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A Search for Short Duration VHE Emission from GRBs with Milagro

David Noyes for the Milagro Collaboration
Presenter: David Noyes (dnoyes@umdgrb.umd.edu), usa-noyes-D-abs1-og24-oral

Milagro is a water-Cherenkov detector capable of observing air showers produced by gamma rays with primary energies of approximately 100 GeV and higher. The wide field of view (∼ 2 sr) and high duty cycle (>90%) of Milagro make it ideal for searching for transient emission from gamma-ray bursts (GRBs). In the absence of a GRB localization provided by another instrument, the Milagro data is searched independently for VHE emission from GRBs. In 2.3 years of searching for bursts with durations ranging from $250\mu s$ to $40s$, no significant evidence was observed for VHE emission from GRBs. Models for different GRB parameters (such as redshift and isotropic energy distributions) are used to constrain the VHE spectrum of GRBs.

1. Introduction

Milagro [1, 2] is a water-Cherenkov detector located in the Jemez Mountains near Los Alamos, New Mexico, and is capable of detecting air showers induced by cosmic rays and gamma rays with primary energies above ∼ 100 GeV. The primary detector consists of a 6-million gallon artificial pond instrumented with 723 photomultiplier tubes (PMTs), arranged in two layers. In addition to this, the pond is surrounded by an array of 175 individual Cherenkov detectors ("outriggers"). Each outrigger consists of a 1500 gallon tank of water, measuring 2.4 m in diameter and 1 m high with a single PMT facing the bottom of the tank.

A number of models predict a Very High Energy (VHE) component to the GRB spectrum [4, 5, 6]. It is widely believed that the prompt keV/MeV emission detected by previous and current instruments is due to synchrotron emission by relativistic electrons. If this is the case, then it is possible for these synchrotron photons to Compton scatter off of the relativistic electrons to higher energies. This is only one possible mechanism for producing VHE emission from GRBs, other possible mechanisms include proton synchrotron emission, photo-meson cascade emission, and others [7].

Milagro's large field of view (∼ 2 sr) and high duty cycle (>90%), allow it to observe a large portion of the sky, nearly all the time, making it well suited to searching for the transient emission produced by GRBs or other sources of short duration VHE gamma-ray flares. The median energy of the events detected by Milagro is a few TeV, however the effective area is still large at hundreds of GeV ($\sim 50m^2$ at 100 GeV). This results in a gamma-ray fluence sensitivity at VHE energies comparable to previous satellite detectors at keV energies. Photons above a few hundred GeV are highly attenuated by infrared (IR) background photons which are a component of the extra-galactic background light (EBL). The attenuation increases with redshift, and limits Milagro to relatively nearby bursts. However, the large effective area at a few hundred GeV makes Milagro sensitive to large sample of the burst population.

2. The Short Duration Burst Search

In the absence of a burst localization provided by another instrument, it is possible to search the Milagro data for VHE emission from GRBs. Due to the large cosmic-ray flux at the earth, the bulk of the events detected by Milagro are air showers induced by cosmic rays. It is therefore necessary to search for emission from a GRB on top of this large cosmic-ray background. In contrast to doing a search for a known source, the start time, duration, and coordinates of a potential GRB are not known a priori, making it necessary to search over the entire sky, at all times, and over multiple durations. The first step in this process is to create a background map using a long period of time (compared to the duration). The background map is normalized to contain the number of events expected from any location on the sky in a time window specified by the start time and the duration. Next, a signal map is created and contains the number of events observed in the time window specified by the start time and the duration. Given these maps, the probability that the number of observed signal events was due to a random fluctuation of the background is calculated for each point on the sky. The signature of a GRB would be a very low probability, inconsistent with being due to a random fluctuation of the background.

The search is done in real time over 27 durations ranging from $250\mu s$ to 40 s. Fig. 1 shows the probability distribution for the 1 s duration search for an entire day of data. Given the fact that the start time, duration, and coordinates of a potential GRB are unknown, a large number of overlapping spatial and time bins are used in the search. An increased number of spatial bins is used whenever a bin is found with a probability less 10^{-4}. This is the origin of the feature in the probability distribution at this probability value. A GRB candidate would appear on this figure as a low probability value, away from the main distribution.

The Milagro data was searched for VHE emission from GRBs from MJD 52353 to MJD 53372 (1020 days). After accounting for the dead time of the detector ($\sim$ 10%) and various data quality cuts, the total number of live days searched was 836.585 (2.3 years), giving a post-cuts duty factor of 82%. In this time period, no evidence for VHE emission from a GRB was observed.

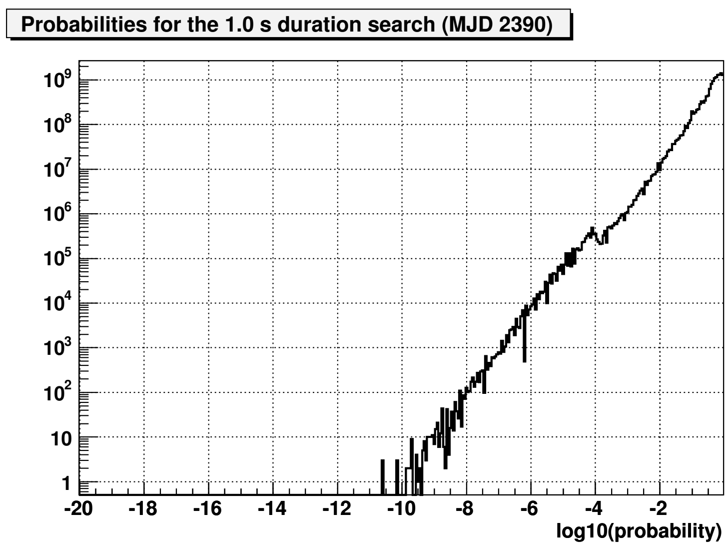

Figure 1. Probability distribution for the 1 s duration search for an entire day of data.

3. Constraining the VHE Spectrum of GRBs

Given the fact that no evidence for VHE from GRBs was observed, it is possible to constrain the VHE component of the GRB spectrum. Little is known about the VHE component of the burst spectrum. EGRET measured a number of bursts up to a few GeV, and were found to be consistent with an extension of the Band spectrum to these energies. However GRB941017 showed a distinct high energy component, which evolved independently of the lower energy component [3]. Furthermore, the redshift and luminosity distributions are not well constrained by observations for the long duration bursts, and have not been observed at all for short duration bursts (except perhaps GRB050509b).

In order to constrain the VHE component of the burst spectrum, simulations are done of burst populations. For the purpose of these simulations, it is assumed that the VHE spectrum is a simple E^{-2} power law between 100 GeV and 10 TeV. Attenuation due to the IR background is accounted for using models for the amount of IR as a function of redshift and photon energy [8, 9]. Then models must be taken for the burst redshift and isotropic energy distributions. The measured BATSE duration distribution is used for the burst durations.

To simulate a burst population, a redshift, duration, isotropic energy, and zenith angle are randomly drawn from their respective distributions. Then the number of photons detected from a GRB at a redshift z, with isotropic energy E_{iso} (radiated in the form of 100 GeV to 10 TeV photons), and at a zenith angle θ for Milagro, is given by

$$N_\gamma(z, E_{iso}, \theta) = I_o(z, E_{iso}) \int_{100GeV}^{10TeV} A_{eff}(E, \theta) E^{-2} e^{-\tau(E,z)} dE, \quad (1)$$

where $I_o(z, E_{iso})$ is the normalization to the spectrum, $A_{eff}(E, \theta)$ is the effective area of Milagro as a function of zenith angle and primary particle energy, and $e^{-\tau(E,z)}$ is the survival probability for absorption on the IR background. The number of photons expected (N_γ) is then compared to the measured Milagro background (N_{bkg}) for the same zenith angle and a fixed duration. If the Poisson probability of observing $N_{bkg} + N_\gamma$ events when expecting N_{bkg} is 5σ or greater after accounting for the large number of trials, then it is considered that the burst would be detectable by Milagro.

A large number of bursts are simulated in this manner in order to determine what fraction of this population would be detectable by Milagro. The models for the E_{iso} distribution apply to the keV/MeV portion of the spectrum. It is then assumed that all bursts have a VHE component to their spectrum, and that the total energy radiated in the form of 100 GeV to 10 TeV photons is a constant factor times that radiated in the form of lower energy photons. For each simulated GRB, this energy ratio ($E_{iso}(VHE)/E_{iso}(keV)$) is varied in order to determine the fraction of the simulated burst population that would be detectable as a function of $E_{iso}(VHE)/E_{iso}(keV)$. This allows an upper limit to be set on the energy ratio. Since no evidence for VHE emission was observed by Milagro in the 2.3 years that were searched, the 90% confidence level (CL) upper limit on the number of GRBs/year in this data set is 2.3/2.3 =1 GRB/year. The value of the energy ratio that gives this many events expected per year is the 90% CL upper limit on the ratio. Given a model of the redshift and isotropic energy distribution of GRBs, a weaker or stronger limit will be set on the energy ratio depending on how many bursts in the model are bright enough and nearby enough for Milagro to detect. For example, Fig. 2 shows the results from a simulation which used a simple fit to the measured GRB redshift and isotropic energy distributions. The top three plots in the figure show the model distributions used in the simulation. The bottom left plot shows the redshift distribution of the simulated bursts that were detectable. The bottom right plot shows the total number of GRBs/year expected to be observed by Milagro as a function of the energy ratio given the model described above. Drawn on this plot is the 90% CL upper limit on the energy ratio, which for this model is 0.21. This means that the total energy released in the form 100 GeV to 10 TeV photons is constrained to be less than 0.21 times that released by keV/MeV photons. This was done for a number of different models of the redshift and isotropic energy distributions. These included theoretical redshift and isotropic energy distributions based on the lag-luminosity relation, redshift distributions based on theoretical distributions of binary mergers and the star formation rate, and isotropic energy distributions derived from the measured BATSE fluence distribution. The different models result in a range of limits on the energy ratio depending on the number of nearby GRBs predicted and how much energy they release. For the models mentioned above, the limit on the energy ratio varies from around 0.2 to 90. Future work will include models for $\gamma\gamma$ absorption at the burst source and taking into account any improved knowledge of the GRB redshift and isotropic energy distributions.

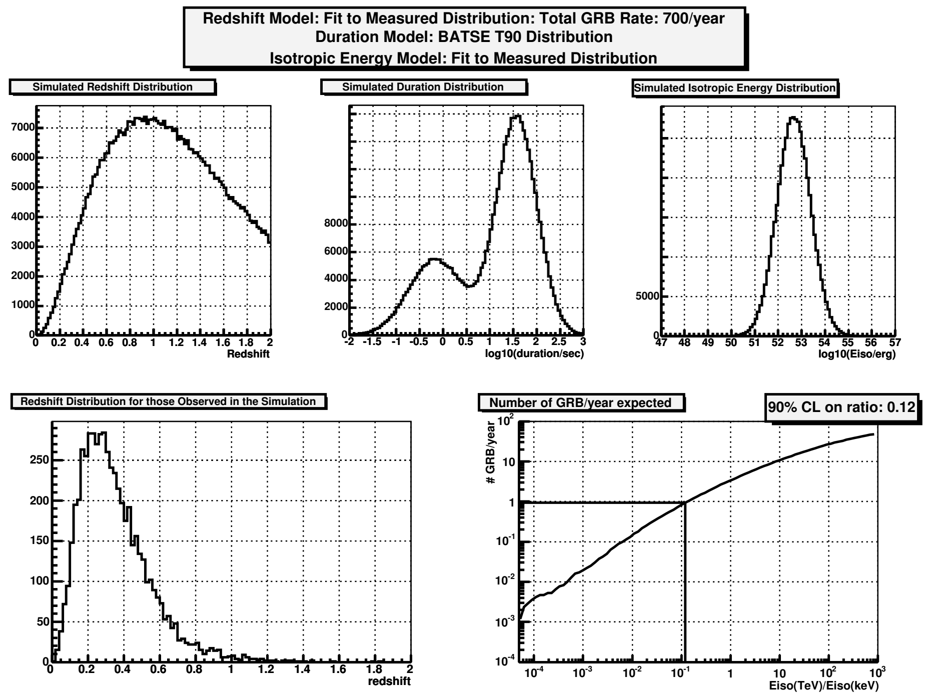

Figure 2. Results of a simulation using fits to the measured redshift and E_{iso} distributions. The top three plots show the model distributions. On the bottom left is the redshift distribution of GRBs that would be detectable in this model for an energy ratio of 1. On the bottom right is the number of GRBs/yr detectable by Milagro, as function of the energy ratio.

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