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The AMANDA search for high energy neutrinos from gamma-ray bursts

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Abstract. If gamma-ray bursts (GRBs) accelerate protons as well as electrons, they may be the source of the highest energy cosmic rays. Detection of neutrinos from GRBs would confirm hadronic acceleration. AMANDA uses the Antarctic icecap as a Cherenkov medium for detecting such high energy neutrinos. We searched data recorded during 1997 for neutrinos coincident with northern hemisphere GRBs detected by BATSE. BATSE provides the time and location information that reduces the background of atmospheric neutrinos from which the high energy neutrinos must be separated. Quality cuts reduce the number of misreconstructed muon tracks, resulting in a nearly background-free search. The search result is consistent with no signal, and we place an upper limit on the neutrino flux from GRBs.

1 Introduction

Gamma-ray bursts (GRBs) are short, intense, and randomly distributed eruptions of high energy photons. The likely mechanism for achieving such high energies is the conversion to radiation of the kinetic energy of ultrarelativistic electrons and protons that have been accelerated in a relativistically expanding fireball.

Gamma-rays are produced primarily by the synchrotron radiation of accelerated electrons. Neutrinos are the decay products of pions produced when accelerated protons interact with the intense radiation field of the burst: p + $\gamma \rightarrow \pi^+ \rightarrow \mu^+ + \nu_\mu \rightarrow$ e$^+$ + ν_e + $\overline{\nu}_\mu$ + ν_μ .

GRB neutrino searches are scientifically important for many reasons (Halzen, 1999). First, their observations are a direct probe of the fireball model of GRBs. Second, they may unveil the source of the highest energy cosmic rays. Third, they may reveal the appearance of ν_τ in what was a ν_e or ν_μ source at its origin. Fourth, the relative timing of the photons and neutrinos over cosmological distances will allow unrivaled tests of special relativity. Fifth, the fact that photons and neutrinos should suffer the same time delay traveling through the gravitational field of our galaxy will lead to better tests of the weak equivalence principle.

2 Data

In 1997, the Antarctic Muon and Neutrino Detector Array (AMANDA-B10) consisted of 10 strings and 302 optical modules (OMs) deployed in the icecap near the geographic South Pole. Relativistic muons produce Cherenkov light that is detected by the OMs. In this analysis, AMANDA uses the earth as a filter, searching for upgoing neutrino-induced muons from the northern hemisphere while rejecting downgoing cosmic ray induced muons from the southern hemisphere. The path of the muon is reconstructed using the timing and topology of the OM detections. See (Andres, et al., 2000) or (Hill, et al., 1999) for more detector details.

We searched data recorded by the AMANDA array during the Antarctic winter, 1997, for high energy upgoing neutrinos coincident with northern hemisphere GRBs detected by the Burst and Transient Satellite Experiment (BATSE). A total of 78 such GRBs triggered by BATSE occurred during normal detector operation. BATSE provides the time and location of the bursts, thereby reducing the background of downgoing muons from which upgoing neutrinos must be separated.

3 Monte Carlo

The neutrino flux can be calculated as a function of the relative ratio of protons and electrons in the fireball. It can be fixed by the assumption that GRBs are the source of the observed highest energy cosmic ray flux (Waxman, 1995a). In this case energy should be approximately equally transferred to electrons and protons in the fireball (Waxman, 1995b; Vietri, 1995). The rest of the calculation follows established particle physics techniques.

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The expected neutrino event rate in AMANDA-B10 has been determined from a full Monte Carlo simulation of the GRB signal and the detector. GRB neutrinos are generated following a broken power law energy-spectrum (Waxman and Bahcall, 1997):

$$\frac{d\phi}{dE_\nu} = \frac{A}{E_B E}\ for\ E < E_B;\ \frac{d\phi}{dE_\nu} = \frac{A}{E^2}\ for\ E > E_B \quad (1)$$

where E_B is the energy of the break in the spectrum. Its value depends on the boost factor of the fireball (see Table 1). The normalization constant A is determined from the assumption that GRBs are the source of the highest energy cosmic rays.

We re-calculated the expected neutrino event rates following the method of (Alvarez-Muniz, et al., 2000) and (Halzen and Hooper, 1999), taking into account burst-to-burst fluctuations in energy and distance. A correction for the absorption of PeV neutrinos in the Earth is also included.

γ	A [TeV cm^{-2} sec^{-1} sr^{-1}]	E_B [TeV]	N_{evt} before cuts	N_{evt} after cuts
100	9.2x10^{-11}	77	2.87	1.1
300	6.1x10^{-12}	700	0.078	0.0234
10^3	6.0x10^{-14}	7777	0.00023	0.00006

Table 1. *Number of events expected in the AMANDA-B10 array for different values of the GRB boost factor. The parameter A and E_B in Eq. (1) are choosen to reproduce the results of (Alvarez-Muniz, et al., 2000). The last two columns are the actual number of events expected for 78 GRBs before and after the angular and quality cuts.*

We draw attention to the fact that neutrino measurements are sensitive to the Lorentz boost factor, γ, which characterizes the expanding fireball (Alvarez-Muniz, et al., 2000). The boost factor has been only indirectly determined by observations. Models show that GRBs would be rendered optically thick if $\gamma << 100$. The efficiency for producing pions in the p-γ fireball collisions varies as γ^{-4} (Waxman and Bahcall, 1997). The neutrino energy varies as γ^2. See (Dar and De Rujula, 2000, 2001) for an alternative GRB model.

Highly transparent sources with large boost factors will preferentially emit photons. However, an even moderately reduced value of γ will create a prolific neutrino source due to a larger effective beam dump. We show the total expected event rate from 78 GRBs for three different values of γ (100, 300, and 1000) in Table 1.

An important consequence of fluctuations is that the signal is dominated by a few very bright bursts, which greatly simplifies their detection. Although we expect much less than one neutrino event in AMANDA-B10 from an average GRB, a burst with favorable characteristics would produce multiple events in the detector.

In order to simulate the signature of GRBs, neutrinos were generated isotropically in the AMANDA-B10 array. Muons produced by neutrinos near the detector are tracked (Lipari and Stanev, 1991) until they reach the OMs. The modeling of the detector includes the simulation of the muon track, its emission spectrum of Cherenkov photons, their propagation in the ice, the OM detection, the pulse transfer from the OM to the surface data acquisition system, and the event trigger. The Monte Carlo events were filtered and reconstructed in the same way as the data.

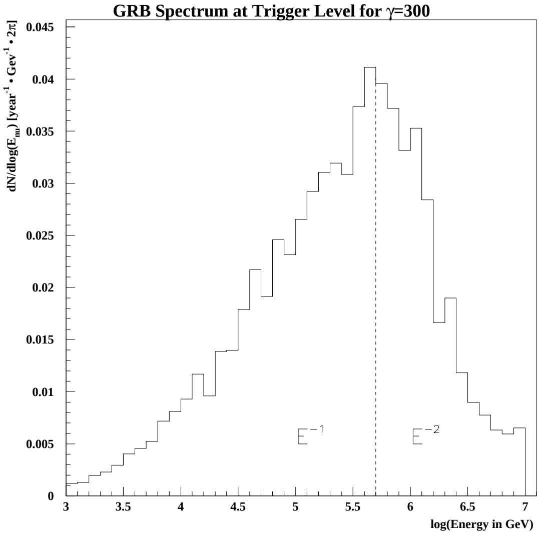

Fig. 1. *GRB spectrum at AMANDA trigger level. The plot is a convolution of the neutrino flux and the probability of conversion to a muon within the range of the detector.*

The GRB spectrum at trigger level is shown in Fig. 1. The result represents the convolution of the neutrino flux of Eq. (1), and the probability of conversion of the neutrinos to muons near the detector. For a boost factor of $\gamma = 300$, the neutrino energy peaks near 700 TeV.

4 Analysis

With 1/3 sky coverage, BATSE detected 304 gamma-ray bursts in 1997. AMANDA data for 78 northern hemisphere bursts detected on-board the BATSE satellite between April 7 and November 10, 1997 met quality criteria (Bay, 2000) and were examined in this analysis.

AMANDA-B10 recorded events at about 70Hz. Using the geometry of the OMs involved in each event, an initial line fit was calculated for each AMANDA event in the two hours surrounding a GRB trigger time. Events with a line fit originating north of a declination of $-40°$ underwent full reconstruction methods (Andres, et al., 2000). These events were searched for up-going neutrino-induced events occurring during GRBs.

Most GRBs last less than 10 seconds, though durations as long as a few minutes have been recorded. Emission of high-energy neutrinos produced in the internal shocks of GRBs should coincide with the gamma-ray emission (Waxman and Bahcall, 1997). To ensure that our search window included the period of initial gamma-ray emission, we used the earlier of the trigger time or T90 start time and then subtracted 1 second. The T90 of a GRB is the interval of time in which 5% to 95% of the GRB flux is accumulated. Neutrinos that may be emitted hours or days later (Dermer, 2000) or before the gamma-ray burst (Meszaros and Waxman, 2001) are not the focus of this search.

We first estimated the background for each angular bin near a given (θ, ϕ), where θ and ϕ are the local zenith and azimuthal coordinates. The background is dominated by downgoing cosmic ray muons that are misreconstructed as upgoing tracks. Events occurring within an hour of the burst (excluding events within [-1, +5] minutes of the burst) were used to estimate the background. A two hour interval provides sufficient statistics to parametrize the background and to minimize systematic effects resulting from any time dependence of the detector's efficiency.

The fraction of background events we expect in the search bin is calculated using the measured fraction of events in the search bin over 2 hours of background:

$$\epsilon(\theta, \phi) = \frac{N_{searchbin}^{offtime}}{N_{allbins}^{offtime}},$$

where $N_{searchbin}^{offtime}$ is the number of events observed in the spatial region of interest during a non-GRB time window (i.e., when no signal is expected) and $N_{allbins}^{offtime}$ is the number of all events observed in the sky (declination $\geq -40°$) during the same non-GRB time window.

We then calculate the expected number of background events in our search bin during the GRB time window as:

$$< n_{bg} >= \epsilon(\theta, \phi) \times N_{allbins}^{ontime},$$

where $N_{allbins}^{ontime}$ is the number of all observed events in the sky during the T90 on-time search window.

Although the overall trigger rate may vary with time, $\epsilon(\theta,\phi)$ is approximately constant. Therefore our background estimates are robust to overall changes of the trigger rate. Deadtime and downtime are also completely accounted for in this way. The stability of the efficiency $\epsilon(\theta,\phi)$ was studied for each burst and from burst to burst to ensure the stability of the background estimate with time. Bursts not meeting the efficiency stability criteria were removed.

Using the simulation, we designed a search that accounts for the zenith dependence of the angular resolution of the AMANDA-B10 detector which is better for vertical than for horizontal muon tracks, the low number of signal events expected, and the number of background events in the search bin, which depends on the GRB zenith angle and T90.

The small statistical levels expected require exact use of Poisson statistics. The optimal search bin size and optimal quality cuts are determined by minimizating the logarithm of the chance probability, $log(P_c)$, of observing a hypothetical neutrino signal N_ν. We assumed $N_\nu = 2$. We optimized on a possible signal, generated for instance by a favorable fluctuation from the average γ, redshift or burst energy (see Table 1), and not on obtaining the best limit. The results are however relatively insensitive to the choice of N_ν.

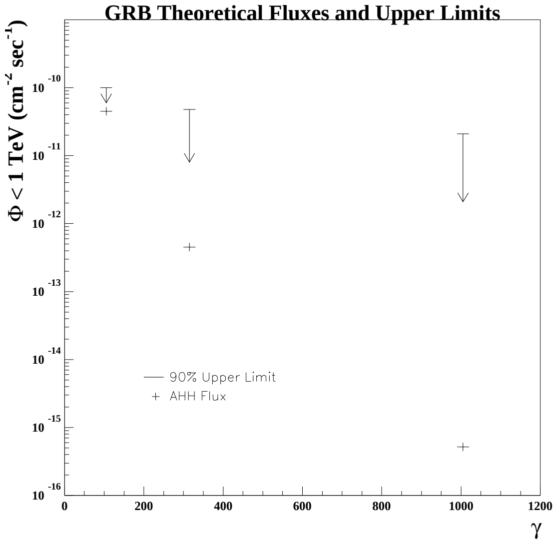

Fig. 2. *Total expected fluxes following (Alvarez-Muniz, et al., 2000) and 90% upper limits from this analysis for GRBs with three distinct values of γ (100, 300, and 1000).*

Optimization was done by dividing the sky into 10 equal bins in zenith angle for values of T90 ranging from 1 to 100 seconds. For each bin in zenith angle, the cut efficiencies for the signal and for the background have been parametrized by a sixth order polynomial.

We found that a cut on the number of "direct" hits gives the best search sensitivity. Direct hits have a small time delay relative to the calculated arrival time of Cherenkov photons from the fitted track hypothesis. They are defined as those hits that are delayed less than 75 nsec by scattering in the ice. Well-reconstructed tracks have many direct hits. The optimal minimum number of direct hits ranges from 5 to 16. The optimal size of the search bin θ_{opt} varies from 7° to $18°$. Both depend on the T90 duration and the zenith position of the GRB. The cuts we applied lead to a background rejection factor of 500 with a signal efficiency of 30%. The effective area averaged over the spectrum of GRBs with $\gamma = 300$ is approximately 17,000m^2.

5 Results

In most cases, the optimization procedure yields optimal bin sizes with no on-source, on-time events as all background events have been removed by the quality cuts. No background or signal is left and therefore the chance probability is 1 in most cases.

Because the search did not yield statistically significant bursts we derive a combined upper limit using the 78 searches. It is calculated by summing the expected number of background events, $< n_{bg}^{tot} >$, and the number of observed events, $N_{searchbin}^{ontime,tot}$) over all 78 bursts. In this analysis, $< n_{bg}^{tot} >=$

γ	ϕ_ν^{uplim} [cm^{-2} sec^{-1}]	ϕ_{source} [cm^{-2} sec^{-1}]
100	1.0 10^{-10}	4.5 10^{-11}
300	4.8 10^{-11}	4.5 10^{-13}
1000	2.1 10^{-11}	5.2 10^{-16}

Table 2. *The combined result of 78 searches places an upper limit on the GRB flux as a function of the Lorentz factor, γ. The number of events is based on the integrated flux at the earth from 1 TeV to infinity. The second column is the upper limit of the integrated flux at a 90% confidence level, based on no observation of GRB neutrinos. The third column is the integrated theoretical flux predictions of neutrinos per year and in 2π sr according to (Alvarez-Muniz, et al., 2000).*

17.2 and $N_{searchbin}^{ontime,tot} = 11$. The event upper limit is calculated according to (Feldman and Cousins, 1998) at 90% and is $n_\nu^{uplim} = 2.48$.

The neutrino flux upper limit is given by

$$\phi_\nu^{uplim}(E_\nu > 1\,TeV, \gamma) \leq \frac{n_\nu^{uplim}}{N_\nu} \int_{1\,TeV}^{\infty} \frac{d\phi_\nu}{dE_\nu}\, dE_\nu,$$

where $\frac{d\phi}{dE_\nu}$ is the total GRB flux and N_ν is the expected number of events from GRB neutrinos after cuts (see Table 1).

In Table 2, the neutrino event upper limit is given for the three Lorentz boost factors, γ, studied. The table also gives the integrated neutrino flux emitted by all the GRBs in a year according to (Alvarez-Muniz, et al., 2000). The results are shown in Fig. 2. AMANDA is not yet sensitive enough to constrain γ.

6 Additional Searches

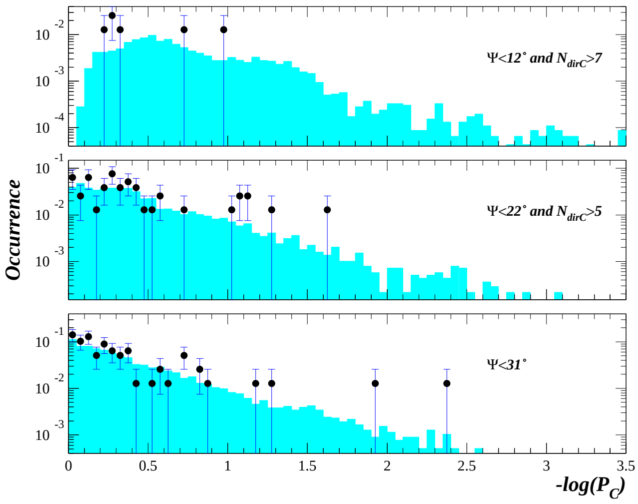

Fig. 3. *Chance probabilities of on-source searches from a second analysis (Bay, 2000) using different cuts. The results are also consistent with no signal.*

Results of an independent analysis are shown in Fig. 3 (Bay, 2000). In this analysis, three search bin sizes (12°, 22°, and 31°) were used, each with a cut on the minimum number of direct hits (> 7, > 5, 0). The shaded area of Fig. 3 represents the chance probability distribution of several thousand searches in random angular bins when no signal is expected. The points represent the chance probability of occurrence for the events observed at each cut level for 78 GRBs. This result is also consistent with no signal.

7 Conclusion and Outlook

BATSE recorded GRBs until it was turned off in May, 2000. We are searching for neutrinos coincident with BATSE bursts in two additional years of AMANDA-B10 data, 1998 and 1999. This data will increase the trials of the current analysis by a factor of $\sim$3.

The 19-string AMANDA-II detector was completed during Antarctic summer 2000 (See talk of S. Barwick, these proceedings.). Despite the loss of BATSE soon after completion, this enlarged detector will continue to search for neutrinos from GRBs detected by other satellites. Currently, GRBs are being observed almost weekly by BeppoSAX and the satellites that constitute the Third Interplanetary Network (IPN3). HETE-2 was launched Oct. 9, 2000, and will detect $\sim$1 burst per week. Future gamma-ray satellites include INTEGRAL, scheduled for launch in 2002, SWIFT in 2003, and GLAST in 2005. The effective area of AMANDA-II for GRB neutrino searches will be approximately 60,000m^2.

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