of the event, challenge some of the standard theoretical models of gamma-ray bursts. If the gamma rays and optical photons arise from the same physical region, as suggested by the similarity of both light curves, then the single zone synchrotron self-Compton model suggests that a second inverse-Compton peak should be found in the tens of GeV energy range. Milagro observed GRB 080319B and no significant gamma-ray signal was detected with either the scaler ($1-100$ GeV) or standard (50 GeV - 100 TeV) analyses. The resulting upper limits on the gamma-ray fluence, particularly those from the lower energy scaler analysis, constrain the gamma-ray emission in the energy range above 1 GeV.

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