Limits on Very High Energy Emission from Gamma-Ray Bursts with the Milagro Observatory

Miguel F. Morales for the Milagro Collaboration

Massachusetts Institute of Technology, Cambridge, MA 02139, mmorales@space.mit.edu

Abstract. The Milagro telescope monitors the northern sky for 100 GeV to 100 TeV transient emission through continuous very high energy wide-field observations. The large effective area and ∼100 GeV energy threshold of Milagro allow it to detect very high energy (VHE) gamma-ray burst emission with much higher sensitivity than previous instruments and a fluence sensitivity at VHE energies comparable to that of dedicated gamma-ray burst satellites at keV to MeV energies. Even in the absence of a positive detection, VHE observations can place important constraints on gamma-ray burst (GRB) progenitor and emission models. We present limits on the VHE flux of 40 s – 3 h duration transients nearby to earth, as well as sensitivity distributions which have been corrected for gamma-ray absorption by extragalactic background light and cosmological effects. The sensitivity distributions suggest that the typical intrinsic VHE fluence of GRBs is similar or weaker than the keV – MeV emission, and we demonstrate how these sensitivity distributions may be used to place observational constraints on the absolute VHE luminosity of gamma-ray bursts for any GRB emission and progenitor model.

INTRODUCTION

The heart of the Milagro observatory is a large water reservoir located at 2600 m altitude in the Jemez mountains of New Mexico. Very high energy gamma rays incident at the earth pair produce in the upper atmosphere and produce extensive air showers (EAS) which propagate to lower altitudes. Milagro uses the water Cherenkov technique to detect EASs by converting the front of relativistic particles in the EAS into a front of Cherenkov light which is detected by the 723 photomultiplier tubes (PMTs) instrumenting the water. Milagro is a very sensitive detector with a low $\sim$ 100 GeV energy threshold and wide >1.8 sr field-of-view and is fully capable of autonomous identification of VHE GRB emission. The low energy threshold is particularly important because of the reduced attenuation by extragalactic background light near 100 GeV, which dramatically increases the volume of space observed.

THE 40 S TO 3 HOUR GRB SEARCH IN MILAGRO

The 40 s to 3 hour transient search implements an analysis developed by Morales et al. [1] which enhances the sensitivity of wide-angle gamma-ray observatories. The 40 s – 3 hour duration window was analyzed using nine separate logarithmically spaced search windows, each covering a 1.84 sr field of view for data taken between 2001 May 2nd and 2002 May 22nd. The search over-samples in both space and time and has $\sim$ 290 days of total observation (see Atkins et al. [2] for details). The observations are entirely consistent with the expected trials factors, and no evidence was observed for transient VHE emission of 40 s to 3 hours duration.

FLUX LIMITS

The flux limits in Figure 1 represent the VHE transient flux at the earth for a concident event which can be excluded by this study at the 90% confidence level. For this paper an $E^{-2.0}$ power-law spectra (as observed local to the earth) from 100 GeV to 21 TeV was chosen. This spectrum serves as a reasonable model for an inverse Compton bump at TeV energies or a hard VHE extension of the observed GRB spectrum past the multi-GeV observations by EGRET. These limits represent the strongest flux limits on VHE GRB emission obtained to date.

CONSTRAINTS ON THE INTRINSIC LUMINOSITY OF GRBS

In an effort to place the current observations in context, a set of assumptions about the emitted spectrum, extragalactic background light (EBL) absorption, and cosmology have been chosen and sensitivity distributions calculated within this theoretical framework. For a set of source luminosities and durations, simulated GRBs were created with an $E^{-2.0}$ emission spectrum from 100 GeV – 21 TeV, an isotropic sky position, and following the star formation rate in z. The EBL absorption was determined by Bullock et al. [3] (similar to Primack et al. [4]) using a ΛCDM cosmology ($\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, h= 0.65). The results are rather insensitive to the emitted spectrum due to the strong EBL absorption which eliminates nearly all emission above 300 GeV at redshift $\sim$ 0.3, and limits the distance to which Milagro can observe VHE emission to redshift < 0.7.

The probability that Milagro would have observed a VHE GRB as a function of the isotropic luminosity, distance, and duration of the source is given in Table 1 of Atkins et al. [2]. The results for a GRB with VHE emission of 80 s duration is plotted as an example in Figure 2.

As an example of the limits on VHE emission which can be made using these probabilities, consider a model which predicts that GRBs follow the star formation rate with all GRBs emitting a characteristic 80 s pulse of VHE emission. The resulting 90% confidence upper limits for this model are 6.2×10^{-8} GRBs/$M_\odot$ of star formation (an average of 4.8 GRBs/Gpc^3/year over 0<z<0.5) for an isotropic luminosity of 10^{51} ergs/s, or 1.1×10^{-8} GRBs/$M_\odot$ of star formation (an average of 0.8 GRBs/Gpc^3/year over 0<z<0.5) for a luminosity of 10^{52} ergs/s, with significantly tighter constraints if the GRB distribution trails the star formation rate (i.e. there are more low redshift GRBs). Of the thirty-six GRBs with known distances, five have a redshift below 0.5. If the GRBs detected by BATSE follow the same distance distribution, a rough estimate of the observed GRB rate yields $\sim$2.6 GRBs/Gpc^3/year, or $\sim 3.4 \times 10^{-8}$ GRBs/$M_\odot$ of

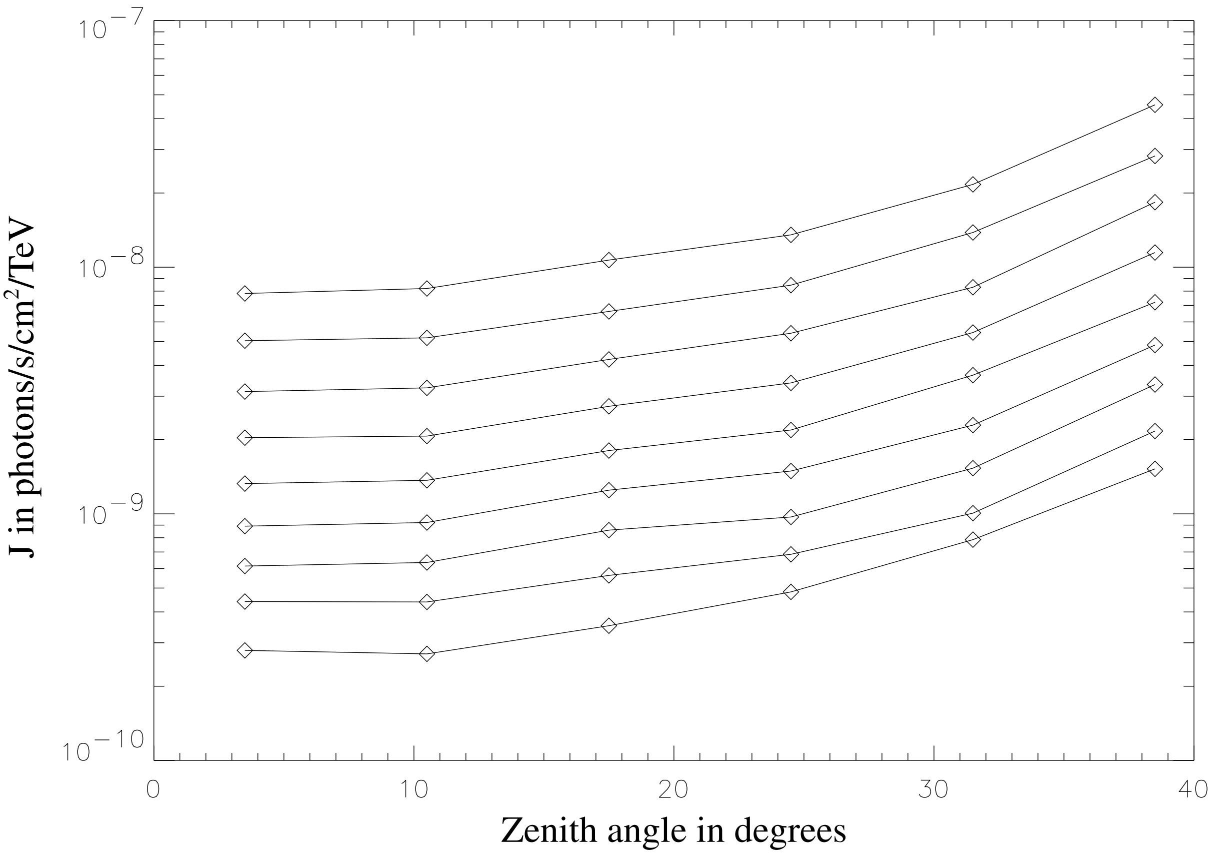

FIGURE 1. The 90% confidence upper limits for an $E^{-2.0}$ spectrum for all nine time scales as a function of zenith angle. The diamonds indicate the calculated limits on the normalization factor J in photons s^{-1} cm^{-2} TeV^{-1} for the spectrum $\frac{dN}{dE} = J(\frac{E}{1\text{TeV}})^{-2.0}$. The time scales are from top to bottom: 40 s, 80 s, 160 s, 320 s, 640 s, 1280 s, 2560 s, 5120 s, and 10240 s. Monte Carlo statistics lead to an error in the upper limits of 19%. Systematic errors are due principally to uncertainties in the Monte Carlo simulation and are estimated to be +40%/-20%, for a total estimated error of +44%/-27%.

star formation if they follow the SFR. While detailed model calculations are needed to convert the probabilities in Atkins et al. [2] into meaningful upper limits, comparison with the limits from this simple model suggests that if GRBs follow the star formation rate, the typical luminosity of 40 s – 3 h VHE GRB counterparts is constrained to be similar to or less than the prompt keV – MeV emission.

ACKNOWLEDGMENTS

We acknowledge Scott Delay and Michael Schneider for their dedicated efforts in the construction and maintenance of the Milagro experiment. This work has been supported by the National Science Foundation (under grants PHY-0070927, -0070933, -0075326, -0096256, -0097315, -0206656, -0302000, and ATM-0002744) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos

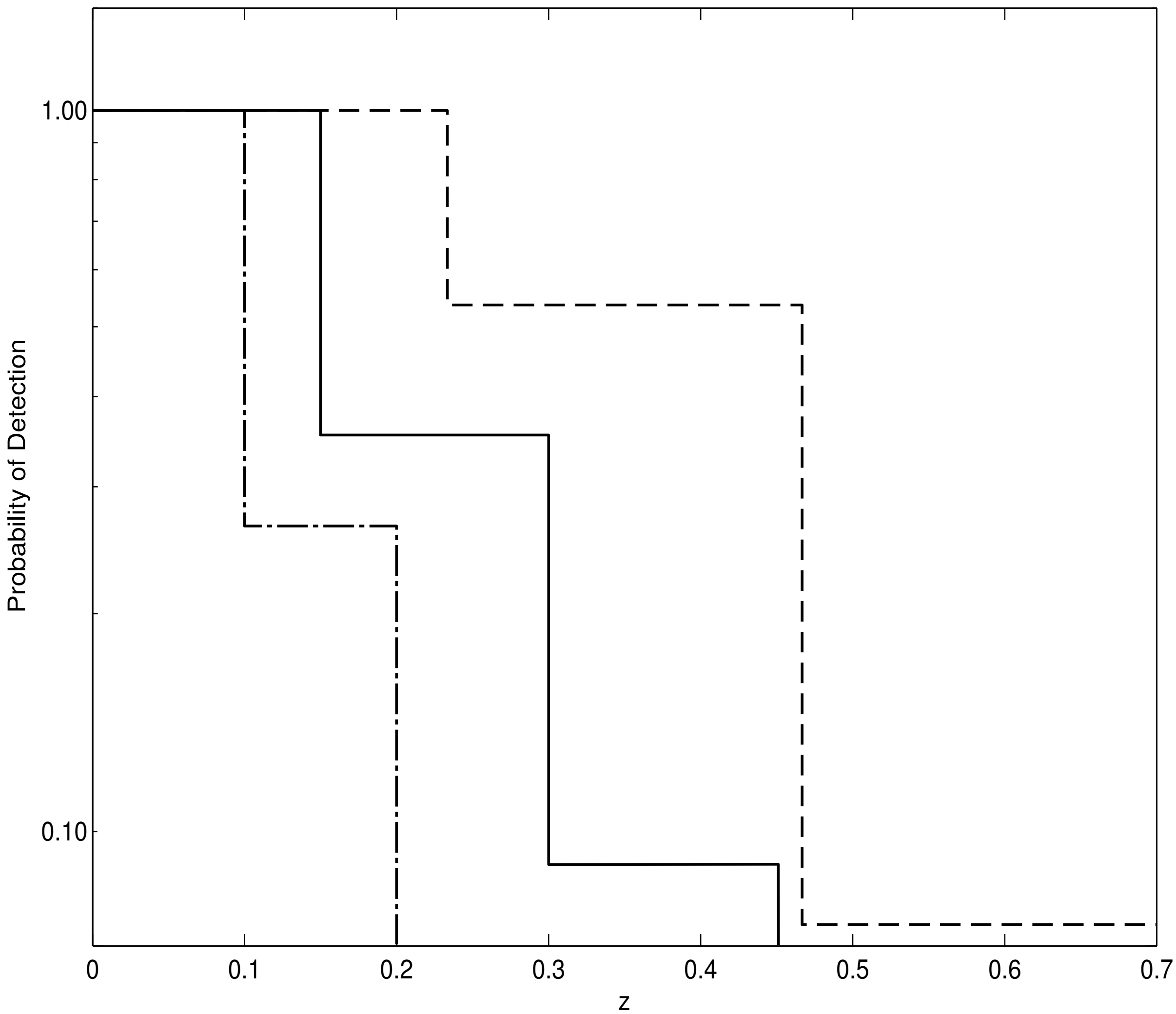

FIGURE 2. The probability of detection for GRBs of 80 seconds duration within the 1.84 sr field of view of Milagro with an isotropic luminosity 10^{50} ergs/s (dash-dot line), 10^{51} ergs/s (solid line), and 10^{52} ergs/s (dashed line) as a function of z. Table 1 in Atkins et al. [2] lists the probabilities for many different luminosity and burst durations

National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics. MFM was a NASA Graduate Student Researcher.

REFERENCES

1. Morales, M. F., Williams, D. A., & DeYoung, T. 2003, *Astropart. Phys., in press,* astro-ph/0303178
2. Atkins, R., et al. 2004, *submitted to ApJL,* astro-ph/0311389
3. Bullock, J. R., Somerville, R. S., Primack, J. R. 2003, *in prep.*
4. Primack, J. R., Bullock, J. S., Somerville, R. S., & MacMinn, D. 1999, *Astropart. Phys.,* 11, 93