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Search for Supernova Neutrino Bursts at Super-Kamiokande

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Abstract: The result of a search for neutrino bursts from supernova explosions using the Super-Kamiokande detector is reported. Super-Kamiokande is sensitive to core-collapse supernova explosions. The expected number of events comprising such a burst is $\sim 10^4$ and the average energy of the neutrinos is in few tens of MeV range in the case of a core-collapse supernova explosion at the typical distance in our galaxy (10 kiloparsecs). The detection efficiency anywhere within our galaxy and well past the Magellanic Clouds is obtained as 100%. We examined a data set which was taken from May, 1996 to July, 2001 and from December, 2002 to October, 2005 corresponding to 2589.2 live days. However, there is no evidence of such a supernova explosion during the data-taking period. The 90% C.L. upper limit on the rate of core-collapse supernova explosions out to distances of 100 kiloparsecs is found to be 0.32 SN $\cdot$ year^{-1}.

Introduction

Super-Kamiokande (Super-K, SK) is an imaging water Cherenkov detector containing 50,000 tons of pure water, and located 1000 meters underground (2,700 meters of water equivalent). The detector consists of a main inner detector and an outer veto detector. The fiducial mass for neutrino measurements is 22.5 ktons with boundaries 2.0 m from the inner surface.

Super-K experiment consists of 2 phases by the end of 2005. The first period (SK-I) started on the 1st of April, 1996, and terminated on the 15th of July, 2001. A total of 11,146 photo multipliers (PMT's) with 20-inch diameter photocathodes provided active light collection over 40% of the entire surface of the inner detector. The second phase (SK-II) started on the 10th of December, 2002, and terminated on the 6th of October, 2005. A total of 5,182 20-inch PMT's, each protected by acrylic and fiber-reinforced plastic (FRP) cases, were mounted on the inner detector, providing 19% photocathode coverage during this period. In the outer detector, a total of 1,885 8-inch PMT's were installed during both periods.

Data analysis

Data set

We use data taken from the 31st of May, 1996, to the 15th of July, 2001, and from the 24th of December, 2002, to the 5th of October, 2005.The livetimes of our detector for supernova searches were 1703.9 days for SK-I, and 885.3 days for SK-II. Livetime efficiency over the course of the entire data-taking period the average efficiency was about 89%.

Vertex and energy reconstruction techniques are the same as those used in our solar neutrino analysis [1]. Fiducial volume for the supernova search is also 22.5 ktons, though the energy thresholds are 6.5 MeV (SK-I) and 7.0 MeV (SK-II) to avoid the higher background rates associated with the lower thresholds used in the solar neutrino analysis. After the noise reductions which are basically the same as in the Ref [1], the remaining event rates are 180 events/day for SK-I, and 164 events/day for SK-II.

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Analysis method

In this section, we introduce our general method of supernova burst search. The procedure of data analysis is as follows: We scan event times using a sliding time-window for the first step. We define a "cluster" if the number of events (the "multiplicity") within a time-window is greater or equal to a certain threshold. In the second step, each cluster found in the first step is checked to determine if it is a real signal from a supernova or the result of background events.

A background cluster consists of either time-correlated non-supernova events or a chance coincidence of uncorrelated low energy events. One of main sources which produce time-correlated clusters is flasher PMT's which act as sources of light, and another main source is spallation product. In both cases, the reconstructed vertices of the resulting events are spatially concentrated. On the other hand, actual supernova events should be generated uniformly in the detector. Therefore, to distinguish real signals from background clusters, clusters are checked by studying the correlation between the multiplicity and the events' spatial distribution (R_{mean}) where R_{mean} is defined by the averaged spatial distance between each event in a cluster.

We simulated supernova events for multiplicity 2, 3, 4, and 8, which are the multiplicity thresholds of various burst searches discussed in later sections of this paper. The threshold of R_{mean} for a cluster with multiplicity equal to 2 is set to 750 cm, and for clusters with multiplicity greater than 2 the threshold is set to 1,000 cm. The efficiencies for supernova events using these criteria are 94%, 96%, 99%, and 100%, respectively.

Distant supernova search

In this section, we search for neutrinos from supernovae in nearby galaxies. Since the expected total number of events at SK from a supernova in the Andromeda galaxy (~700kpc) is around two events and the duration of the neutrino burst is expected as 10 to 20 seconds, we set our criteria as $\geq$ 2 events / 20 seconds. We reduce backgrounds by setting a higher energy threshold because the average energy of the emitted positron from the interaction $\overline{\nu}_e \, p \rightarrow e^+ \, n$ is higher than that of most low energy background events. The threshold value is then obtained as 17 MeV with both background rate and detection efficiency considered, where the single event rate with this energy threshold is 0.762 event/day for SK-I, and 1.03 event/day for SK-II.

Figure 1 is a scatter plot of R_{mean} versus the multiplicity for each cluster which satisfies the criteria with an energy threshold of 17 MeV. Three candidate clusters exist that have R_{mean} more than 1000 cm, but the event times of those candidates actually coincide with times of mine blasting. Because of the physical vibration of PMT's due to blasting, huge electrical noise occurred, and those noises caused time-clustered a few hundreds events within a few seconds during or after blasting. It was also confirmed that these events including the candidate cluster events have a characteristic PMT hit pattern nearly in the same area of the inner detector, and hence they should be eliminated as potential supernova events. Therefore, no real supernova signal was observed during the data-taking periods.

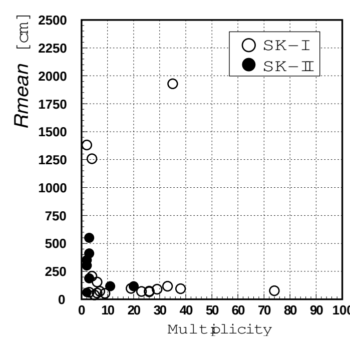

Figure 1: Correlation between the multiplicity and R_{mean} for obtained clusters from distant supernova search. There were 19 clusters observed in SK-I and 8 clusters in SK-II.

Supernova burst search with low energy threshold

In this section, we set various time-windows of 0.5, 2, and 10 seconds with a lower energy threshold of 6.5 MeV for SK-I and 7.0 MeV for SK-II to search for signals from a supernova in this lower energy region.

Since a lot of background events due to spallation or flasher PMT's still remain in the lower energy regions, we set criteria of higher multiplicity for each time-window as $\geq$ 3 events / 0.5 seconds, $\geq$ 4 events / 2.0 seconds, and $\geq$ 8 events/ 10 seconds. Figure 2 shows the correlation between R_{mean} and multiplicity for obtained clusters. As mentioned in the previous section, the only three candidate clusters which had large R_{mean} values in SK-I consist of the same events which were found during periods of mine blasting.

In conclusion, the remaining candidate clusters were all caused by mine blasting, and so there is no clear evidence for any supernova neutrino burst during the periods.

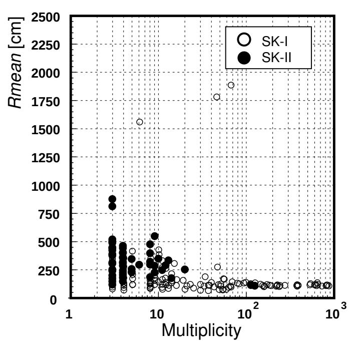

Figure 2: Correlation between the multiplicity and R_{mean} for obtained clusters from wide energy range burst search. There are 121 and 53 clusters observed in SK-I and SK-II respectively.

Neutronization burst search

We conducted another burst search with shorter time-windows to investigate the short-lived neutronization burst of ν_e events which occur prior to the core explosion, and many ν_e's are emitted via the reaction $e^- + p \rightarrow \nu_e + n$.

The duration of the neutronization burst is on the time scale of the shock wave propagation, which is less than 10 milliseconds. The expected number of neutronization burst neutrinos which will be observed at SK is between one and six (depending on neutrino oscillation models) in the case of a supernova at a distance of 10 kpc from the earth [3]. It might be possible to observe only the neutronization burst without the main burst, for example, if a black hole forms shortly after the neutronization stage, then the main burst of supernova neutrinos might not be able to escape from the black hole [4].

Based on the theoretical expectations, we set time-windows of 1, 10, and 100 milliseconds. The multiplicity threshold is two events for each time window. Because recoil electrons will have lower energies from neutrino–electron scattering which is the dominant interaction in this case, we use the same sample as the SK-I solar neutrino analysis [1], whose energy threshold is 5 MeV and livetime is 1496 days, and we use the same sample as in previous sections for SK-II.

Since the threshold of multiplicity for a candidate cluster is two events, there would be a lot of chance coincidences. To reduce the backgrounds, the directional information can be used because the recoil electrons have almost the same direction as the incident neutrinos. To check the isotropy of events in a candidate cluster, a new variable is defined as follows:

$$Sumdir = \frac{\left|\sum_{i=1}^{M} \vec{dir_i}\right|}{M} \quad . \qquad (1)$$

where $\vec{dir_i}$ is a reconstructed direction vector of events in a cluster, and M is the multiplicity of the cluster . By this definition, $Sumdir$ will be close to 1 in the case of a real supernova cluster. From Monte Carlo simulation, we set the threshold of $Sumdir$ for a supernova candidate cluster to 0.75 as this is the point at which the signal-to-noise ratio exceeds unity; the efficiency for the signal is estimated to be 84%.

Table 1 shows the number of observed candidates after R_{mean} and $Sumdir$ cuts. There is good agreement between the number of observed clusters and the number of expected backgrounds. Because the main backgrounds after R_{mean} cut are chance coincidences, the number of expected background can be obtained by the single event rate from Poisson-based estimation.

Since there were no candidates with stricter criteria: $\geq$ 3 events / 1 msec, $\geq$ 3 events / 10 msec, or $\geq$ 3 events / 100 msec, also in agreement with the expected background as shown in Table 1, we

Table 1: Number of candidates and expected BG in neutronization burst search

	SK-I		SK-II	
Criterion	Candidate	BG	Candidate	BG
$\geq$ 2events/1msec	1	2.10	0	0.125
$\geq$ 2events/10msec	19	19.1	0	1.25
$\geq$ 2events/100msec	194	191	10	12.5
$\geq$ 3events/1msec	0	9.90×10^{-6}	0	1.65×10^{-7}
$\geq$ 3events/10msec	0	9.78×10^{-4}	0	1.65×10^{-5}
$\geq$ 3events/100msec	0	9.78×10^{-2}	0	1.65×10^{-3}

conclude that no signal from a real neutronization burst was observed during this period.

Discussion and conclusions

We have searched the SK-I and SK-II data for neutrino burst signals from supernova explosions. We conclude that no real signals of supernova bursts occurred during the data taking periods between 31st of May, 1996 and 5th of October, 2005, which corresponds to a total livetime of 2589.2 days

In order to estimate detection probability of a supernova as a function of distance from the earth, we simulate neutrino events in the SK tank. The incident neutrinos are assumed to be emitted by a supernova of the model used by the Livermore group [2]. The detection probability of a supernova at a certain distance is determined as a probability in which one simulated neutrino burst satisfies each criterion given in previous sections after basic data reduction.

As shown in Figure 3, full(100%) detection probability is maintained out to around 100 kpc. Therefore, the upper limit at 90% C.L. for the supernova explosion rate out to 100 kpc — within which our Galaxy, the LMC, and the SMC may be found — is determined to be 0.32 per year by combining the results from SK-I and SK-II. Furthermore, the probability of the distant supernova search is still 0.075 at 700 kpc — a distance to Andromeda galaxy, which demonstrates the benefit of conducting a long time-window search in addition to the usual burst search.

We have also performed, for the first time, a systematic search for neutrinos from neutronization bursts. However there was no such signal observed in the data set with a total livetime of 2,381.3 days.

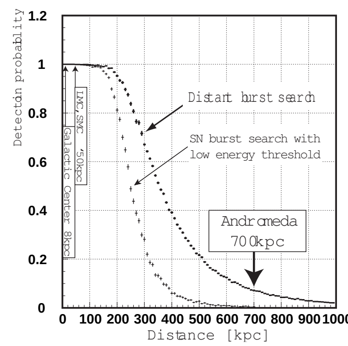

Figure 3: The probability of detecting supernovae assuming a specific supernova model at SK.

References

[1] Hosaka, J. *et al.*, 2006, Phys. Rev. D **73**, 112001

[3] Takahashi, K. *et al.*, 2001, Phys. Rev. D **64**, 93004.

[4] Sumiyoshi, K. *et al.*, 2006, Phys. Rev. Lett. **97**, 91101.

[2] Totani, T. *et al.*, 1998, Phys. Rev. Lett. **80**, 2039.