Supernova Detection

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Abstract. The detection of supernova neutrinos is reviewed, focusing on the current status of experiments to detect supernova burst neutrinos and supernova relic neutrinos. The capabilities of each detector currently operating and in development are assessed and the likely neutrino yield for a future supernova is estimated. It is expected that much more information will be obtained if a supernova burst were to occur in our Galaxy than was obtained for supernova SN1987A. The detection of supernova relic neutrinos is considered and it is concluded that a large volume detector with a neutron tagging technique is necessary.

1. Introduction

It had been presumed that a type-II supernova is a process of core collapse of a massive star followed by the formation of a neutron star or a black hole. It was predicted that almost 99% of the energy of the explosion is transported by neutrinos. On February 23, 1987, the Kamiokande[1], the IMB[2] and the Baksan[3] detectors recorded a pulse of neutrinos emitted by the supernova SN1987A, confirming the presumed scenario. The number of events observed in each experiment was 11, 8 and 5 in Kamiokande, IMB and Baksan, respectively. Although the observed number of events was small, it was possible to estimate the binding energy of the neutron star and the temperature of the neutrino sphere. The binding energy obtained from the Kamiokande and IMB data, assuming equipartition (i.e. the energy released by each neutrino species is the same and the total energy is six times the energy released by $\bar{\nu_e}$), was $\sim 3\times10^{53}$ erg, which is consistent with the standard scenario of a core collapse supernova. The $\bar{\nu_e}$ temperature obtained from the Kamiokande and IMB data was 3.5 ± 0.5 MeV[4]. This is somewhat smaller than that obtained by simulations of a supernova burst.

In order to further investigate the details of the supernova burst mechanism, it will be necessary to observe the next supernova. The distance to SN1987A is 50 kpc and hence if the next supernova occurs in our Galaxy, many more events are expected even at several hundred ton detectors.

Figure 1 shows the history of supernova detectors in the world since 1980 sensitive to supernovae of at least a distance of 10 kpc. The Baksan detector is the longest running detector, commissioned in 1980 with about 90% live time[5]. It consists of 3150 liquid scintillation counters with a total target mass of 330 tons. About 100 $\bar{\nu_e}p \rightarrow e^+n$ events are expected for a supernova at 10 kpc. As seen in the figure, detectors have been searching for a Galactic supernova for about 30 years. However, none have yet been observed. In the next section, the current supernova detectors are reviewed.

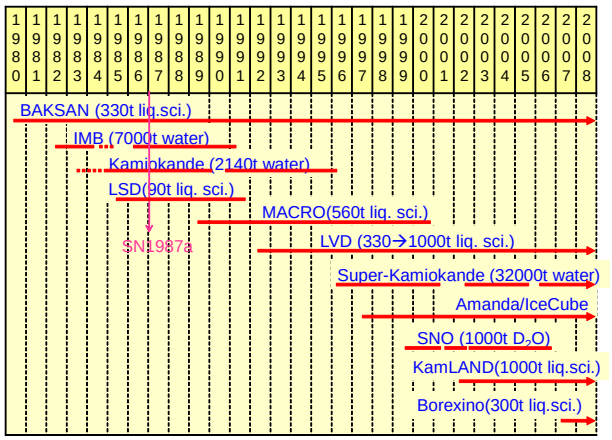

Figure 1. History of supernova detectors since 1980.

2. Current detectors

At the Kamioka observatory in Japan, the Super-Kamiokande (SK) and KamLAND experiments are running. The LVD and Borexino detectors are running at Gran Sasso in Italy, and the Baksan detector at the Baksan observatory in Russia. At the SNO laboratory, the construction of the SNO+ detector has begun, and the HALO detector using a lead and ^{3}He counter has been proposed. At the South Pole, the IceCube detector is running. In this section, the expected data from a Galactic supernova for each of these detectors are discussed.

Before discussing the expected data, it is important to remark on the distance to a supernova. Since the expected number of events follows $1/R^2$ (R is the distance to the supernova), the number of events critically depends on the distance. The average distance to supernovae is 10.7 kpc and the r.m.s. is 4.9 kpc[6]. 7% of supernovae occur within 3.16 kpc, and for this case the expected number of events is more than ten times larger than at 10 kpc. 16% of supernovae are within 5 kpc with four times the number of events. For 3% of cases, a supernova is more than 20 kpc away and the expected number of events is less than a quarter of that at 10 kpc. If a detector is sensitive up to 20 kpc, it covers more than 97% of supernovae in our Galaxy. In the following, the sensitivity of detectors is discussed assuming a typical distance of 10 kpc. However, it is possible that we may observe many more events from the next supernova than expected for a 10 kpc supernova. The supernova model used in the following estimations is the Livermore simulation[7], except when explicitly stated.

The SK detector is a 32,000-ton water Cherenkov detector. The SK detector is able to detect about 7300 $\bar{\nu_e}p \to e^+n$ events,$\sim$300 $\nu + e \to \nu + e$ scattering events, $\sim$360 ^{16}O neutral current gamma events and $\sim$100 ^{16}O charged current events for a 10-kpc supernova[9]. $\nu + e \to \nu + e$ scattering events show the direction of the supernova with an accuracy of about 5°. The large statistics of $\bar{\nu_e}p \to e^+n$ events allows precise energy spectrum measurement and enables us to discuss models of supernova simulation. Figure 2 shows the expected event rate and mean $\bar{\nu_e}$ energy for various models[8]. The error bars in the figure are for the case of a 10-kpc supernova. Hence, even a single supernova at a distance of 10 kpc is statistically sufficient to discriminate these models.

The LVD detector is a segmented liquid scintillator type detector with 840 counters and a total target mass of 1000 tons. It can detect about $\sim$300 $\bar{\nu_e}p \to e^+n$ events for a 10-kpc supernova[10]. The energy threshold of the counter is 4 MeV and it can tag neutrons with an efficiency of 50$\pm$10%. Figure 3 shows the online trigger efficiency as a function of distance to a supernova for a stand-alone mode ($<$ 1 fake events per 100 years). The efficiency is more than

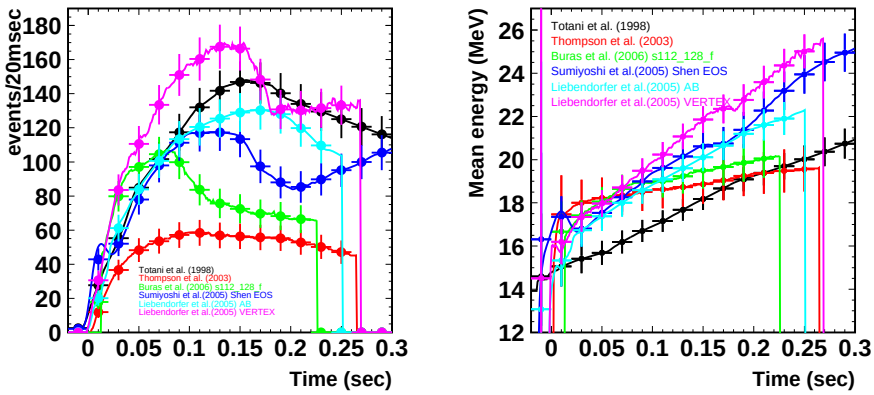

Figure 2. Comparison of supernova models for event rate and mean $\bar{\nu}_e$ energy expected at Super Kamiokande for a 10-kpc supernova. Models from Ref. [8].

90% for a distance of less than 40 kpc.

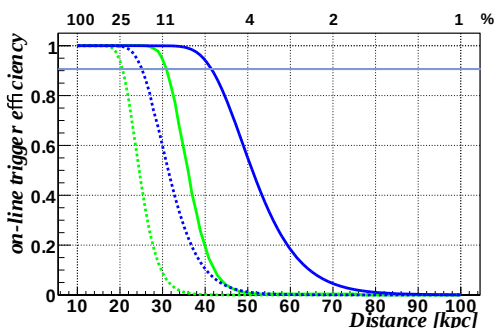

Figure 3. On-line trigger efficiency of an LVD detector as a function of distance (lower scale) and percentage of SN1987A signal at 10 kpc (upper scale) for an analysis threshold energy of 7 MeV (light green) and 10 MeV (blue) for an active total mass of 330 tons (dotted) and 1000 tons (solid).

KamLAND[11], Borexino[12] and SNO+[13] are single volume liquid scintillation detectors with 1000-ton, 300-ton and 1000-ton detection volumes, respectively, and are able to detect various interaction channels. The expected number of events for a 10-kpc supernova per 1000-ton target mass is ~300 $\bar{\nu}_e p \to e^+ n$, several tens of CC and NC events on ^{12}C and ~300 $\nu p \to \nu p$ NC events. The neutral current interaction $\nu p \to \nu p$ gives the original temperature of the ν_X (X=$\nu_\mu, \bar{\nu}_\mu, \nu_\tau, \bar{\nu}_\tau$) [14]. Figure 4 shows the expected visible energy spectrum of $\nu p \to \nu p$(left) and demonstrates how well the temperature and total energy can be retrieved from the measured energy spectrum. Since $\nu p \to \nu p$ is a neutral current interaction, the expected energy spectrum does not depend on neutrino oscillations. Hence, it is possible to measure the ν_X spectrum originating at a supernova explosion.

The IceCube detector has a giga-ton target volume and photo-sensors deployed three dimensionally in the target volume. Currently, 40 strings of optical modules (out of a total of 75 strings) are deployed, and is planned to be completed by 2011. The IceCube detector cannot detect each neutrino event individually, but a burst can be observed as a coherent increase of PMT dark noise[15]. Figure 5 shows a simulation of a supernova burst signal at 10-kpc distance. IceCube can measure the time variation of the energy release quite precisely

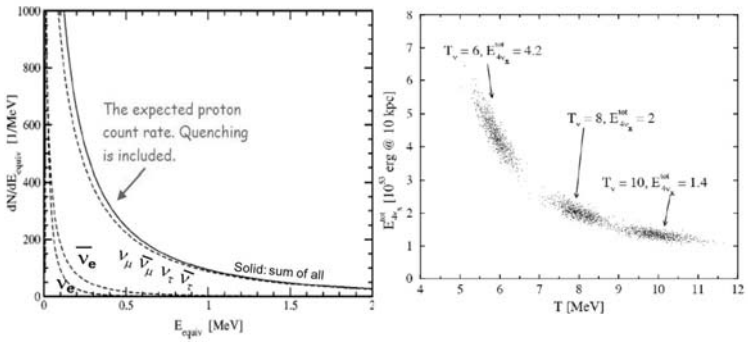

Figure 4. (Left) Expected visible energy spectrum of $\nu p \rightarrow \nu p$. (Right) Simulation of reconstructed temperature and total energy from simulated data. The data points are simulations assuming the input parameters as indicated in the labels with arrows. Figures are taken from Ref. [14].

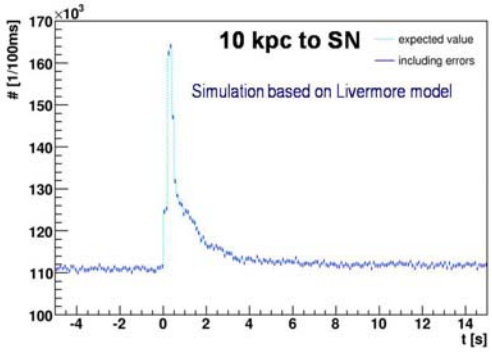

Figure 5. Simulation of a supernova burst signal at the IceCube detector for a 10-kpc distant supernova.

with ~0.75% statistical error at the peak time of the explosion (binned with 100 msec). Even for a supernova in the Large Magellanic Cloud (50 kpc away), the IceCube detector can achieve a 5σ level signal.

As described above, if a supernova burst occurs in our galaxy, we will be able to gather much more information than was possible for SN1987A. In order to initiate optical measurements as soon as neutrino signals are observed, prompt information from supernova detectors is necessary. The SNEWS system (Supernova Early Warning System) will support this communication[16].

3. Supernova relic neutrinos

As described in the previous section, the next supernova (hopefully in our Galaxy) will supply a large number of neutrino events. However, we will be able to detect at most only one or two supernova bursts in our lifetime. Supernovae have occurred since the beginning of the universe, and the neutrinos from all these supernovae exist as diffuse neutrinos in our universe, called supernova relic neutrinos (SRNs). Since the SRNs are accumulated neutrinos from the beginning of the universe, they could tell us much about the star formation history of the universe. Predicted spectra of SRN[17] are shown in Fig. 6.

Atmospheric neutrinos are the main source of the background above ~30 MeV. At lower

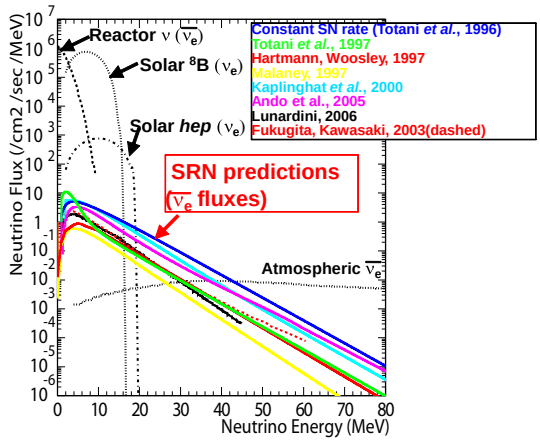

Figure 6. Expected energy spectra of supernova relic neutrinos. The spectra are taken from Ref. [17].

energies, solar neutrinos and reactor neutrinos are the main source of the background. A summary of experimental limits of SRN searches compiled by C. Lunardini[18] is shown in Fig. 7. The limits on the $\bar{\nu}_e$ flux were determined by SK and KamLAND, and the limits for ν_e were determined by SNO and SK (interpreted by Lunardini). Compared with a typical

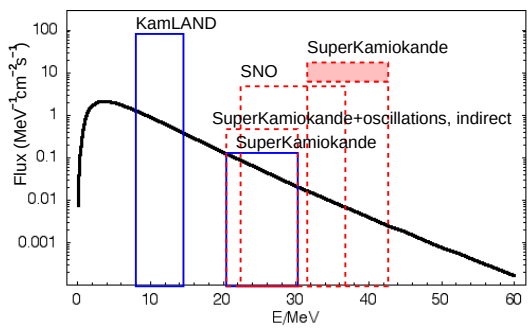

Figure 7. Summary of experimental limits of SRN searches compiled by C. Lunardini[18] The blue solid histograms are the limits on $\bar{\nu}_e$ and the red dotted histograms are ν_e limits.

predicted spectrum of SRN as shown in the figure, the most stringent limit is given by the SK direct search on $\bar{\nu}_e$. Its latest upper limit is < 1.08 /cm^2/sec (preliminary) using SK-I and SK-II data[19]. The SK limit is higher than the model predictions, but is within a factor of three of most of the predictions. So far, SK has been searching for "single" events, i.e. without tagging neutrons. The most significant background in a "single" search is atmospheric muon neutrinos, whose charged current interactions produce muons below the Cherenkov threshold and for which only decay electrons are observed (called the "invisible muon" background). It has been proposed to add about 0.2% of a gadolinium compound to the SK water and to tag neutrons by $Gd(n,\gamma)Gd$ interactions[20]. This neutron tagging technique has been studied at SK[21]. By tagging neutrons, the energy threshold of the SK SRN search can be lowered to $\sim$10 MeV. This is because the current background in the energy range 10–18 MeV, which is mainly due to spallation background, are "single" background events. The expected number of events in the SRN signal in 10 years of SK data is about 10–33 events for 10–30 MeV assuming

an SRN flux model from Ref. [17]. If the "invisible muon" background is reduced by a factor of five by neutron tagging, the total number of background events in the corresponding energy range is about 27. Therefore, it could be possible to detect finite SRN signals if the SK took measurements with gadolinium.

Another detector that could observe SRN is the proposed LENA experiment[22]. This proposed detector includes a several tens of kilotons liquid scinitillator, in which 2.2-MeV gamma signals from the $p(n,\gamma)d$ reaction give a tagging signal of neutrons.

4. Conclusions

The history and future prospects of supernova detectors are reviewed. If the next supernova occurs in our galaxy, we could expect to detect a large number of events and various types of interactions. From these we will gain important information for investigating the detailed mechanism of supernova explosions.

The flux upper limit of supernova relic neutrinos is approaching model predictions. Big detectors (> several tens of kilotons) with neutron tagging should be able to obtain a definite signal of supernova relic neutrinos.

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