Very High Energy Observations of Satellite-Detected Gamma-Ray Bursts

Taylor Aune*, the Milagro Collaboration† and the VERITAS Collaboration**

*Department of Physics and the Santa Cruz Institute for Particle Physics
University of California, Santa Cruz, 1156 High Street, Santa Cruz, CA, 95064, USA
†http://scipp.ucsc.edu/milagro/papers/authorlist.pdf
**http://veritas.sao.arizona.edu

Abstract. Recent results from the Fermi Gamma-ray Space Telescope indicate that gamma-ray bursts (GRBs) are capable of producing photons with energies up to $\sim$ 90 GeV in the rest frame of the burst. The *Fermi*-LAT may not be sensitive to the highest energy photons associated with GRBs and ground-based, very high energy (VHE) gamma-ray observatories offer the means by which characterization of GRBs from tens of GeV to TeV energies may be accomplished. Milagro and VERITAS are two such observatories and searches for VHE emission from GRBs have been conducted at both during the past decade. Milagro, an extensive air shower array located near Los Alamos, NM was operational from January, 2000 until May, 2008 and during that time obtained data on nearly 140 satellite-detected GRBs. VERITAS, an imaging atmospheric Cherenkov telescope array has been performing follow-up observations of GRBs since mid 2006 and continues to maintain an active GRB observing program. No significant VHE emission from GRBs has been detected by either experiment. Results from both experiments are presented including those from the Milagro observation of the exceptional "naked-eye" burst GRB 080319B which place stringent constraints on some models of the burst emission, and the VERITAS observation of GRB 080310 which began during the prompt phase of the burst and included a large X-ray flare during the early afterglow.

Keywords: VHE, Gamma-ray bursts
PACS: 98.70.Rz

VHE EMISSION FROM GRBS

Observations of GRBs and their afterglows over the last decade are generally consistent with those predicted by the relativistic fireball framework (e.g. [1]). Within this framework, a number of theories have been proposed that predict very high energy (VHE, >100 GeV) photon production. Inverse Compton (IC) and synchrotron mechanisms, or some combination (e.g. synchrotron self Compton [2, 3], SSC) are both candidates for generating photons above the GeV scale. In addition to emission models that predict prompt VHE emission (e.g. [4, 5]), there are also predictions of VHE photon production during the very early afterglow phase ($t - T_0 = 100 - 1000$ s) [6]. At even later times ($t - T_0 < 10000$ s), VHE emission from the external forward shock [7, 8] arising from SSC processes [9] may be too weak to detect with the *Fermi*-LAT, but is potentially detectable with current ground-based VHE observatories [10]. IC scattering of photons from X-ray flares with forward shocked electrons has also been proposed as a means of VHE photon generation [5]. Detection of VHE photons from X-ray flares in GRBs by current ground-based detectors should be possible [8, 11]. Finally it has been suggested that GRBs may be the source of ultra high energy cosmic rays (UHECRs) e.g. [12, 13] and in such a model, VHE gamma rays are produced by the energetic leptons that are created from cascades initiated by photopion production [14]. Despite decades of searches by several instruments, no conclusive detection of VHE emission has yet been observed. Understanding the behavior of GRBs at high energies is critical to unraveling the physics of these events.

THE SEARCH FOR PROMPT VHE γ-RAY EMISSION WITH MILAGRO

Milagro was an extensive air shower detector located outside of Los Alamos, NM. It consisted of a large central pond (50 x 80 x 8 m) instrumented with 723 photomultiplier tubes (PMTs) surrounded by an array of "outrigger" detectors (a single PMT in a small, water-filled tank) covering roughly 4×10^4 m^2. It had a $\sim$ 2 sr field of view (FOV), a $> 90\%$ duty cycle and operated nearly continuously from January, 2000 to May, 2008.

Two complimentary methods of data analysis are possible with the Milagro experiment. One is a standard event-by-event shower reconstruction where the direction and energy of each primary gamma ray is determined. The other is the “scaler” or single particle technique [15, 16], the results of which are discussed here. In brief, the scaler analysis consists of summing the counts from each PMT every second and searching for rates above background which are temporally coincident with interesting events such as GRBs. Since there is no individual event reconstruction, directional and energy information is lost, but because the scaler analysis is sensitive to smaller air showers, the energy threshold is lower than that of the conventional analysis. The scaler analysis method was used to search for gamma-ray emission coincident with T_{90} (the duration over which 90% of the gamma-ray emission in the satellite band is detected). Over the eight year lifetime of the experiment >130 GRBs fell in the Milagro FOV. No significant emission associated with these GRBs was detected by Milagro and fluence limits as low as $3 \times 10^{-6}\,\mathrm{erg\,cm^{-2}}$ are calculated assuming an intrinsic GRB spectrum of $\frac{dN}{dE} \propto E^{-2}$ and taking into account the extragalactic background light (EBL) model of [17].

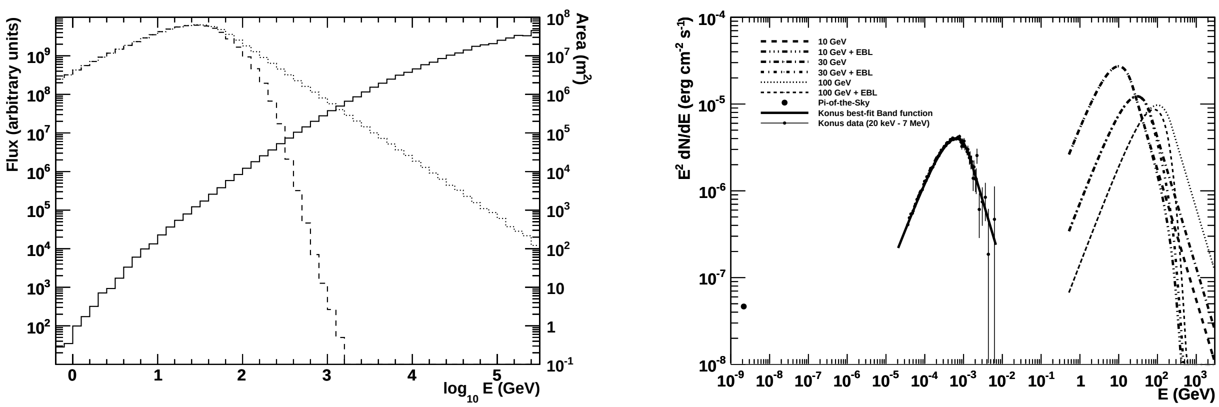

FIGURE 1. (Left) The intrinsic VHE spectrum of GRB 080319B assuming the second IC component is a Band function with $E_{peak} = 30\,\mathrm{GeV}$ before (dotted line) and after (dashed line) attenuation by the EBL according to the model of [17]. The solid line, which corresponds to the right axis shows the scaler effective area of the Milagro instrument. (Right) A spectral energy distribution showing the optical and gamma-ray measurements along with the 99% confidence level upper limits on the second IC Band function component with $E_{peak} = 30$, 100, 300 GeV obtained with Milagro.

On March 19, 2008, several space-based and ground-based instruments observed the extremely bright “naked-eye” burst, GRB 080319B. Due to its proximity in both time and direction to GRB 080319A, the prompt emission of GRB 080319B was detected over several orders of magnitude in photon energy, from the optical to the gamma-ray bands. The burst was determined to have a redshift of $z = 0.937$ [18] and a duration of $T_{90} = 60$ s [19]. During the prompt phase of the burst, the optical and gamma rays show a rough temporal correlation, which may indicate they arise from the same region, but the gamma-ray Band function does not extrapolate down to the optical wavelengths, which indicate that different mechanisms are responsible for the two photon populations [20]. The WIND instrument on board the *Konus* spacecraft detected gamma rays from GRB 080319B from 20 keV to 7 MeV, sampling well the peak of the Band spectrum, which was determined to lie at $\sim 650\,\mathrm{keV}$ (see right panel of Figure 1). If the gamma rays detected by *Konus*-WIND arise from the first order inverse Compton (IC) process, then the standard synchrotron self Compton (SSC) model [3] predicts a VHE second order IC component with a νF_ν peak at several tens of GeV and with an energy content more than an order of magnitude greater than that of the first IC component. GRB 080319B was located in the Milagro FOV at an elevation of $\sim 50°$. Milagro detected no significant excess associated with GRB 080319B. The 99% confidence level upper limits on the flux obtained with Milagro strongly constrain the amount of energy contained in the second IC component. If one assumes a second IC component which peaks at 100 GeV, the Milagro limits fall nearly a factor of five below the flux predicted by the standard SSC model. The upper limits obtained with Milagro assuming different peak energies of the second IC Band function component are shown in Figure 1.

RAPID FOLLOW-UP OBSERVATIONS OF GRBS WITH VERITAS

The Very Energetic Radiation Imaging Telescope Array System (VERITAS) is a VHE gamma-ray observatory located in southern Arizona, which utilizes the imaging atmospheric Cherenkov technique (IACT) to reconstruct the direction and energy of primary gamma rays with an uncertainty of $\sim 0.1^\circ$ and 15%, respectively. The array is sensitive from 100 GeV to 30 TeV, takes data for $\sim$ 1000 hours per year and has a field of view of 3.5°. A program of GRB follow-up observations has been ongoing at VERITAS since mid-2005 and follow-up observations of more than 40 GRB positions have been made since that time. In order to facilitate rapid follow-up observations of GRBs detected by the *Fermi, Swift*, *AGILE*, or *INTEGRAL* satellites, VERITAS control computers are set to receive notices in real time from the GRB coordinates network (GCN)[1] over a socket connection. This, combined with the fact that GRBs take the highest priority of all VERITAS observations, allows for an average delay of less than five minutes from burst detection to the beginning of VERITAS GRB observations. In several cases, this delay has been less than two minutes and in the particular case of GRB 080310, VERITAS was able to begin observations before the prompt phase of the burst had ended. When a GRB is well localized by a satellite, VERITAS observations of the GRB last for a maximum of three hours but this is frequently truncated due to unavoidable observing constraints.

For the results presented here, a subset of 16 GRBs observed between autumn 2007 and spring 2009, with good localization, elevation, and observing conditions are selected. A search for VHE emission from these GRBs was performed. The analysis was optimized for a weak (3% Crab Nebula flux) source and a burst spectrum of $\frac{dN}{dE} \propto E^\Gamma$ where $\Gamma = -2.5$ for the "standard" source analysis and $\Gamma = -3.5$ for the "soft" source analysis. During observations, VERITAS simultaneously records events from both a signal and background regions and the statistical significance of the number of events in the signal region is calculated using equation 17 of [21]. However, if either the number of events in the signal region or the normalized number of events in the background region is too few (<10), the method of the ratio of Poisson means is used to calculate the significance instead [22, 23]. In addition to an analysis of all VERITAS data available for each burst, a search for VHE emission on timescales optimized for a GRB with temporal characteristics similar to the LAT-detected GRBs ($\frac{dN}{dE} \propto t^{-1.5}$) [24] was also performed. All searches found no significant evidence for gamma-ray emission in the VERITAS energy band from any of the GRBs. Using the method of [25], 99% confidence level upper limits of 10^{-10} – 10^{-12} ph cm^{-2} s^{-1} were obtained.

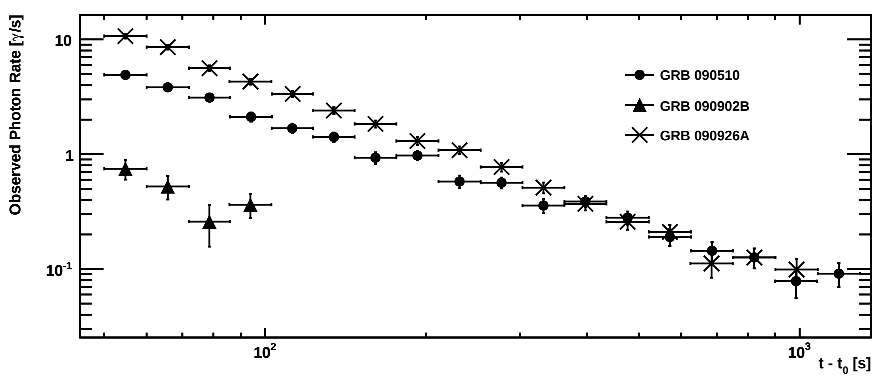

FIGURE 2. Predicted VERITAS lightcurves for the LAT-detected bursts, GRB 090926A [26], GRB 090510 [27], and GRB 090902B [28]. This extrapolation assumes no intrinsic spectral cutoff but does assume gamma-ray attenuation by the EBL according to the model of [17]. The burst elevation is taken to be 70° and all points on the lightcurve correspond to a VERITAS detection of $> 3\sigma$.

Although no definitive detection of VHE emission associated with GRBs has yet been made, recent results from the *Fermi*-LAT indicate that GRBs are capable of producing photons of up to $\sim$ 100 GeV in the rest frame of the burst [28]. As can be seen in Figure 2, extrapolating the spectral and temporal properties of several LAT-detected GRBs results in gamma-ray fluxes which can be an order of magnitude above the VERITAS detection threshold, even after including the effects of the EBL [17]. A simultaneous LAT-VERITAS observation of a LAT-detected burst is expected to occur

---

[1] http://gcn.gsfc.nasa.gov

over the lifetime of the instruments and such an observation could greatly impact the current theoretical models of GRB emission at high energies. VERITAS is continuing to perform follow-up observations on GRBs detected by *Swift*, *Fermi*, *AGILE* and *INTEGRAL*. Although not explicitly discussed here, searches for emission associated with X-ray flares is also ongoing at VERITAS.

CONCLUSIONS

No VHE emission from GRBs has yet been detected by any ground-based instrument. VHE observations are ongoing at VERITAS and limits that are among the most stringent to date are being set on VHE gamma-ray emission during the early afterglow phase. Efforts are currently underway to improve the response time of VERITAS to GRBs and other transient phenomena [29]. This is especially important considering the power-law decay in the temporal domain of the bright *Fermi*-LAT bursts. As evidenced by the Milagro limits on GRB 080319B, VHE observations can strongly constrain the parameters in the theoretical models of gamma-ray bursts. The standard single zone synchrotron self Compton model of GRB emission is strongly disfavored by the Milagro observations of GRB 080319B. The successors to Milagro and VERITAS (HAWC and CTA, respectively) will offer significant improvement for ground-based gamma-ray astronomy and GRB science stands to benefit immensely from the increased sensitivity, reduced energy thresholds, and increased fields of view that these instruments will have with respect to their predecessors.

ACKNOWLEDGMENTS

This research is supported by grants from the US Department of Energy, the US National Science Foundation, the Smithsonian Institution, Los Alamos National Laboratory, the University of California, by NSERC in Canada, by Science Foundation Ireland, and by STFC in the UK. T. Aune gratefully acknowledges the support provided by a NASA Graduate Student Research Program fellowship.

REFERENCES

1. T. Piran, *Physics Reports* **314**, 575 (1999).
2. B. Zhang, and P. Mészáros, *The Astrophysical Journal* **559**, 110 (2001).
3. X. Y. Wang, et al., *The Astrophysical Journal* **556**, 1010 (2001).
4. A. M. Beloborodov, *The Astrophysical Journal* **618**, L13 (2005).
5. X.-Y. Wang, et al., *The Astrophysical Journal* **641**, L89 (2006).
6. Y.-C. Zou, et al., *Monthly Notices of the Royal Astronomical Society* **396**, 1163 (2009).
7. P. Meszaros, and M. J. Rees, *R.A.S. MONTHLY NOTICES V.269* **269**, L41 (1994).
8. Y.-Z. Fan, et al., *Monthly Notices of the Royal Astronomical Society* **384**, 1483 (2008).
9. A. Panaitescu, *Monthly Notices of the Royal Astronomical Society* **385**, 1628 (2008).
10. R. R. Xue, et al., *The Astrophysical Journal* **703**, 60 (2009).
11. A. Galli, and L. Piro, *Astronomy and Astrophysics* **489**, 1073 (2008).
12. E. Waxman, *The Astrophysical Journal* **606**, 988 (2004).
13. C. D. Dermer, *The Astrophysical Journal* **664**, 384 (2007).
14. M. Bottcher, and C. D. Dermer, *Astrophysical Journal Letters v.499* **499**, L131 (1998).
15. G. D. Sciascio, and T. D. Girolamo, *arXiv* **astro-ph** (2006), `astro-ph/0609317v1`.
16. D. Allard, et al., *arXiv* **astro-ph** (2005), `astro-ph/0508441v1`.
17. R. C. Gilmore, et al., *Monthly Notices of the Royal Astronomical Society* **399**, 1694 (2009).
18. P. M. Vreeswijk, et al., *GRB Coordinates Network* **7444**, 1 (2008).
19. S. Golenetskii, et al., *GRB Coordinates Network* **7482**, 1 (2008).
20. J. L. Racusin, et al., *Nature* **455**, 183 (2008).
21. T. Li, and Y. Ma, *Astrophysical Journal* (1983).
22. S. N. Zhang, and D. Ramsden, *Experimental Astronomy (ISSN 0922-6435)* **1**, 145 (1990).
23. R. Cousins, et al., *Nuclear Instruments and Methods ...* (2008).
24. G. Ghisellini, et al., *Monthly Notices of the Royal Astronomical Society* **403**, 926 (2010).
25. W. A. Rolke, et al., *Nuclear Instruments and Methods in Physics Research Section A* **551**, 493 (2005).
26. T. Uehara, *DECIPHERING THE ANCIENT UNIVERSE WITH GAMMA-RAY BURSTS. AIP Conf. Proc.* **1279**, 451 (2010).
27. M. D. Pasquale, et al., *The Astrophysical Journal Letters* **709**, L146 (2010).
28. A. A. Abdo, et al., *The Astrophysical Journal Letters* **706**, L138 (2009).
29. D. A. Williams, *these proceedings* (2011).