Search for Neutrinos from Gamma-Ray Bursts Using Super-Kamiokande

Dusan Turcan[1]
for the Super-Kamiokande Collaboration
(1) Physics Department, University of Maryland, College Park, MD, USA

Abstract

Using the Super-Kamiokande detector, a search was conducted for neutrinos produced in coincidence with gamma-ray bursts observed by the BATSE detector. Super-Kamiokande data in the neutrino energy range of 7 MeV∼100 TeV were analyzed. For gamma-ray bursts that occurred between April 1996 and May 2000, no statistically significant correlated neutrino signal was detected. Implied upper limits on associated GRB neutrino production are presented and compared with similar limits obtained from other experiments.

1. Introduction

Theoretical models of gamma-ray bursts (GRBs) predict that a considerable portion of their total energy may be carried away by neutrinos created during the burst. Therefore, we performed a time and direction correlation analysis between GRBs and Super-Kamiokande (SK) events from the neutrino data samples used in the solar neutrino, atmospheric neutrino, and "upward-going" muon analyses (the full paper of this analysis can be found in [1]). SK is a 22.5 kton fiducial volume water Cherenkov neutrino detector located in the Kamioka Mine in Gifu, Japan. It is sensitive to neutrinos in the energy range: 7 MeV∼100 TeV. Because of the lack of specificity in models, the present analysis is spectrum-independent and was done for all neutrino energies to which SK is sensitive.

2. Data Sets

SK's low energy (LE) neutrino data sample (E_ν=7∼80 MeV) consists of recoil electron events from ν - e elastic scattering of solar neutrinos, as well as background events due to radioactivity and interactions and decays of cosmic-ray muons [2]. The high energy (HE) data sample (E_ν=200 MeV∼200 GeV) contains fully-contained and partially-contained electron and muon events from neutrino-nucleon interactions of atmospheric neutrinos [3]. The upward-going muon (upmu) sample yields the highest energy events at SK (E_ν=2 GeV∼100 TeV),

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consisting of upward-going muons created by neutrino interactions in the rock beneath the detector [4].

The list of GRBs selected for the analysis was obtained from the BATSE online catalog [5] and the non-triggered supplement to the BATSE catalog [6]. BATSE (Burst And Transient Source Experiment) was a high energy astrophysics experiment in Earth orbit on NASA's Compton Gamma-Ray Observatory. From the official start of data taking at SK on 1 April 1996 (31 May 1996 for LE and HE) until the end of the BATSE mission in 2000 May, a total of 1454 GRBs (1371 for LE and HE) were selected for the analysis.

3. GRB-neutrino correlation analysis

In order to search for a possible GRB neutrino signal, we conducted a time correlation analysis of GRBs using SK's LE and HE events, and a direction-time correlation analysis using SK's upmu events. The goal of all three (LE, HE, and upmu) correlation analyses was to search for an excess in the number of events correlated with GRBs above expected background. The LE and HE mean background rates were assumed to be constant and were measured to be $(79.8 \pm 0.3) \times 10^{-5}\,\mathrm{s}^{-1}$ and $(9.9 \pm 0.1) \times 10^{-5}\,\mathrm{s}^{-1}$, respectively. The background for the upmu sample was calculated by a Monte-Carlo simulation for each GRB separately, because there is directional variation of the events.

In the LE and HE searches, time windows of $\pm 10\,\mathrm{s}$, $\pm 100\,\mathrm{s}$, and $\pm 1000\,\mathrm{s}$ were used with respect to the GRB time, while in the upmu search, a time window of $\pm 1000\,\mathrm{s}$ and a direction cut of $15°$ were used. The windows were chosen by considering BATSE T90 times and direction uncertainty, and assuming negligible neutrino flight time delay (due to mass). In addition to this initial search, we searched for directional correlation in the time-correlated LE and HE events, as well as clustering of the upward-going muons. We also scanned a $\pm 24\,\mathrm{hr}$ period around each GRB for possible non-coincident correlations. In all the searches, the distributions of the observed events were consistent with Poisson fluctuations of the background.

4. Upper Limits on Neutrino Fluence

In the absence of any clear neutrino signal from the GRBs, 90% C.L. GRB neutrino and antineutrino fluence upper limits were calculated. In principle, a fluence limit, $F[\mathrm{cm}^{-2}]$ is given by

$$F = \frac{N_{90}}{N_t \int \lambda(E_\nu)\sigma(E_\nu)\epsilon(E_\nu)dE_\nu} \,. \tag{1}$$

However, because there is no generally accepted GRB neutrino spectrum, $\lambda(E_\nu)$, it is impossible to directly calculate the neutrino fluence. Instead, we calculated a fluence limit "Green's function", $\Phi(E_\nu)$, by replacing $\lambda(E_\nu)$ by a delta function $\delta(E-E_\nu)$. In order to obtain the total integrated neutrino fluence limit, F, one needs to convolute $\Phi(E_\nu)$ with a particular $\lambda(E_\nu)$:

$$F = \left[\int \frac{\lambda(E_\nu)}{\Phi(E_\nu)} dE_\nu \right]^{-1} \quad . \tag{2}$$

The 90% C.L. upper limit on the number of SK events per GRB, N_{90}, was obtained by assuming a Poisson process with background [7]. The detection cross section, $\sigma(E_\nu)$, for E_ν<100 MeV comes predominantly from $\nu\ e^- \rightarrow \nu\ e^-$ and $\bar{\nu}_e\ p \rightarrow n\ e^+$; for E_ν>100 MeV, neutrinos are detected by $\nu\ N \rightarrow l\ N'$ and deep inelastic scattering (π production). The efficiency, $\epsilon(E_\nu)$, of SK at each neutrino energy was calculated by generating MC interactions of mono-energetic neutrinos and simulating the detector response to the resulting interaction products.

Figure 1 shows the fluence limit "Green's function", $\Phi(E_\nu)$, for ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$ obtained from SK's LE, HE, and upmu data samples. In each calculation we assume that all GRB neutrinos are emitted with the same flavor.

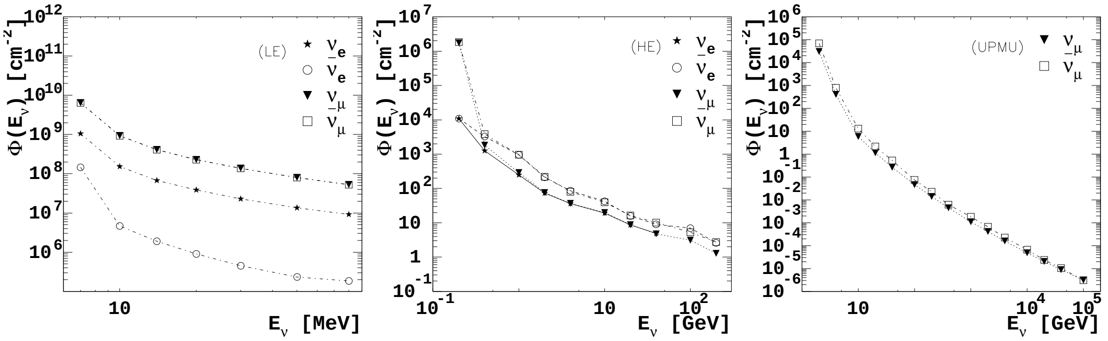

Fig. 1. The "Green's function", $\Phi(E_\nu)$, of the 90% C.L. upper limits on GRB neutrino and antineutrino fluence per GRB.

In order to demonstrate SK's sensitivity to GRB neutrinos, we assumed an E^{-2} neutrino spectrum to calculate the 90% C.L. upper limit on ν_e, $\bar{\nu}_e$, ν_μ, and $\bar{\nu}_\mu$ total fluence. For comparison, we also calculated a rough estimate of the expected neutrino fluence, F, from a cosmological GRB. In the calculation we assumed an E^{-2} neutrino spectrum, a distance to the GRB of z=1 ($\mathrm{D_L} \approx 6.6\,\mathrm{Gpc}$), the total neutrino energy of 10^{53} erg [8] emitted isotropically, the fact that all GRB neutrinos are emitted with the same flavor, and that the energy range of emitted neutrinos coincides with the energy range of each data sample. Table 1 shows this total fluence calculated for neutrinos produced in SK's three neutrino energy ranges. These rough fluence estimates are a factor of $\sim 10^6$, 10^4, and 30 lower than SK's best upper limit in the three energy ranges, respectively.

Comparing SK's fluence limits to previously published GRB neutrino fluence upper limits from the IMB detector [9], we find that our limits are better

Table 1. GRB neutrino total fluence upper limits (90% C.L.) for a E^{-2} spectrum.

E_ν range	F_{ν_e}[cm^{-2}]	$F_{\bar{\nu}_e}$[cm^{-2}]	F_{ν_μ}[cm^{-2}]	$F_{\bar{\nu}_\mu}$[cm^{-2}]	Prediction
7MeV...80MeV	4.44×10^7	9.52×10^5	2.65×10^8	2.65×10^8	1.4
0.2GeV...200GeV	1.66×10^2	2.97×10^2	1.39×10^2	3.00×10^2	1.7×10^{-2}
2GeV...100TeV	...	...	3.83×10^{-2}	4.96×10^{-2}	1.1×10^{-3}

roughly by a factor of 10^2 for $E_\nu \geq 1$ GeV. SK's fluence limit on upward-going muons per average burst (0.31×10^{-9} cm^{-2}) is comparable to a similar limit by the MACRO detector [10]. SK's neutrino fluence limits are consistent with the recent predictions for SK of a fireball model with a collapsar progenitor [11]. SK's GRB neutrino fluence limits at energies below 100 MeV are currently the only such limits in the world.

5. Conclusion

A time and direction correlation analysis of SK events with BATSE GRBs was performed for SK's solar neutrino, atmospheric neutrino, and upward-going muon data samples. No signal in excess of the expected background fluctuations was found. A 90% C.L. fluence upper limits on neutrino and antineutrino emission from an average GRB were calculated at various discrete neutrino energies to which SK is sensitive. We also calculated the total GRB neutrino fluence upper limits for an E^{-2} spectrum in SK's three energy ranges. We found that our limits are *at least* a factor of 30 higher than our rough estimate of GRB neutrino emission, and are consistent with most model predictions. SK's limits are the most stringent fluence upper limits for GRB neutrinos at energies 7 MeV∼100 TeV.

6. References

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