

Search for neutrinos from Gamma-Ray Bursts with the Baikal neutrino telescope NT200

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Abstract. We present an analysis of neutrinos detected with the Baikal neutrino telescope NT200 for correlations with gamma-ray bursts (GRB). No neutrino events correlated with GRB were observed. Assuming a Waxman-Bahcall spectrum, a neutrino flux upper limit of $E^2\Phi < 1.1 \times 10^{-6} \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \text{ GeV}$ was obtained. We also present the Green's Function fluence limit for this search, which extends two orders of magnitude beyond the energy range of the Super-Kamiokande limit.

Keywords: Neutrino telescope, BAIKAL, Gamma-ray burst

I. INTRODUCTION

The Baikal neutrino telescope NT200 [1], [2] is operating in Lake Baikal, Siberia, at a depth 1.1 km since April, 1998. NT200 consists of 8 strings of 70 m length: 7 peripheral strings and a central one. Interstring distances are about 20 m. Each string includes 24 pairwise arranged optical modules (OM). Each OM contains a 37-cm diameter hybrid photodetector QUASAR-370.

A number of relevant physics results has been obtained so far with the NT200 telescope, e.g. limits on the diffuse flux of extraterrestrial high energy neutrinos, limits on neutrino fluxes from Dark Matter annihilation (Sun, Earth), and on the flux of relativistic and slow magnetic monopoles [2], [3], [4].

This work is devoted to the search of neutrino events correlated with observations of more than 300 gamma-ray bursts (GRBs) reported from 1998 to 2000 by the Burst and Transient Source Experiment (BATSE) [5].

The detection strategy for neutrino events with the NT200 telescope is based on a search for Cherenkov light from relativistic up-going muons produced by neutrino interactions. Information about the GRB time and location on the sky allows to reduce the atmospheric muon background and, as a result, significantly increases the sensitivity of the neutrino telescope to neutrino events correlated with GRB.

II. EXPERIMENTAL DATA

For the present analysis, the experimental data obtained with NT200 from April 1998 to May 2000 were used. The selected data sample contains those events which were formally reconstructed as up-going muons. Taking into account the high level of background for directions close to the horizon, only events with zenith angles larger than 100° were selected. The average rate of such events was 0.037 Hz. Most fake events are due to misreconstructed muons close to horizon and to muon bundles.

For the present analysis of time and directional correlations with NT200 events we used the information about GRB location, time, duration T_{90} , and location error from the basic BATSE 4B catalog [5] (triggered bursts) and from the catalog of non-triggered GRB [6]. The error distribution of BATSE GRB locations was taken from [7]. A total of 303 GRBs (155 triggered and 148 non-triggered) at zenith angles larger than 100° and occurring during periods of stable operation of NT200 have been selected.

III. DATA SELECTION CRITERIA AND DETECTOR EFFECTIVE AREA

The optimization of the data selection criteria was performed on the basis of simulated neutrino events [8] and events of atmospheric muon background [9] in NT200. Taking into account the varying NT200 configurations during the considered time period, calculations have been performed for nine basic detector configurations, most of them closely corresponding to the real status of the detector.

The results of the reconstruction of simulated events were used to estimate the reconstruction efficiency and to calculate the background. Event reconstruction and data selection for NT200 are described in detail in [8]. There, selection criteria were designed and optimized for atmospheric neutrino separation. They provide a rejection factor of atmospheric muons larger than 10^7 . For GRB, the additional information about detection time and location on sky, however, allows softening the requirements to the background rejection. This increases the registration probability for useful events and therefore greatly increases the effective neutrino detection area. Following the approach of [8], $P_{hit} \times P_{nohit}$ and Z_{dist} were chosen as basic parameters for event selection. Z_{dist} is the maximal distance between all projections of the triggered OM coordinates onto the reconstructed muon trajectory. P_{hit} is the normalized probability of fired channels to be hit, and P_{nohit} is the probability of non-fired channel not to be hit.

For the present correlation analysis, two sets of criteria for event selection were chosen:

Cut-A:

$$(Z_{dist} > 30m) \& (P_{hit} \times P_{nohit} > 0.1) \& (\Psi < 10^\circ),$$

Cut-B:

$$(Z_{dist} > 30m) \& (\Psi < 5^\circ),$$

where Ψ is the angle between up-going muon and GRB-direction.

Cut-A dominantly selects neutrinos with energies below $\sim 10^6$ GeV. Cut-B allows a significant extension of the energy range, but the expected background is approximately four times larger than for Cut-A.

Calculating the effective area of NT200 for the two sets of criteria, we took into account the absorption of neutrinos passing through the Earth, as well as the production, propagation, detection and reconstruction within a given angular cut Ψ of muons. The calculated effective areas for the Cut-A and Cut-B samples are presented in Fig. 1 as a function of neutrino energy.

The effective areas for the two sets are close to each other up to $\sim 10^5$ GeV. For larger energies, the effective area for Cut-A stays essentially constant. The behavior for $E > 10^6$ GeV is largely defined by neutrino absorption in the Earth.

The energy range of the NT200 sensitivity was estimated for an E^{-2} neutrino spectrum. The 90% sensitivity range of NT200 extends up to $\sim 10^6$ GeV and $\sim 10^7$ GeV for selection criterion A and B, respectively.

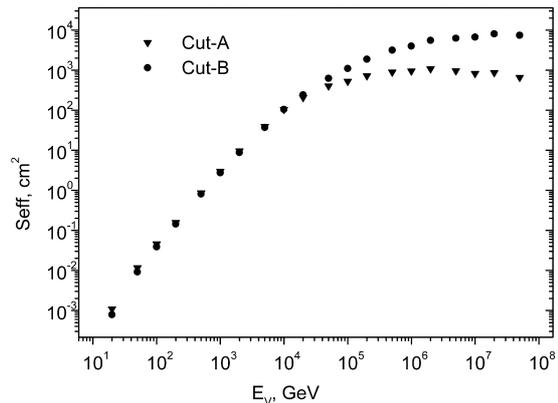


Fig. 1. NT200 effective area averaged over zenith angles between 100° and 180° as a function of neutrino energy, for selection criteria Cut-A and Cut-B.

A global estimation of the background, expected for the GRB search time window, was obtained from the NT200 raw event rate (0.037 Hz), the calculated atmospheric muon rejection factor for Cut-A and Cut-B, and the total GRB duration T_{GRB} ($\sim 1.8 \times 10^4$ s). T_{GRB} was calculated as the sum of the T_{90} intervals for all 303 triggered and non-triggered GRB. For compensation of possible event time uncertainties, five seconds were added at both sides of the time intervals T_{90} . For cases of missing information on T_{90} (about 25% of the triggered GRB), a fixed time interval was used. The expected background values, obtained from the full detector livetime interval, are 0.8 and 3.1 events for Cut-A and Cut-B, respectively.

IV. DATA ANALYSIS AND RESULTS

The basic objective of this study was to verify a sufficiently precise detector response simulation, to search for events correlated with GRBs, and to provide a solid background estimation.

To check the simulation procedures, the calculated atmospheric muon rejection factors were compared to experimental values. The results are presented in Table I for different criteria $P_{hit} \times P_{nohit}$ (Z_{dist} is set to 30 m). The simulated values are in agreement with the experimental results within the systematic error of our calculation, about 20%.

TABLE I
ATMOSPHERIC MUON REJECTION FACTOR: EXPERIMENT AND SIMULATION

$P_{hit} \times P_{nohit}$	≥ 0.1	≥ 0.2	≥ 0.3
<i>Experiment</i>	0.053	0.012	0.0035
<i>Model</i>	0.062	0.014	0.0040

This search for correlation with NT200 neutrino events uses 303 GRBs (triggered and non-triggered), selected from the total sample of 736 BATSE GRBs

recorded in 1998-200. The search for events selected according to criteria A and B was done for the time intervals T_{GRB} (see section III). For a detailed background estimation, we used a time interval ± 1000 sec with respect to the start time of the GRB (excluding the T_{GRB} window) and an angle between GRB and up-going muon $\Psi \leq 10^\circ$.

No events were found according to criterion A and one event for criterion B. Table II shows the number of signal and background events, the event upper limit μ_{90} that was obtained in accordance with [9], the number of GRB corrected for coefficient β (the probability to detect events associated with gamma-ray burst in the given angle interval Ψ , given the location error of the GRB), and the 90% C.L. upper limit on the number of events per GRB $N_{90} = \mu_{90} / (N_{GRB} \times \beta)$. Data are presented for all GRB (triggered and non-triggered), as well as separately for triggered GRB selected according to Cut-B.

TABLE II
RESULTS OF GRB ANALYSIS

Selection	Signal	Backgr	μ_{90}	$N_{GRB} \times \beta$	N_{90}
Cut-A, all	0	0.56	1.9	236	0.0085
Cut-B, all	1	2.7	2.1	199	0.010
Cut-B, trig	1	1.6	2.8	120	0.023

No excess of events associated with a GRB was observed. The limit on the neutrino flux associated with gamma-ray bursts was obtained using the approach from [11]. According to this approach, the limit $F(E_\nu)$ is presented as a function of neutrino energy, the "Green's function"

$$F(E_\nu) = N_{90}/S_{eff}(E_\nu), \quad (1)$$

$S_{eff}(E_\nu)$ is the detector effective area, N_{90} the 90% C.L. upper limit on number of events per GRB. The main advantage of this approach is that its result does not depend on assumptions about the neutrino energy spectrum.

Figure 2 shows the 90% C.L. upper limits of the GRB neutrino fluence Green's function $F(E_\nu)$ for NT200 (for Cut-B, all), Super-Kamiokande [11] and AMANDA [12]. The Super-Kamiokande and NT200 limits are mainly for GRB from the southern sky, while the AMANDA limit is for the northern sky.

Since predictions for the energy spectrum of neutrinos from GRB differ from model to model, we prefer to present our basic experimental result as a Green's function $F(E_\nu)$, which allows to calculate limits for any neutrino energy spectrum. In addition, we translate our result to a benchmark spectrum. We have chosen that of E.Waxman and J.Bahcall [14], and E.Waxman [15], [16]. Following these works, the muon neutrino differential

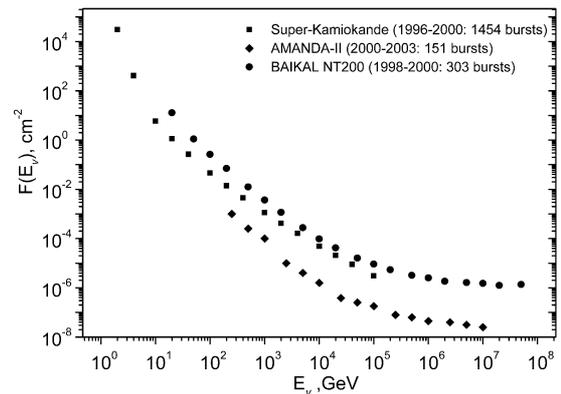


Fig. 2. 90% C.L. upper limits on the GRB neutrino fluence Green's function $F(E_\nu)$ for NT200, Super-Kamiokande and AMANDA.

flux $\Phi_{W-B}(E_\nu)$ in the energy range up to 10 PeV is

$$E_\nu^2 \Phi_\nu^{W-B}(E_\nu) = A^{W-B} \times \min(1, E_\nu/E_{\nu b}), \quad (2)$$

$E_{\nu b} = 100$ TeV, $A^{W-B} \approx 8 \times 10^{-9} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$.

The Model Rejection Factor MRF for the Waxman-Bahcall spectrum was calculated as

$$MRF = N_{90}/N_{ex}, \quad (3)$$

where N_{90} is the upper limit on the number of events per GRB and N_{ex} the expected number of events, calculated for the given spectrum as

$$N_{ex} = \int \Phi_\nu^{E_{arth}}(E_\nu) \times S_{eff}(E_\nu) \times (4\pi/n) dE_\nu. \quad (4)$$

Here, $n \approx 2.2 \times 10^{-5} \text{ s}^{-1}$ is the average GRB rate in $4\pi \text{ sr}$ (~ 700 events within the detection range of BATSE per year) and $\Phi_\nu^{E_{arth}}(E_\nu) = 0.5 \times \Phi_\nu^{W-B}(E_\nu)$ the neutrino flux at the Earth.

Taking into account that the estimation of the expected event number in the given approach is made for the BATSE burst detection rate, the MRF was calculated only for triggered GRB ($N_{GRB} \times \beta = 120$, see Table II). From that Green's function (approximately twice that of the (CUT-B, all) sample, see Fig.2), the resulting MRF value is 2.8×10^2 , and the corresponding GRB neutrino flux limit is

$$E_\nu^2 \Phi_\nu \leq 1.1 \times 10^{-6} \text{ GeV cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1} \quad (5)$$

This diffuse limit is considerably weaker than that of the AMANDA muon analysis [12], and two times higher than their cascade analysis [13]. In view of a search for bright individual GRBs, our result may be considered as complementary to AMANDA, since variations in absolute energy output, Lorentz factor and distance may lead to a GRB neutrino detection with a less sensitive detector, while that source was outside the other detectors field of view. NT200+ is presently complementing the ANTARES detector, in particular for those cases where the GRB is above horizon with respect to this instrument.

We also note that, normalized to a single GRB, NT200 exceeds the sensitivity of Super-Kamiokande by a factor of 2 for neutrino energy above 1 TeV.

V. CONCLUSION

We have presented results of a search for neutrino induced muons detected with the Baikal Telescope NT200 in coincidence with 303 gamma-ray bursts recorded from 1998 to 2000 by BATSE. NT200's field of view covers most part of the Southern hemisphere. No evidence for neutrino-induced muons from gamma-ray bursts is found. The resulting Green's Function fluence limit for this search extends that of Super-Kamiokande by two orders of magnitude in energy. Assuming a Waxman-Bahcall spectrum, a neutrino flux upper limit of $E_\nu^2 \Phi_\nu \leq 1.1 \times 10^{-6} \text{GeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ is obtained.

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