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A Search for Bursts of TeV Gamma Rays with Milagro

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Abstract. The Very High Energy (VHE, $E > 100$ GeV) component of Gamma-Ray Bursts (GRBs) remains unmeasured, despite the fact that models predict that the spectrum of GRBs extends beyond 1 TeV. Satellite detectors capable of observing GRBs lack the sensitivity to detect γ-rays with energies greater than $\approx$ 30 GeV due to their small effective area. Air Čerenkov telescopes, capable of detecting TeV point sources with excellent sensitivity have limited sensitivity to GRBs due to their small fields of view and limited duty cycles. The detection of TeV emission from GRBs is further complicated by the attenuation of VHE photons by interaction with the intergalactic infrared radiation. This process limits the horizon for TeV observations of GRBs to $z < 0.3$ or less. As only about 20 GRBs have well measured redshifts, the fraction of GRBs close enough to observe at TeV energies remains unknown. The Milagro Gamma Ray Observatory began operation in June 1999. The detector consists of a large man-made pond (4800 m^2) instrumented with an array of photo-multiplier tubes. Milagro operates 24 hours a day and continuously observes the entire overhead sky ($\approx$2 sr). Because of its wide field of view and high duty cycle Milagro is uniquely capable of searching for TeV emission from GRBs. An efficient algorithm has been developed to search the Milagro data for GRBs with durations from 250 microseconds to 40s. The search, while designed to search for the TeV component of GRBs, may also be sensitive to the evaporation of primordial black holes, or some other yet undiscovered phenomenon. The results of this search are presented.

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1 Introduction

Despite the fact that 3 decades have past since their discovery, the source GRBs remains unclear. The spectrum of GRBs above the 30 MeV has only been measured for a few very bright bursts within the field of view of the EGRET detector (Esposito 1999),citedingusgrb . At energies beyond the reach of EGRET, $E > 100$ GeV, high sensitivity measurements have not been made. It has been suggested that the γ-ray radiation from GRBs detected in the 30 keV to 1 MeV range is due to synchrotron radiation from a population of very high energy electrons. Alternatively, the electron population could lose their energy via inverse Compton (IC) scattering off of synchrotron photons (or photons from an external source) producing a very high energy IC γ-ray component along with lower energy synchrotron γ-rays. Several models of GRB origins predict TeV scale radiation (Dermer, Böttcher and Chiang 2000) from the IC, or other processes, with comparable fluence to the well measured MeV scale radiation. Measuring the VHE component of GRBs may be critical to the understanding of 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. Both IR photons from the vicinity of the origins 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 is well modeled. Attenuation of VHE γ-rays from this source is likely to limit the horizon of VHE measurements to $z \approx 0.3$.

One approach to searching for VHE emission from GRBs is to search for bursts in the Milagro data that are coincident in time and direction as GRBs detected by the BATSE experiment (Paciesas 1999), or another GRB monitor. The Milgrito experiment, a predecessor to Milagro, observed evidence for TeV emission from from GRB970417a in a search conducted for GRBs coincident with the BATSE detector (Atkins et al, 2000). But since the loss of BATSE due to the de-orbit of the Compton Gamma-ray Observatory, there is no all-sky GRB monitor with a high sensitivity. The rate of satellite observations of GRBs within Milagro's field of view has dropped from one per week when BATSE was active to less than one per month for the existing GRB sensitive satellites. For this reason, it is important to conduct a search for GRBs in the Milagro data without the constraint that the burst be coincident with a satellite GRB detector

2 The Milagro Detector

The Milagro Detector (Sullivan 2001) is an air-shower array that employs a large man-made pond of water instrumented with photo-multiplier tubes (PMTs) to detect Čerenkov radiation from secondary shower particles in extensive air showers. The detector is located in the Jemez Mountains near Los Alamos, New Mexico at an altitude of 2650m (750g/cm^2 of overburden). The detector consists of a rectangular reservoir measuring 80m x 60m and 8m deep instrumented with 2 layers of PMTs. The top layer contains 450 PMTs distributed in an 25 x 18 grid at a depth of 1.4m and is used primarily for measurement of the arrival times of secondary shower particles. The bottom layer contains 273 PMTs on a smaller 21 x 13 grid at a depth of 6m. This deep layer provides a calorimetric measurement of secondary shower particles and is used to distinguish deeply penetrating muons and hadrons, common in hadron induced air showers, from electrons and γ-rays. Simple cuts on measured quantities in the bottom layer allow for the removal of $> 90\%$ of the hadronic background while preserving $> 60\%$ of γ-ray induced showers increasing the sensitivity of the detector by a factor of $\approx$1.8. The technique has been verified through observations of MRK-421 (Benbow 2001) and the Crab nebula (Sinnis 2001).

Milagro is operated with a trigger that requires roughly 50 PMTs to be hit within a 200ns time window. Under normal operating conditions, this trigger will provide about 1500 triggers/sec. In winter months when snow accumulates on the cover, slightly increasing the detector's overburden, the trigger rate is lower.

3 Searching for GRBs

The goal of this work is to conduct a search for GRBs in the vast Milagro data set without the any prior knowledge of the GRBs position in the sky, start time or duration. Milagro has only limited γ-hadron separation, so γ-ray sources are identified as non-statistical excesses on top of an isotropic background of cosmic-ray hadrons. The task of searching the Milagro data, which contains more than 50 Billion events, is computationally challenging.

The search of the data is a fundamentally simple binned analysis. The events collected for a candidate start time and duration, are binned into a fine, $0.2^o \times 0.2^o$, map in Hour Angle (HA) and declination (δ). For each position on the fine grid, all the neighboring bins within $\frac{1.0^o}{cos\delta}$ in HA and 1.0^o within δ are summed to give the number of measured events at the candidate position. The sum corresponds to a 2.2^o square bin which was determined with simulations to be roughly optimal for point source searches in the Milagro data. The background is then estimated from data collected in the half hour prior to the GRB candidate time, and the Poisson probability that the number of measured events, or more, is observed given the measured background is calculated. All the points within the fine map with zenith angle less than 45^o are considered. Finally, the candidate start time is advanced by 10% of the GRB candidate duration and the procedure is repeated. This procedure is independently performed for 27 candidate GRB durations ranging from $250\mu s$ to $40s$, with each subsequent candidate duration 58% longer than the last. This procedure employs a high degree of overlap spatially, temporally and in candidate duration maximizing 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 overhead of constructing 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 $0.6^o \times 0.6^o$ degree grid, one third the density of the final search. If a GRB candidate position is located using the coarse search that yields an excess with Poisson probability less than 10^{-4}, the eight nearest neighbor bin surrounding the candidate source position are subsequently searched. The loss in sensitivity from not searching the entire sky with the finer (0.2^o) binsize is negligible, because a probability threshold of typically $P_{Poisson} < 10^{-13}$ (7.5σ) 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.

Figure 1 shows the distribution of Poisson probabilities for

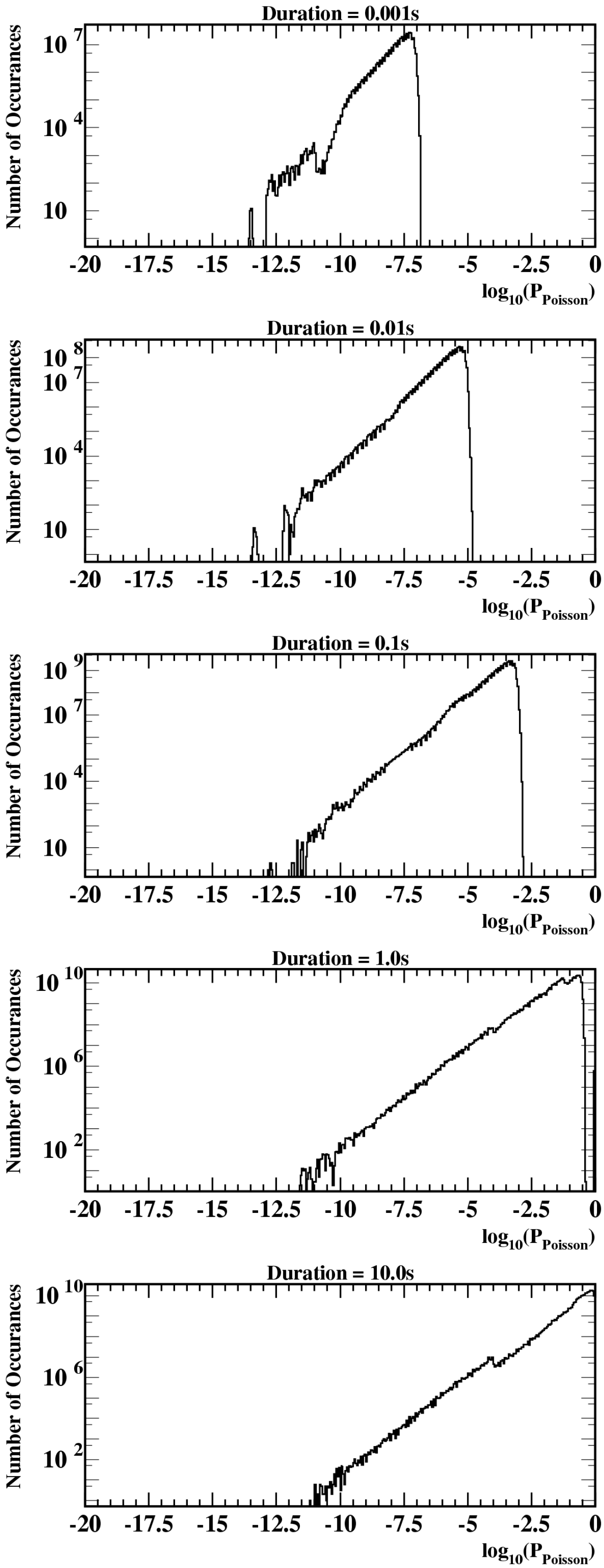

Fig. 1. Probability distributions for 5 of the 27 GRB candidate durations.

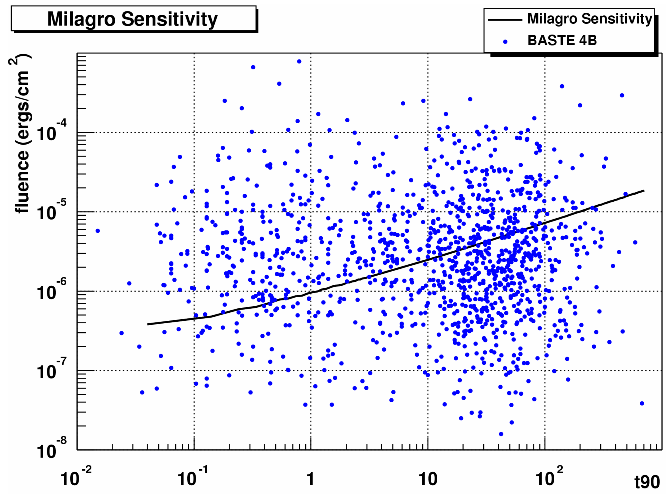

Fig. 2. The fluence sensitivity of the Milagro detector as a function of GRB duration (black line). The fluence estimate is for a $\frac{dN}{dE} \propto E^{-2.4}$ particle spectrum with no cutoff. The fluence is taken to be the integral of the GRB energy above the median energy of the Milagro detector (typically a few TeV). Also plotted (the blue points) are the measured fluences and durations of an ensemble of BATSE detected GRBs.

5 of the 27 GRB candidate durations searched for Milagro data collected between September 14, 2000 and April 28, 2001. The figures show that the number of candidates with a probability decreases, as is should, by 1 decade for each decade in increasing probability. For the first three plots, the probabilities for GRB candidate positions with less than 2 events are excluded by the search algorithm, leaving the high probability region vacant. The kink in the probability distributions for the final 2 plots at $log_{10}P = -4$ is due to the increase in the search grid density for regions of large excess employed by the second search algorithm described above. A GRB on these plots would show up as a cluster of points with very low probability (high significance) substantially separated to the from the statistical background. No GRBs were found in the initial search of this data set.

4 Sensitivity of Milagro to GRBs

Although, the γ-ray flux from GRBs is almost certainly low at energies greater than 100 GeV, the large effective area of Milagro and it's large aperture make Milagro's sensitivity to GRB fluence comparable to that of BATSE. Figure 2 shows the fluence sensitivity of Milagro (at the TeV scale) vs the duration of the GRB compared to an ensemble of measured 100 keV scale GRB fluences and duration by BATSE.

5 Conclusion

A search was conducted for GRBs in a subset of the Milagro data on timescales ranging from $250\mu s$ to $40s$. The search yielded no GRB detections. The calibration and the reconstruction algorithms have been substantial improved since the collection of these data. Updated results and upper limits will be presented at the conference.

In the event that Milagro should observe GRBs, we are implementing online GRB search software. The system will search the Milagro data as it is collected and conduct the search described in this paper for GRBs. Should a GRB occur within Milagro's sensitivity, the system will be capable identifying it within 4s of the completion of the burst. Milagro could provide prompt notification of GRBs with position localization of about 0.2^o. A Target of Opportunity proposal to rapidly follow up a future Milagro GRB detection with the RXTE satellite has been approved.

During 2001, the Milagro detector will be substantially upgraded to increase it's sensitivity to GRBs. A critical limitation to the detection of GRBs at energies greater than $\approx$ 50 GeV is the absorption of VHE γ-rays by the IR background radiation. To increase our sensitivity, it is therefore vital to lower the energy threshold of the instrument. Milagro, as currently functioning, triggers when 50 of the 450 top layer PMTs are hit within a 200ns window. Our detector simulations show that we can reliably reconstruct the direction of γ-ray induced showers with as few as 25 hits in the top layer of PMTs. Unfortunately, backgrounds from single muons presently prevent us from lowering our trigger threshold allowing the detector to trigger on showers with lower energies. A smart trigger card that can identify and veto on the single muon background while preserving the air-shower events will be installed during the Summer of 2001 (Hays and Noyes 2001). Figure 3 shows the effective area of Milagro as a function of energy for the current Milagro trigger (High Threshold) and the planned Milagro trigger (Low Threshold). The increase in area while nominal at energies greater then 3 TeV is quite substantial at energies below 300 GeV. This upgrade will substantially increase our sensitivity to distant GRBs.

Additionally, an array of outrigger tanks (Shoup 1999) is being constructed around the Milagro detector. The array will improve the angular resolution and the γ-hadron separation of Milagro providing an overall increase in the flux sensitivity of about a factor of 2.

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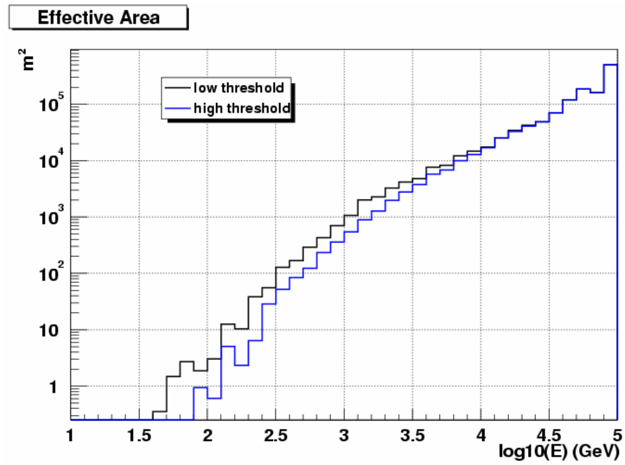

Fig. 3. The effective area of the Milagro detector as a function of Energy for a or current trigger (High Threshold) and our planned trigger upgrade (Low Threshold).

References

Atkins et al., ApJL, 533, L119.
Benbow, W. et al, ICRC 2001.
Dermer, C.D., Böttcher, M., Chiang, J., ApJ, 537, 255-260, 2000.
Dingus, B.L., Catelli, J.R. & Schneid, E.J. 1998, 4th Huntsville GRB Symposium, AIP, 428, 349, 1998.
Esposito, J.A., et al, ApJS 123, 203, 1999.
Hays E., Noyes D. et al Gamma 2001 Proceedings, 2001.
Paciesas, W.S. et al, ApJS 122, 465, 1999.
Sinnis, G. et al, ICRC 2001.
Shoup, A. et al, ICRC 1999.
Sullivan, G. et al, ICRC 2001.