The Search for Muon Neutrinos from Gamma-Ray Bursts with AMANDA B-10 and AMANDA-II

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Gamma-ray bursts have been observed for more than three decades, and yet much about their nature remains a mystery. Here we describe the results of the ongoing search for high energy muon neutrinos from gamma-ray bursts with the Antarctic Muon and Neutrino Detector Array (AMANDA). Current results are consistent with no neutrino emission; thus preliminary upper limits are derived for the event rate, four-year combined flux, and single year fluence. We also address plans for improving these limits in the future.

1. Introduction

Gamma-ray bursts (GRBs) are among the most energetic phenomena in the universe. All are characterized by prodigious gamma-ray emission, hypothesized to occur as a result of the collapse of a massive star or the merger of compact objects. Aspects of these theories have been corroborated by recent observations [1]; however, many questions about the nature of GRBs still remain. For example, are protons accelerated by the GRB event, and if so, will they interact to produce a measurable neutrino flux? The most promising technique currently available to answer such questions is to use underwater or under-ice detectors to observe high-energy neutrinos from these sources [2,3]. The search for neutrino emission from GRBs will help to test fireball [2–4] and cannonball [5] scenarios, and the search for precursor neutrinos may constrain models of GRB progenitors [6,7].

AMANDA uses the ice at the South Pole to detect Cherenkov radiation from neutrino-induced muons from both atmospheric interactions and astrophysical sources [8,9], including, potentially, GRBs. In its initial configuration (AMANDA-B10), the detector consisted of an array of 302 photo-detectors beneath the surface of the ice cap; the current configuration of 677 photo-detectors is known as AMANDA-II.

2. Observation and Analysis

The AMANDA GRB search relies on spatial and temporal correlations with GRB observations from the Burst and Transient Source Experiment (BATSE) and the satellites of the Third Interplanetary Network (IPN) [10]. The BATSE bursts are taken from the final burst catalog [11], the non-triggered burst search of Stern et al. [12], and the GUSBAD catalog [13]. For each GRB, the period searched for coincident neutrino emission is the burst duration (or BATSE t_{90}), plus the associated timing errors, plus the 10 seconds prior to the burst start.

To determine the background rate for each burst, a further period of one hour and 50 minutes of data is analyzed–from one hour before the burst to one hour after the burst. The 10 minute period during and immediately surrounding the burst is excluded, to ensure that the analysis is not biased by the act of setting data quality cuts. The cuts are determined by minimizing the Model Rejection Factor [14], based on a comparison of observed background events with Monte Carlo simulations of signal events. Beyond temporal coincidence, the cuts relevant for this analysis include the number of optical modules (OMs) which record signals (the “hit” OMs), the angular mismatch between the burst position and the reconstructed event track (based upon a maximumlikelihood pattern recognition algorithm applied to the timing of the hit OMs), the likelihood of the track reconstruction, and the uniformity of the spatial distribution of the hit OMs.

In addition, the event rate per 10 second time bin during the background period is compared to the expected (temporally uncorrelated) distribution of background events. This test determines if there are significant fluctuations in data rate due to any intrinsic instability in the detector which could be misinterpreted as a signal event. All data included in this analysis satisfy the criteria established for stable detector operation.

The detector's effective area (A_{eff}, shown in Figure 1 for the AMANDA-II detector) is determined after all cuts are applied, and helps to determine the sensitivity of the detector as a function of energy. This A_{eff} is significantly larger than any other currently-operating neutrino detector, and is also larger than the area for most other AMANDA-II analyses, due to the modest background rejection requirements.

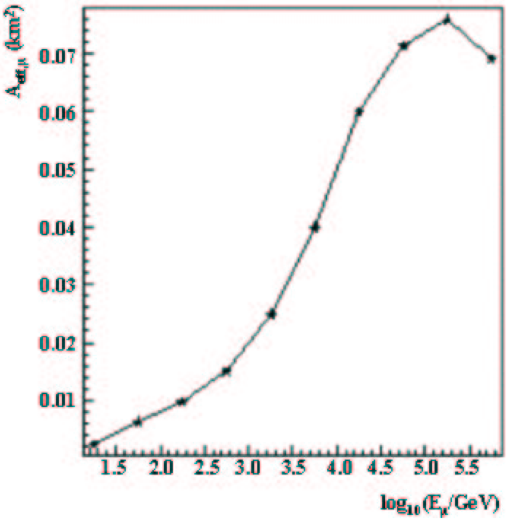

Figure 1. Effective area as a function of muon energy at closest approach to the center of the telescope, averaged over zenith angle and volume, and including neutrino attenuation by the earth.

3. Results

After the application of all quality cuts, we observe zero events during all bursts (Table 1). Given the predicted background rate ($N_{BG,Predicted}$) for each subset of bursts, we set a 90% confidence level upper limit on the number of neutrino events for those bursts. The combined 1997-2000 observations (based upon the 312 BATSE triggered bursts only) lead to a flux limit (at Earth) of 4×10^{-8} GeV cm^{-2} s^{-1} sr^{-1}, for a Waxman-Bahcall-type neutrino spectrum.

The Green's Function fluence method (detailed in [16]) is applied to the AMANDA-II data, leading to a fluence limit ϕ_ν as a function of energy, independent of the assumed neutrino spectrum. The limit derived from observations of all 114 (BATSE + IPN) bursts during 2000 (Figure 2, circles) is significantly lower than the Super-Kamiokande limit (stars), and the energy range of the AMANDA-II result also extends to higher energies. We also determine the fluence limit based solely on the BATSE triggered bursts (squares).

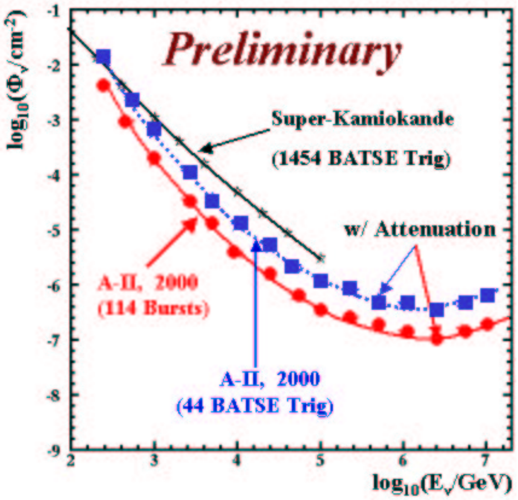

Figure 2. Fluence limit as a function of neutrino energy for Super-Kamiokande and AMANDA-II (all bursts and BATSE triggered bursts only), including neutrino attenuation by the earth.

Table 1
Summary of Observations

Year	Detector	N_{Bursts}	$N_{BG,Predicted}$	$N_{Observed}$	Event U.L.
1997	B-10	78 (BT)*	0.06	0	2.41
1998	B-10	94 (BT)	0.20	0	2.24
1999	B-10	96 (BT)	0.20	0	2.24
2000	A-II (2 analyses)†	44 (BT)	0.83, 0.40	0, 0	1.72, 2.05
2000	A-II	24 (BNT)	0.24	0	2.19
2000	A-II	46 (New)	0.60	0	1.88
97-00	B-10/A-II	312 (BT)	1.29	0	1.45

∗ BT=BATSE Triggered, BNT=BATSE Non-Triggered, New=IPN + GUSBAD † See [15] for discussion

Once the Green's Function fluence limit is determined for each energy, it can be combined with a particular energy spectrum to derive an upper limit on the total integrated fluence [16]. For example, using the 114 AMANDA-II bursts, and assuming a neutrino spectrum proportional to E^{-2} integrated over the energy range $250 - 10^7$ GeV, we obtain a 90% confidence level upper limit on the total fluence of $F_\nu = 3.7 \times 10^{-6}$ cm^{-2}.

4. Conclusions and Outlook

The preliminary limits on neutrino emission from gamma-ray bursts presented in this work are the most stringent to date, and they will be improved even more by further observations. We are currently analyzing additional bursts from 2001 and 2002, which should nearly double the size of the AMANDA-II dataset. With a few more years of data (including the precise burst localizations available with the advent of Swift [17]), we should begin to approach the neutrino flux predictions of the most common burst models. Looking beyond AMANDA-II, observations from IceCube [18] and future km^3 water detectors will continue to probe those theories that remain beyond reach.

In the past several years, the host galaxies of many GRBs have been observed, allowing the distances to these objects to be determined precisely. This in turn allows more precise determinations of the expected neutrino fluxes from these particular bursts [19]. An independent analysis of the AMANDA observations during these bursts is currently being performed.

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REFERENCES

1. Price, P., et al., Nature **423** (2003) 844
2. Waxman, E., and J. Bahcall, PRL **78** (1997) 2292
3. Alvarez-Muñiz, J., et al., PRD **62** (2000) 3015
4. Dermer, C., and A. Atoyan, PRL **91** (2003) 1102
5. Dar, A., and A. DeRújula, astro-ph/0105094
6. Razzaque, S., et al., PRD **68** (2003) 3001
7. Mészáros, P., and E. Waxman, PRL **87** (2001) 1102
8. http://amanda.uci.edu
9. Ahrens, J., et al., ApJ **583** (2003) 1040
10. Hurley, K., Astron Telegram #19 (1998)
11. http://f64.nsstc.nasa.gov/batse/grb/catalog/current
12. Stern, B.E., et al., ApJ **563** (2001) 80
13. Schmidt, M., ApJ **523** (1999) L117
14. Hill, G.C., and K. Rawlins, Astropart Phys **19** (2003) 393
15. Hardtke, R., et al., Proc 28th ICRC, Tsukuba, Japan (2003)
16. Fukuda, S., et al., ApJ **578** (2002) 317
17. http://swift.gsfc.nasa.gov
18. Karle, A., et al., Nuc Phys B Proc Supp **118** (2003) 388
19. Guetta, D., et al., astro-ph/0302524