Proceedings of the 30th International Cosmic Ray Conference
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008

Vol. 3 (OG part 2), pages 1135–1138

ID 674

30TH INTERNATIONAL COSMIC RAY CONFERENCE

ICRC'07 Mérida, México

A Blind Search for Transient Bursts of Very High Energy γ Rays Using Milagro

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Abstract: Milagro is a water-Cherenkov detector capable of observing air showers produced by γ rays. The wide field of view ($\sim$2 sr) and high duty cycle (>90%) of Milagro make it ideal for searching for transient very high energy emission. We will report on the results of a blind search of the Milagro data for very high energy γ-ray outbursts within the Milagro field of view for durations ranging from 160 μs to 6 minutes. While this analysis is primarily aimed at detecting γ-ray bursts (GRBs), it could also be sensitive to other phenomena like primordial black-hole evaporation and soft γ-ray repeaters. No trigger from another instrument is required, instead the entire reconstructed data set is systematically searched in time, space and emission duration. Four years of Milagro data are searched, which corresponds to 2920 sr days of exposure. While the peak sensitivity of Milagro is above 1 TeV, the detector has substantial effective area at lower energies ($\sim$50 m^2 at 100 GeV, $\sim$2500 m^2 at 1 TeV).

Introduction

A number of models predict a very high energy[1] (VHE) component to the GRB spectrum [1, 2, 3, 4]. It is widely believed that the prompt keV/MeV emission detected by previous and current instruments is due to synchrotron radiation from a population of 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. Other possible mechanisms for VHE emission from GRBs include proton synchrotron emission, photo-meson cascade emission [5, 6]. Measuring the VHE component of GRBs is critical to understanding the environment of the charged particle acceleration.

The difficulty of measuring the TeV component of GRB radiation is complicated by the fact that VHE radiation is attenuated by infrared (IR) photons due to pair production [7]. Both IR photons from the vicinity of the burst and the intergalactic IR background radiation can dissipate the VHE γ-ray component of the GRB spectrum. While the IR photon density in the vicinity of the burst is unknown, the intergalactic IR background has been modeled. The attenuation increases with redshift and photon energy, and photons at energies greater than 100 GeV are highly attenuated for redshifts greater than z=0.5. This implies that, in order to observe VHE emission from a GRB, the GRB must be either relatively nearby or release a large amount of energy [8]. However, the large effective area at a few hundred GeV makes Milagro sensitive to a large sample of the burst population.

While this analysis is primarily aimed at detecting emission from GRBs, it can also be sensitive to emission from primordial black-hole evaporation and soft γ-ray repeaters. Primordial black holes (PBHs) [9] were created by the collapse of the density fluctuations of the early universe. They continuously emit radiation (Hawking radiation) with a luminosity that is inversely proportional to their mass. The final stage of their lives is a spectacular explosion with infinite luminosity, but with a finite integral flux. Black holes with masses of $\sim 10^{14}$ grams at the time of the Big Bang would be evaporating now [10]. Soft γ-ray repeaters (SGRs) are compact sources of persistent X-ray emission and repeating bursts of soft γ rays. They are believed to be highly magnetized young neutron stars (known as magnetars). Their γ-ray emission is

1. E>100 GeV

characterized by a short (<0.5 sec) and very intense burst that is followed by a long (100 sec) pulsating soft tail.The energies emitted by most SGRs follow a power-law distribution with spectral index -5/3 [11]. It has been suggested that a fraction of short duration GRBs could be due to giant flares of soft γ-ray repeaters (SGRs) in nearby galaxies.

The Milagro detector

Milagro [12] is a water-Cherenkov detector at an elevation of 2630 m (750 g/cm^2 of overburden) located in the Jemez Mountains near Los Alamos, NM. It consists of a central rectangular 60m x 80m x 7m reservoir filled with purified water and surrounded by a sparse 200 m x 200 m array of 175 “outrigger” (OR) tanks. The reservoir is covered with a light barrier and is instrumented with two layers of 8” photomultiplier tubes (PMTs). The top “air-shower” (AS) layer consists of 450 PMTs under $\sim$1.5 m of water, while the bottom “muon” (MU) layer has 273 PMTs located $\sim$6 m below the surface. Each outrigger tank contains $\sim$4000 l of water and one PMT. The PMTs collect the Cherenkov light produced by the air shower particles, as they transverse the detector’s water volume. The AS layer allows the accurate measurement of the air shower particle arrival times and is used for direction reconstruction and triggering. The outrigger array improves the accuracy of the core location reconstruction and the angular resolution of the detector by providing a longer lever arm with which to reconstruct events. The greater depth of the muon layer ($\sim$17 radiation lengths) is used to distinguish deeply penetrating muons and hadrons, which are common in hadron induced air showers, from electrons and γ-rays and to provide a calorimetric view of the energy deposition in the detector.

The median energy of the γ rays detected from a Crab-like source is $\sim$3 TeV. Milagro’s large field of view ($\sim$2 sr) and high duty cycle (>90%) allow it to continuously monitor most of the overhead sky, making it well suited to search for transient emission produced by GRBs or for other short duration VHE γ-ray flares.

The fluence sensitivity of the Milagro detector as a function of the GRB duration is shown in figure 1.

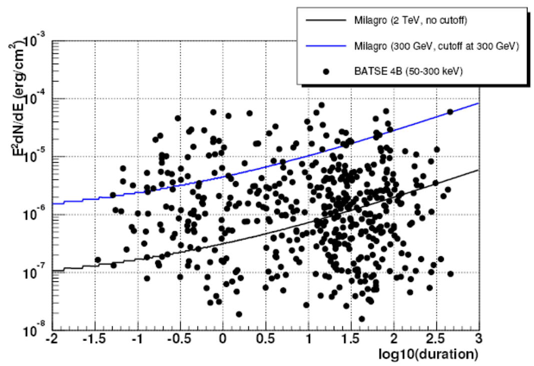

Figure 1: Fluence sensitivity of the Milagro detector as a function of the GRB duration. Two cases are shown. Both correspond to an exponential spectrum with spectral index -2.4 but with a different energy cutoff. The black line is for no cutoff while the blue line is for a cutoff at 300 GeV. The median energies of the triggered events are at 2 TeV and 300 GeV respectively. Also plotted (the black points) are the measured fluences and durations of an ensemble of BATSE detected GRBs.

The GRB search

One approach to searching for VHE emission from GRBs is to search for bursts that are coincident in time and direction with GRBs detected by another instrument. The Milagrito experiment, a predecessor to Milagro, observed evidence for TeV emission from GRB970417a in a search conducted for GRBs coincident with the BATSE detector [13]. No significant events have been found in the Milagro data from searches performed in coincidence with triggers by other instruments [14, 15, 16].

Alternatively, as in this work, one can search the entire Milagro data set with no a priori knowledge of the start time, duration, or coordinates of a potential GRB. 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. A γ-ray signal will be identified as an excess on top of the isotropic cosmic-ray background, larger than expected from statistical fluctuations of the background alone

The search is a fundamentally simple, binned analysis. The only cuts applied to the data are that the reconstructed zenith angle of the event be less than 45^o and that at least 15 PMTs participated in the fit used in the reconstruction of the initial direction of the air shower initiating particle.

The data were searched for GRB emission in 35 durations ranging from 250 μsec to 6 minutes. For each duration searched, the number of events counted in a time window equal to the search duration is binned into a $0.2^o \times 0.2^o$ map in right ascension (RA) and declination (δ). For each position on the grid, all the neighboring bins within $1.5^o/cos\delta$ in RA and 1.5^o within δ are summed to give the number of measured events at the candidate position. The sum corresponds to a $3^o \times 3^o$ square bin, which was determined with simulations to be roughly optimal for point source searches and for sub-TeV energy events. The background at each candidate position is estimated using the "direct integration" method described in [17]. The probability of a chance fluctuation resulting in the observed number of events or larger is calculated, assuming a Poisson distribution with the average number of background events. The signature of a GRB would be a very low probability, inconsistent with a random fluctuation of the background. After all probabilities for that signal map have been evaluated, the start time of the search is advanced by 10% of the search duration and the procedure is repeated. This procedure is independently performed for all the different durations.

This procedure employs a high degree of overlap spatially, temporally, and in candidate duration, maximizing the sensitivity to bursts of unknown time and position. The search was conducted using two nearly identical algorithms: One optimized for the case where the search region has a low event density and the other for regions with a high event density. For the former case, a table of candidate search positions is constructed by considering only those positions in the vicinity of at least two events. In cases where the average number of events in the signal bin is low ($<< 1$), this method is considerably faster than just a simple grid search. When the event density is high (> 2), most positions in the sky are included in the candidate table, and the time required to construct the table of candidate positions slows down the search. In this case a second search algorithm is used. The second algorithm performs a relatively coarse search on a $0.6^o \times 0.6^o$ grid, one third the density of the final search. If the coarse search locates a GRB candidate position that yields an excess with probability $P_{Poisson} < 10^{-4}$, the eight nearest neighbor bins surrounding the candidate source position are subsequently searched. The loss in sensitivity from not searching the entire sky with the finer (0.2^o) bin size is negligible, because a probability threshold of typically $P_{Poisson} < 10^{-13}$ (7.4σ) is required to identify an excess as a GRB, and the coarser search will always yield a probability less than 10^{-4} in the vicinity of such an excess. Fig. 2 shows the probability distribution for the 250msec duration search for the entire dataset searched. The feature in the probability distribution at $P_{Poisson} = 10^{-4}$, is due to the different step size in the spatial searches defined above.

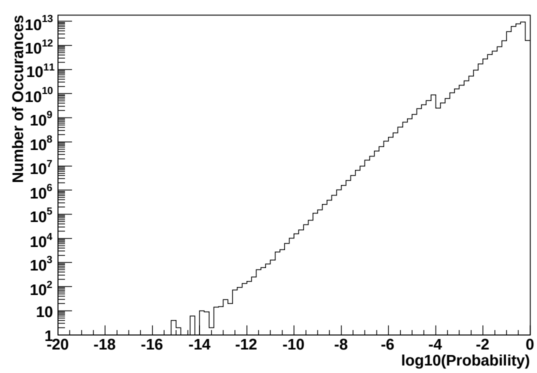

Figure 2: Distribution of the Poisson probabilities calculated for the 250msec duration search in 4 years.

Results

The Milagro data were searched for VHE emission from GRBs from MJD 52774 to MJD 54234 (4 years). Taking account the the down time of the detector because of scheduled repairs or other unexpected problems, 3.6 years worth of data have been searched. No significant events have been observed.

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-0245234, -0302000, -0400424, -0504201, -0601080, and ATM-0002744) the US Department of Energy (Office of High-Energy Physics and Office of Nuclear Physics), Los Alamos National Laboratory, the University of California, and the Institute of Geophysics and Planetary Physics.

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