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A Search for Neutrinos Accompanied with Gamma-Ray Bursts

by

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Abstract

Time correlation between low energy neutrino events observed in Kamiokande and gamma-ray bursts detected by BATSE is analyzed. No significant excess of neutrino events correlated with gamma-ray bursts is found for the neutrino energy range from 7 MeV to 20 MeV. From the number of neutrino events during twelve minutes time window between two minutes before and ten minutes after the start of the gamma-ray burst, we calculate the upper limit of the flux of anti electron neutrinos. Assuming the average energy of neutrinos are 7 MeV, 10 MeV and 20 MeV, obtained 90% C. L. upper limits are $5.2\times10^5\,cm^{-2}\,sec^{-1}$, $2.6\times10^5\,cm^{-2}\,sec^{-1}$ and $6.4\times10^4\,cm^{-2}\,sec^{-1}$, respectively. Flux upper limits per gamma-ray burst with 90% C. L. are also obtained, which are $3.6\times10^8\,cm^{-2}\,burst^{-1}$, $1.8\times10^8\,cm^{-2}\,burst^{-1}$, $4.4\times10^7\,cm^{-2}\,burst^{-1}$ for 7 MeV, 10 MeV and 20 MeV, respectively.

1. Introduction

Since the discovery of gamma-ray burst in 1973 [1], the origin of the phenomena has been remained mysterious puzzle for a long time. However from the early 1990's, the big progress in understanding of gamma ray bursts has been undergone. The first, BATSE (Burst and Transient Source Experiment), one of the onboard detector to the Compton Gamma-Ray Observatory launched in 1991, discovered that gamma-ray bursts are distributed isotropically over the sky [2]. The result rules out the neutron star model which favour the distribution along the Galactic disk, and strongly supports the cosmological model [3]. Second, in 1997

BeppoSAX discovered X-ray afterglow of gamma-ray burst [4], which supports the fireball model. Since then more than ten counterparts are found by optical [5] [6], radio [7] and X-ray wave lengths, and several of them are measured cosmological red shift [8]. These results strongly favour the cosmological fireball model [9] [10] [11] [12]. However there are still many unsolved problems both in observational and in theoretical.

In the gamma-ray burst fireball model, the high energy photons are emitted by the dissipation of the kinetic energy of a relativistic expanding fireball. Recent observations show the gamma-rays are produced by synchrotron emission of high energy electrons, and in such a region proton is also expected to be accelerated. Then we expect fireball energy is converted to neutrinos via mesons. For high energy neutrinos, such as 10^{14}eV, some authors calculate the estimated flux of neutrinos (for example see [13]), which suggest the flux is comparable to the flux of atmospheric neutrinos. For low energy neutrinos ($\sim 5-10$ MeV), there is a calculation for binary neutron star mergers [14], which predicts the flux to be similar to a supernova neutrino signal. It's too small to detect by the present detectors, if the gamma-ray bursts are the cosmological phenomena. The searches for neutrinos or neutrino-produced muons have been performed at several places [15] [16] [17], but none of those experiments have detected such neutrinos or muons. However it is significant to study the correlation between neutrinos and gamma-ray bursts observationaly with higher sensitivity. In Kamiokande III, for low enegy neutrino, the correlation search was tried once [18]. In this article, we update both the gamma-ray burst data and neutrino data and show the results of searching for the low enegy neutrino events observed in Kamiokande acompanied with gamma-ray bursts observed by BATSE.

2. Kamiokande III detector

Kamiokande III detector is a large ring image water Cherenkov detector filled with 3,000 tons of pure water and is located in Kamioka mine, Kamioka-cho, Gifu, Japan. The detector is a cylindrical steel tank of 16 m in hight and 15.6 m in diameter, and has a rock overburden of about 1,000 m (2,700 m. w. e.) in vertical. 2,400 tons of the detector is defined as the inner detector and is viewed by 948 PMT's covering 20% of the surface. 4π anticounter layer, viewed by 124 PMT's, surrouds the inner detector. Inner and outer layers are optically separated by black plastic sheets. The type of PMT which we use is R1449 provided by Hamamatsu Photonics, whose diameter is 20″.

For the energy range below 50 MeV, the elementary neutrino interaction in water are :

$$\bar{\nu}_e p \rightarrow e^{+} n \quad (1)$$

$$\nu e^{-} \rightarrow \nu e^{-} \quad (2)$$

$$\bar{\nu} e^{-} \rightarrow \bar{\nu} e^{-}. \quad (3)$$

To detect the low energy neutrinos of astrophysical origin, these electron or positron is measured. The advantages of this detection techniques are real time observation, strong directionality of the recoil electron or positron for reaction (2) and (3) and an ability to obtain the energy spectrum.

3. Data reduction and analysis

The gamma-ray burst data which we used is BATSE data observed from April 1991 to March 1993 [19]. Their energy range is between ~ 1 keV and ~ 100 MeV. The peak flux of gamma-ray bursts distributes the range from 10^{-8} to 10^{-2} erg cm^{-2} sec^{-1} and the duration ranges from 10^{-2} to 10^{2} sec or longer. 486 gamma-ray bursts which occur during the stable operation of Kamiokande III are selected and used in this analysis.

The low energy neutrino data which we used here is the final sample of Kamiokande III for the solar neutrino analysis. The energy range of them is between 7 MeV and 20 MeV.

We define the on-source A data, on-source B data and off-source data. on-source A data means the neutrino data getting during the time window between two minutes before and ten minutes after the starting time of gamma-ray burst. On-source B data is those obtained during the time window which is the time t_{90}, occupied from 5% to 95% of integral energy flux, plus before and after 10 seconds each of t_{90}. Off-source data means the summation of data during six 10 minutes windows whose time center is placed 125 minutes, 65 minutes and 35 minutes before, and 35 minutes, 65 minutes and 125 minutes after the starting time of gamma-ray bursts, respectively. Amount of time windows for on-source A, on-source B and off-source are 3.36×10^{5} sec, 1.15×10^{4} sec and 1.68×10^{6} sec, respectively

For 486 gamma-ray bursts, the number of neutrino events of on-source A data and on-source B data are summed up respectively, and are compared statistically to the expected background neutrino event rate which is obtained from off-source data.

4. Results and Discussion

During the periods which we analyzed the low energy event data, the off-source event rate is almost constant. So we regard its event rate as the background rate. From the number of low energy events observed off-source time, the background rate is calculated to be 7.55 $\times 10^{-5}$ events sec^{-1}.

The number of expected back ground events for on-source A and on-source B are 25.4 and 0.9 respectively. So the number of excess events are 2.6 for on-source A and 0.1 for on-source B. Comparing to the number of background events, these excess numbers are statistically insignificant. Estimated 90% confidence level (C. L.) upper limits are 12.0 and 1.7 for on-source A and on-source B respectively. These results are summarized in Table 1.

Table 1 Summary of the results of the statistical analysis

	on-source A	on-source B	off-source
# of neutrino events	28	1	127
periods (10^5sec)	3.36	0.115	16.8
event rates ($10^{-5}sec^{-1}$)	8.33	8.69	7.55
expected background	25.4	0.9	
# of excess events	< 12.0 (90%C. L.)	< 1.7 (90%C. L.)	

Now, assuming the reaction (1), the upper limit of neutrino flux acompanied with gamma-ray bursts is calculated. The total flux F [cm^{-2}] is written as

$$F = nS, \quad (4)$$

where n is the number of observed excess events. S is called sensitivity and is expressed as follows ;

$$S \equiv (\sigma N V \varepsilon)^{-1}, \quad (5)$$

where σ is the cross section of the reaction (1), N is the number density of the proton in the fiducial volume of water tank, V is the fiducial volume of water tank and ε is the neutrino detection efficiency. For convenience, the detection efficiency for ^8B solar neutrino is taken as the numerical value of ε, which is 0.099 [20]. Numerical values of the other parameters which we take here are $\sigma = 8.9\times10^{-42}(E_e/10\ \mathrm{MeV})^2\mathrm{cm}^2$, $N = 6.7\times10^{22}\ \mathrm{cm}^{-3}$ and $V = 2.14\times10^9\mathrm{cm}^3$. Being divided by the sum of the time windows, the time averaged flux is obtained from the total flux. The average time integrated flux for each gamma-ray bursts is also obtained by dividing the total flux by the number of gamma-ray bursts.

For simplicity, monochromatic energy of 7 MeV, 10 MeV and 20 MeV are assumed, and 90% C. L. upper limits of the flux are evaluated. The results are shown in Table 2. No significant excess of neutrino events is found for over all gamma-ray bursts.

Table 2 Summary of the estimated 90% C. L. upper limit of the neutrino flux for all gamma-ray burst

	energy [MeV]	on-source A	on-source B
time averaged flux ($\mathrm{cm}^{-2}\ \mathrm{sec}^{-1}$)	7	$< 5.2\times10^5$	$< 2.2\times10^6$
	10	$< 2.6\times10^5$	$< 1.1\times10^6$
	20	$< 6.4\times10^4$	$< 2.7\times10^5$
average flux per burst (cm^{-2})	7	$< 3.6\times10^8$	$< 5.1\times10^7$
	10	$< 1.8\times10^8$	$< 2.5\times10^7$
	20	$< 4.4\times10^7$	$< 6.2\times10^6$

Then we try to search excess events for on-source A by considering the characteristics of the gamma-ray bursts. As already mentioned, the duration time of gamma-ray burst distributes a wide range. However, the distribution has two peaks, one is around 0.4 sec and another is around 20 sec (Figure 1). No explanation has not been given to this observational fact. Here,

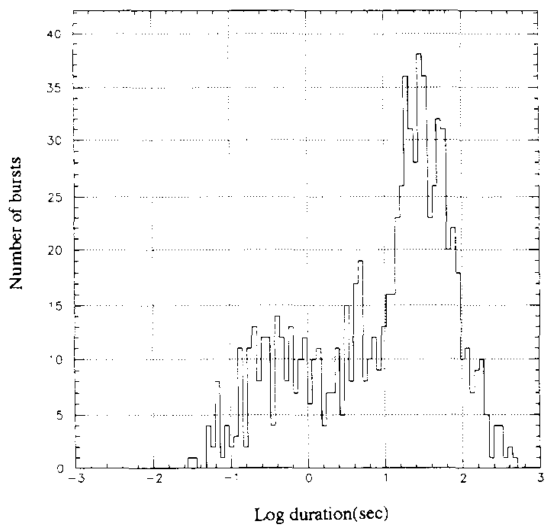

Fig. 1 Distribution of the duration of gamma-ray bursts.

we classify the gamma-ray bursts to three groups by their duration, whether it is shorter than 2 sec, between 2 sec and 120 sec, or longer than 120 sec. Table 3 shows the summary of the neutrino events classified by the duration of gamma-ray bursts for on-source A data. Again no significant excess is found for any classified data sets.

Table 3 Summary of the on-source A neutrino data classified by the duration of gamma-ray bursts

Duration (sec)	< 2 sec	2 sec < & < 120 sec	120 sec <
# of gamma-ray bursts	114	346	26
# of neutrino events	5	23	0
periods (10^4 sec)	7.78	23.9	1.87
expected background	5.9	18.1	1.4
upper limit (90%C. L.)	< 4.2	< 8.3	< 1.4

It is easy to suppose that the high fluence in high energy band may favour the neutrino events. So the gamma-ray bursts are classified by energy band and their fluence. For example, fifty two gamma-ray bursts with more than 10^{-5} erg cm^{-2} in the energy band higher than 300 keV are selected. The number of neutrino events detected within on-source A time window is four events. On the other hand, expected number of background events from the off-source data is 2.4 events. Then we can only obtain the 90% C. L. upper limit of neutrino events to be 4.9 and the corresponding flux upper limit is 9.4×10^5 cm^{-2} sec^{-1} for 10 MeV. The results are almost the same for any other energy bands and any other fluence regions and no significant excesses are found.

We have also tested the correlation for different neutrino energy range. The low energy data sample is divided into two groups, one of which is lower than 10 MeV and the other is higher than 10 MeV. There is no significant excess in both cases. In addition to those data sets, high energy neutrino data was also analyzed, whose energy range is above 30 MeV. Only two events are observed within on-source A time window, while the number of expected background is 0.6. Then, if the neutrino energy assumed to be 30 MeV, only upper limit with 90% C. L. is obtained to be 9.1×10^3 cm^{-2}.

Assuming the merge rate R of two neutron stars is 8×10^{-8} Mpc^{-3} yr^{-1} [21], we can estimate the neutrino flux accompanied with neutron merge using low energy neutrino production model [22]. The number of gamma-ray bursts observed for one year is assumed to be 300, and the distance to the merger which we can observe assumed to be about 1Gpc. Then the total flux N_ν (cm^{-2}) is estimated as follows :

$$N_\nu = \int_0^{1Gpc} R \frac{\left(\frac{E}{\langle E_\nu \rangle}\right)}{4\pi r^2} 4\pi r^2 dr \left(\frac{488 \text{ bursts}}{300 \text{ bursts yr}^{-1}}\right)$$

$$= 6.1\times10^4 \left(\frac{E}{10^{53}\text{ erg}}\right)\left(\frac{T_{eff}}{4\text{ MeV}}\right), \quad (6)$$

where E and $\langle E_\nu \rangle$ are the total and mean neutrino energy emitted from one merger respectively. As discussed above, only the upper limit of the neutrino events which are accompanied with gamma-ray bursts are obtained. From this result the upper limit to the total neutrino energy per one merger is derived to be

$$E < 2\times10^{59} \text{ erg (90\% C. L.)}. \quad (7)$$

Here we assume neutrino energy is 10 MeV and supernova like thermal neutrino emission with $T_{eff} = 4$ MeV occur.

Recently, the evidence of non-zero neutrino mass was reported [23], but we didn't consider the time delay. Assuming the square of the neutrino mass is the same order of $\Delta m^2(\sim3\times10^{-3})$, the neutrino energy is 10 MeV, and the source distance is $z=1$, the time lag between gamma-ray bursts and neutrino events are estimated to be 1.2×10^{-2} sec, which is negligibly small for the present analysis.

Now the Super Kamiokande detector is operating and its neutrino detection sensitivity is several tens times higher than that of Kamiokande III. So the new data is expected to be useful for this kind of analysis.

5. Summary

We statistically analize the low energy neutrino data observed in Kamiokande III in order to search for the correlation with 486 selected gamma-ray bursts observed by BATSE. There is no significant excess in any energy range, any duration range and any fluence range of gamma-ray bursts.

Assuming the monochromatic neutrino energy, 90% C. L. upper limits of neutrino flux within twelve minute time windows are obtained to be 5.2×10^5 cm^{-2} sec^{-1}, 2.6×10^5 cm^{-2} sec^{-1} and 6.4×10^4 cm^{-2} sec^{-1}, for 7 MeV, 10 MeV and 20 MeV, respectively.

Flux upper limits per gamma ray burst with 90% C. L. are also obtained, which are 3.6

$\times 10^8$ cm^{-2} burst^{-1}, 1.8×10^8 cm^{-2} burst^{-1}, 4.4×10^7 cm^{-2} burst^{-1} for 7 MeV, 10 MeV and 20 MeV, respectively.

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