Searching for High Energy Muon Neutrinos from Gamma-Ray Bursts with AMANDA

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Abstract

The discovery of neutrinos from GRBs would confirm acceleration of cosmic rays in the GRB fireball and herald a new era of neutrino-based astronomy. The Antarctic Muon and Neutrino Detector Array (AMANDA) is a neutrino telescope with a PeV muon effective area $\sim 50,000$ m^2. AMANDA data sets spanning 1997-2000 were examined for high-energy neutrinos that were spatially and temporally coincident with 317 triggered GRBs, detected by the Burst and Transient Source Experiment (BATSE) on NASA's Compton Gamma-Ray Observatory (CGRO) satellite, and 153 non-triggered GRBs, obtained by searching the BATSE archived data. Our preliminary results are consistent with no GRB neutrino signal. We derive a four year combined neutrino event upper limit of 1.45 for the 317 BATSE triggered bursts. The determination of systematic uncertainties is still in progress. Future and ongoing GRB search methods are also discussed.

1. Introduction

The generic mechanism responsible for generating the tremendous energy ($\sim 10^{53}$ ergs) released in GRBs is described via the phenomenology of the fireball model [1]. High-energy ($E \geq 10^{14}$ eV) neutrinos are the decay products of photopions produced via the following mechanism: $p+\gamma \rightarrow \Delta^+ \rightarrow \pi^+[+n] \rightarrow \mu^+ + \nu_\mu \rightarrow e^+ + \nu_e + \bar{\nu_\mu} + \nu_\mu$. AMANDA [2] is a neutrino telescope that uses the ice near the geographic South Pole as a Cherenkov medium. The detector background primarily consists of *down-going* atmospheric muons (of negative declination) detected at a rate of about 100 Hz. Neutrino induced muons, via charged current interactions such as: $\nu_\mu + N \rightarrow \mu^\pm + X$, represent signal events and are separated from the background via the exclusive use of *up-going* muon reconstructed events (of positive declination). In this manner, the Earth is used as an atmospheric muon filter. From 1997-1999, the detector was known as AMANDA-B10 and was comprised of 10 strings and 302 optical modules (OMs). Since 2000, it has been

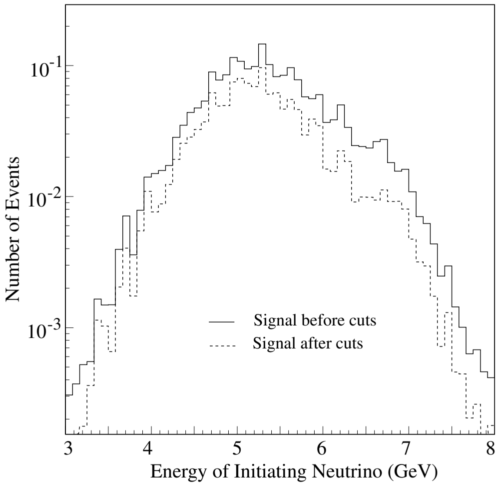

Fig. 1. GRB MC-signal [8] before (solid) and after (dashed) cuts for AMANDA-II (analysis 2000A).

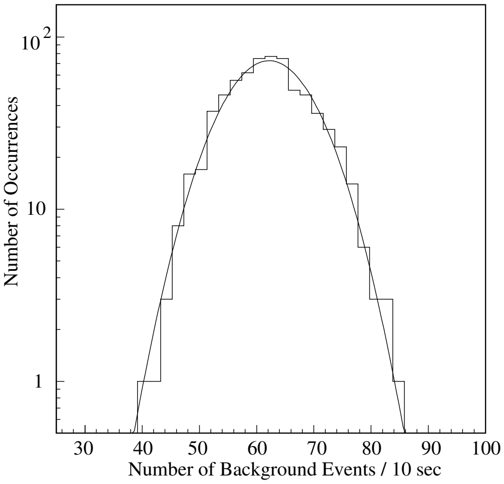

Fig. 2. Background event rate for AMANDA-B10 on 2/22/98 (before and after BATSE GRB 6610).

known as AMANDA-II and has consisted of 19 strings and 677 OMs.

2. Data & Monte Carlo

AMANDA data sets from April 1997 to May 2000 were searched for high-energy up-going neutrinos that were spatially and temporally coincident with 317 triggered (BATSE) and 153 non-triggered [3] GRBs. BATSE documented the trigger time, duration and position of each triggered GRB [4]. BATSE's positional uncertainty is a function of burst intensity and nominally ranges from $\sim 1^\circ - 10^\circ$, while systematic uncertainty is $\sim 1.6^\circ$ [5]. At TeV energies, the offset between the direction of the incident neutrino and the secondary muon in AMANDA is $\sim 1^\circ$. The topology and timing of the OM data is used to reconstruct the muon track to within $\sim 2^\circ - 3^\circ$. The strict spatial and temporal constraints of each GRB dramatically reduce the detector background. The expected neutrino event rates are determined from a full Monte Carlo simulation of the GRB signal, neutrino propagation through the Earth and the response of the AMANDA detector. Figure 1 illustrates the effect of selection criteria ("quality cuts") on the Monte Carlo GRB signal flux. The cuts retain $\sim 62\%$ of the original signal while removing all background events in AMANDA-II (for AMANDA-B10, $\sim 35\%$ of the signal is retained). More details about the quality cuts are given in the next section.

3. Analysis

In order to ensure that the analysis was not biased by the act of setting cuts or looking for a signal, a blinded approach was adopted. For each GRB, an approximately two-hour long interval (centered on the trigger time) was ex-

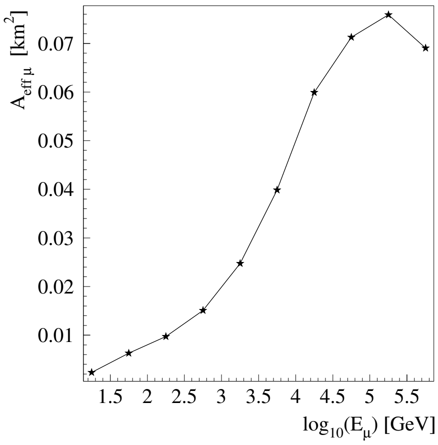

Fig. 3. Angle-averaged effective muon area as a function of energy for AMANDA-II (analysis 2000A).

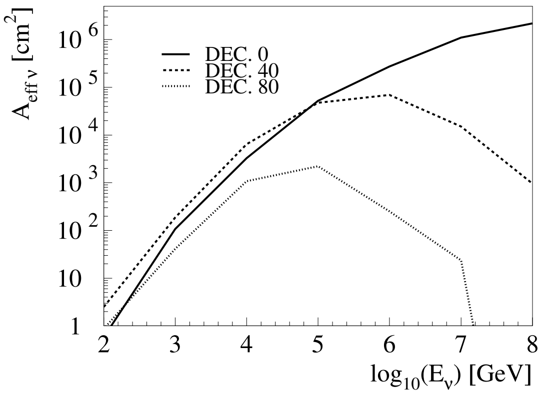

Fig. 4. Effective ν-area as a function of energy for a few declinations (DEC.) in AMANDA-II (2000A).

tracted from AMANDA data in order to characterize the background. Blinding consisted of avoiding on-time and on-source analysis during a time period centered on the GRB trigger time. The stability and quality of the data were verified by analyzing the distributions of the time between consecutive events (Δt) and the number of background events over 10-second intervals. Figure 2 exemplifies data of good stability (the mean $\pm$ RMS of the data and the mean $\pm$ σ of the Gaussian fit were both $\sim$ 6.22 $\pm$ 0.75 Hz). Bursts occurring within periods of non-Gaussian background event distributions or within periods of large time gaps between consecutive events (Δt $\gg$ 10 seconds) were not used in the analysis.

Quality cuts were based upon analysis of the measured background (off-time and off-source) and signal Monte Carlo data. For AMANDA-B10, the quality cuts involved the angular search bin size and the number of direct hits (i.e. events arriving within the expected Cherenkov arrival time). For the 2000 (AMANDA-II) data set, two complementary analyses were performed (denoted as *2000A* and *2000B*), which utilized independently derived quality cuts on the number of channels hit, the number of direct hits, the smoothness (i.e., distribution of hits along the reconstructed track) and the track reconstruction likelihood. All of the AMANDA-II cuts were optimized via the Model Rejection Potential (MRP) technique [6].

4. Results, Interpretation and Future Outlook

Our results are consistent with no coincident GRB-neutrino signal as shown in table 1. Preliminary effective muon and neutrino area plots for AMANDA-II (based upon the spectrum of figure 1) are shown in figures 3 and 4 respectively. The cuts for 2000A and 2000B, lead to a similar MRP sensitivity (the gain in

2000B background rejection is offset by its loss of signal sensitivity). This demonstrates the robustness of the analysis. Dual entries for the row of 2000B in table 1 denote triggered and the sum of triggered and non-triggered GRB values respectively. The event upper limit [7] of 1.45 (based upon the combination of 1997-1999 and 2000A triggered BATSE GRB results) may be used to calculate a limit on the flux of neutrinos, measured at the Earth, from the 317 triggered BATSE GRBs. If we assume that each GRB follows a Waxman-Bahcall [8] type spectrum (with $E_B = 100$ TeV and $\Gamma = 300$), then the normalization constant of this flux limit is $\sim 4 \times 10^{-8}$ GeV cm^{-2} s^{-1} sr^{-1}. To interpret this as a limit on the total output of neutrinos at the GRB sources, one must incorporate the luminosity function (red shift distribution) of these sources as well as the effect of neutrino oscillations. An analysis comparing individual BATSE GRB flux predictions [9] with the AMANDA data archive will be published elsewhere. Ongoing GRB analysis will continue, using data from the Third Interplanetary Network (IPN3). Future analysis will involve Swift and eventually the superior sensitivity of IceCube [10].

Table 1. Preliminary Results of the 1997-2000 GRB-neutrino Analyses

Year	Number of GRBs	Total background	Events observed	Event upper limit
1997	78	0.06	0	2.41
1998	99	0.20	0	2.24
1999	96	0.20	0	2.24
2000A	44	0.83	0	1.72
2000B	44/68	0.40/0.64	0/0	2.05/1.90
Sensitivity$_{(1997-1999\&2000A)}$	317	1.29		3.4 (avg.)
Total$_{(1997-1999\&2000A)}$	317	1.29	0	1.45

References

1. Piran T. 1998 astro-ph/9810256
2. Ahrens J. *et al.* 2002 astro-ph/0205109
3. ftp://ftp.astro.su.se/pub/head/grb/catalogs/table13.txt
4. http://f64.nsstc.nasa.gov/batse/grb/catalog/current/
5. Briggs M.S. *et al.* 1999 astro-ph/9901111
6. Hill G.C., Rawlins K. 2003 Astropart. Phys. **19** 393
7. Feldman G.J., Cousins R.D. Phys. Rev. D 1998 **57** 3873
8. Waxman E., Bahcall, J. 1997 Phy. Rev. Lett. **78** 2292
9. Guetta D. *et al.* 2003 astro-ph/0302524
10. Karle A. 2002 astro-ph/0209556