COSMIC STAR FORMATION HISTORY AND THE FUTURE OBSERVATION OF SUPERNova RELIC NEUTRINOS

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ABSTRACT

We investigate the flux and event rate of supernova relic neutrinos (SRNs) and discuss their implications for the cosmic star formation rate. Since SRNs are diffuse neutrino background emitted from past core-collapse supernova explosions, they contain fruitful information on the supernova rate in the past and present universe, as well as on the supernova neutrino spectrum itself. As reference models, we adopt the supernova rate model based on recent observations and the supernova neutrino spectrum numerically calculated by several groups. In the detection energy range $E_\nu > 10$ MeV, which will possibly be a background-free region in the near future, the SNR event rate is found to be $1$–$2$ yr$^{-1}$ at a water Cerenkov detector with a fiducial volume of 22.5 kton, depending on the adopted neutrino spectrum. We also simulate the expected signal with one set of the reference models by using the Monte Carlo method and then analyze these pseudodata with several free parameters, obtaining the distribution of the best-fit values for them. In particular, we use a parameterization such that $R_{SN}(z) = R_{SN}^0 (1 + z)^\alpha$, where $R_{SN}(z)$ is the comoving supernova rate density at redshift $z$ and $R_{SN}^0$ and $\alpha$ are free parameters, assuming that the supernova neutrino spectrum and luminosity are well understood by way of a future Galactic supernova neutrino burst or the future development of numerical supernova simulations. The obtained 1 $\sigma$ errors for these two parameters are found to be $\delta \alpha / \alpha = 30\%$ (7.8%) and $\delta R_{SN}^0 / (R_{SN}^0) = 28\%$ (7.7%) for a detector with an effective volume of 22.5 kton $\times$ 5 yr (440 kton $\times$ 5 yr), where one of the parameters is fixed. On the other hand, if we fix neither of the values for these two parameters, the expected errors become rather large, $\delta \alpha / \alpha = 37\%$ and $\delta R_{SN}^0 / (R_{SN}^0) = 55\%$, even with an effective volume of 440 kton $\times$ 5 yr.

Subject headings: diffuse radiation — galaxies: evolution — neutrinos — supernovae: general

1. INTRODUCTION

In recent years we have made remarkable progress in our knowledge concerning how the cosmic star formation history proceeded in the past and concerning the fraction of baryons locked up in stars and gas in the local universe. These points were inferred from observations of the light emitted by stars of various masses at various wavelengths. Madau et al. (1996) investigated the galaxy luminosity density of rest-frame ultraviolet (UV) radiation up to $z \sim 4$, and they converted it into the cosmic star formation rate (SFR). The rest-frame UV light is considered to be a direct tracer of star formation because it is mainly radiated by short-lived massive stars. After the pioneering study by Madau et al., a wealth of data have become available in the form of the cosmic SFR in a wide range of redshifts; these data were inferred from observations using far-infrared (FIR)/submillimeter dust emission (Hughes et al. 1998; Flores et al. 1999) and near-infrared (NIR) H$\alpha$ line emission (Gallego et al. 1995; Gronwall 1998; Tresse & Maddox 1998; Glazebrook et al. 1999), as well as the rest-frame UV emission from massive stars (Lilly et al. 1996; Cowie et al. 1996; Connolly et al. 1997; Sawicki, Lin, & Yee 1997; Treyer et al. 1998; Madau, Pozzetti, & Dickinson 1998b; Pascale, Lanzetta, & Fernandez-Soto 1998; Steidel et al. 1999).

In these traditional methods, however, there are a fair number of ambiguities when the actual observables are converted into the cosmic SFR (Somerville, Primack, & Faber 2001). First, observable samples are generally flux-limited, and thus the intrinsic luminosity of the faintest objects in the sample changes with redshift. In order to understand the true redshift dependence of the total luminosity density, this incompleteness is generally corrected by using a functional form (i.e., a Schechter function) of the luminosity function obtained from the observations themselves. Unfortunately, since the luminosity function is not well established observationally (especially for high-$z$ regions), it is uncertain whether the Schechter-function fit is good enough or not. Second, the conversion from luminosity density to SFR generally relies on stellar population models, an assumed star formation history, and an initial mass function (IMF), which are not also well established yet. Finally, if the tracer of star formation is an optical or UV luminosity, then the effects of dust extinction are nonnegligible. Although this problem is less critical in other wave bands such as NIR H$\alpha$ or FIR/submillimeter, the bulk of current data consists of rest-frame UV observations, especially of high-redshift regions. After adopting some correction law for dust extinction, the rest-frame UV data become rather consistent with H$\alpha$ or submillimeter data points; still, in this case it is unknown whether the UV and submillimeter sources are identical, which is very important for measuring the cosmic SFR.

Thus, our knowledge concerning the cosmic SFR is quite crude, and therefore another type of observation that is independent of the above methods would be very important. In this paper we consider supernova relic neutrinos (SRNs), i.e., a diffuse background of neutrinos that were emitted from past supernova explosions. Type Ia, Ib, and II supernova explosions are considered to have traced the cosmic SFR, because they are directly connected with the death of massive stars with $M \geq 8 M_\odot$ and their lifetime is expected to be very short compared with the timescale of star formation. These events are triggered by gravitational collapse, and 99% of the gravitational binding energy is released as neutrinos; this basic
The SRN flux and the event rates at a currently working large-volume water Cerenkov detector, Super-Kamiokande (SK), have been investigated by many researchers using theoretically/observationally modeled SFRs (Totani & Sato 1995; Totani, Sato, & Yoshii 1996; Malaney 1997; Hartmann & Woosley 1997; Kaplinghat, Steigman, & Walker 2000; Ando, Sato, & Totani 2003). More recently, the SK collaboration obtained a 90% CL upper limit on the SRN flux, i.e., 1.2 cm$^{-2}$ s$^{-1}$ in the energy range $E_\nu > 19.3$ MeV (Malek et al. 2003). This severe constraint is only about factor of 3–6 larger than the typical theoretical models and is very useful for obtaining several rough estimations of the cosmic SFR (Fukugita & Kawasaki 2003; Strigari et al. 2003) and probing the properties of neutrinos as elementary particles (Ando & Sato 2003a; Ando 2003).

However, we need a further ~40 years to reduce the current limit by a factor of 3 if we use the SK detector with current performance. This is because there is no energy window for SRN detection where the SRN signal dominates other background events coming from various sources, such as solar, reactor, and atmospheric neutrinos, as well as cosmic-ray muons (Ando et al. 2003). Therefore, current observations are seriously affected by the other backgrounds and take much more time to reach the required sensitivity. In order to overcome this difficulty, a very interesting and promising method was proposed to directly tag electron antineutrinos ($\bar{\nu}_e$), and it is now in the research and development phase (Beacom & Vagins 2003). The basic idea is to dissolve 0.2% gadolinium trichloride (GdCl$_3$) into the pure water of SK. With this mixture, 90% of the neutrons produced by the $\bar{\nu}_e p \rightarrow e^+ n$ reaction are captured on Gd and then decay with 8 MeV gamma cascades. When we detect these gamma cascades, as well as the preceding Cerenkov radiation from positrons, it indicates that these signals come from original $\bar{\nu}_e$ not from other flavor neutrinos or muons. With this method, we can remove the background signals in the energy range 10–30 MeV, in which before removal there is a huge amount of background from solar neutrinos ($\nu_e$) and atmospheric muon-neutrinos ($\nu_{\mu}, \nu_{\tau}$) or cosmic-ray muon induced events. Because the expected SRN rate is estimated to be 1–2 yr$^{-1}$ in the energy range 10–30 MeV, the Gd-loaded SK detector (Gd-SK) would enable us to detect a few SRN events each year.

Therefore, it is obviously important and urgent to make a detailed investigation of the performance of such future detectors. In this paper we focus on how far we can probe the cosmic supernova rate by SRN observations at Gd-SK and at the hypothetical Gd-loaded Hyper-Kamiokande (Gd-HK) detector or Gd-loaded Underground Nucleon Decay and Neutrino Observatory (Gd-UNO). Because the expected event rate of SRNs is about 1–2 yr$^{-1}$ in the detectable energy range (10–30 MeV) using a detector with the size of SK, it would be quite difficult to obtain the spectral information of SRNs, even if we observed for 5 years. On the other hand, with the currently proposed megaton-class detectors such as HK and UNO, we can expect to obtain a great deal of information about the SRN spectrum, which will be useful for inferring the SFR-$z$ relation. Using the Monte Carlo (MC) method, we simulate an expected SRN signal at these future detectors, and then we analyze these hypothetical data with a few free parameters and discuss implications from future SRN observations.

This paper is organized as follows. In § 2 we give the formulation for calculating the SRN flux and discuss several models that are adopted in our calculations, and in § 3 we show the results of our calculation with some reference models. In § 4 the MC simulation of the expected signal at the future Gd-loaded detectors, which is generated from the reference models, is presented, and then we analyze these hypothetical data using several free parameters concerning the cosmic SFR. Finally, we discuss other possibilities in § 5.

2. FORMULATION AND MODELS

2.1. Formulation

The present number density of SRNs ($\bar{\nu}_e$), whose energy is in the interval $E_\nu \sim E_\nu + dE_\nu$, emitted in the redshift interval $z \sim z + dz$, is given by

$$dn_\nu(E_\nu) = R_{SN}(z)(1 + z)^3 \frac{dt}{dz} \frac{dN_\nu(E_\nu)}{dE_\nu}(1 + z)^{-3}$$

where $E_\nu = (1 + z)E_\nu$ is the energy of neutrinos at redshift $z$, which is now observed as $E_\nu$; $R_{SN}(z)$ represents the supernova rate per comoving volume at $z$, and hence the factor $(1 + z)^3$ should be multiplied to obtain the rate per physical volume at that time; $dN_\nu/dE_\nu$ is the number spectrum of neutrinos emitted by one supernova explosion; and the factor $(1 + z)^{-3}$ comes from the expansion of the universe. The Friedmann equation gives the relation between $t$ and $z$ as

$$\frac{dz}{dt} = -H_0(1 + z)\sqrt{(1 + \Omega_m z)(1 + z)^3 - \Omega_\Lambda (2z + z^2)},$$

and we adopt the standard $\Lambda$CDM cosmology ($\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ h$^{-1}$ km s$^{-1}$ Mpc$^{-1}$). We now obtain the differential number flux of SRNs, $dF_\nu/dE_\nu$, using the relation $dF_\nu/dE_\nu = c \, dn_\nu/dE_\nu$:

$$\frac{dF_\nu}{dE_\nu} = c \frac{H_0}{1 + \Omega_m z(1 + z)^2} R_{SN}(z) \frac{dN_\nu(E_\nu)}{dE_\nu} (1 + z)^{-3} \frac{dz}{\sqrt{(1 + \Omega_m z)(1 + z)^3 - \Omega_\Lambda (2z + z^2)}},$$

where we assume that gravitational collapses began at the redshift $z_{\text{max}} = 5$.

1 Although we use the specific cosmological model here, the SRN flux itself is completely independent of such cosmological parameters, as long as we use observationally inferred SFR models (see their cancellation between eqs. [3] and [4]), as already discussed in Ando et al. (2003).
around 0.5 $M_\odot$, and that all stars with $M > 8 M_\odot$ explode as core-collapse supernovae, i.e.,

$$R_{\text{SN}}(z) = \frac{\int_0^{125 M_\odot} dm \phi(m)}{\int_0^{125 M_\odot} dm m \phi(m)} \psi_e(z) = 0.0122 M_\odot^{-1} \psi_e(z).$$

The resulting local supernova rate agrees within errors with the observed value of $R_{\text{SN}}(0) = (1.2 \pm 0.4) \times 10^{-4} h_{70}^3$ yr$^{-1}$ Mpc$^{-3}$ (e.g., Madau, della Valle, & Panagia 1998a and references therein). In fact, the totally time-integrated neutrino spectrum from massive stars ($\geq 30 M_\odot$) could be very different from the models that we use (and give in the next subsection), possibly because of, e.g., black hole formation. However, the conversion factor appearing in equation (5) is highly insensitive to the upper limit of the integral in the numerator; for instance, if we change the upper limit in the numerator to 25 $M_\odot$, the factor becomes 0.010 $M_\odot^{-1}$, which is only slightly different from the value in equation (5).

### 2.3. Neutrino Spectrum from Supernova Explosions

For the neutrino spectrum from each supernova, we adopt three reference models by different groups, i.e., simulations by the Lawrence Livermore (LL) group (Totani et al. 1998) and Thompson, Burrows, & Pinto (2003, hereafter TBP), and the MC study of spectral formation by Keil, Raffelt, & Janka (2003, hereafter KRJ). In this field, however, the most serious problem is that the recent sophisticated hydrodynamic simulations have not obtained the supernova explosion itself; i.e., the shock wave cannot penetrate the entire core. Therefore, many points still remain controversial, e.g., the average energy ratio among neutrinos of different flavors, or how the gravitational binding energy is distributed to each flavor. All these problems are quite serious for our estimation, since the binding energy released as $\nu_e$ changes the normalization of the SRN flux, and the average energy affects the SRN spectral shape. Thus, we believe that these three models from different groups will be complementary.

The numerical simulation by the LL group (Totani et al. 1998) is considered to be the most appropriate for our estimation, because it is the only model that succeeded in obtaining a robust explosion and in calculating the neutrino spectrum during the entire burst ($\sim 15$ s). According to their calculation, the average energy difference between $\bar{\nu}_e$ and $\nu_x$, where $\nu_x$ represent the nonelectron-flavor neutrinos and antineutrinos, was rather large and the complete equipartition of the binding energy was realized, $L_{\nu_e} = L_{\nu_x} = L_{\nu_{\alpha}}$, where $L_{\nu_{\alpha}}$ represents the released gravitational energy as $\alpha$-flavor neutrinos. The neutrino spectrum obtained by their simulation is well fitted by a simple formula, which was originally given by KRJ as

$$\frac{dN_{\nu}}{dE_{\nu}} = \frac{(1 + \beta_\nu)^{1+\beta_\nu} L_{\nu}}{\Gamma(1 + \beta_\nu) E_{\nu}^{\beta_\nu}} e^{-(1+\beta_\nu)E_{\nu}/\bar{E}_{\nu}},$$

where $\bar{E}_{\nu}$ is the average energy; the values of the fitting parameters for the $\bar{\nu}_e$ and $\nu_x$ spectrum are summarized in Table 1.

Although the LL group succeeded in obtaining a robust explosion, their result has recently been criticized because it lacked many relevant neutrino processes that are now recognized as important. Thus, we adopt the recent result of another hydrodynamic simulation, the TBP one, which included all
the relevant neutrino processes, such as neutrino bremsstrahlung and neutrino-nucleon scattering with nucleon recoil. Their calculation obtained no explosion, and the neutrino spectrum ends at 0.25 s after core bounce. In the strict sense, we cannot use their result as our reference model because the fully time-integrated neutrino spectrum is definitely necessary in our estimate. However, we adopt their result in order to confirm the effects of recent sophisticated treatments of neutrino processes in the supernova core on the SRN spectrum. The TBP calculations include three progenitor mass models, i.e., 11, 15, and 20 $M_{\odot}$; all of these models are well fitted by equation (6), and the fitting parameters are summarized in Table 1. The average energy for both $\bar{\nu}_e$ and $\nu_x$ is much smaller than that by the LL calculation. Although we do not show this in Table 1, it was also found that at least for the early phase of the core-collapse, the complete equipartition of the gravitational binding energy for each flavor was not realized. However, it is quite unknown whether these trends hold during the entire burst. In this study, we adopt the average energy given in Table 1 as our reference model, while we assume perfect equipartition between flavors, i.e., $L_{\bar{\nu}_e} = L_{\nu_x} = 5.0 \times 10^{52}$ ergs.

In addition, we also use the model by KRJ. Their calculation did not couple with the hydrodynamics, but it focused on the spectral formation of neutrinos of each flavor using an MC simulation. Therefore, the static model was assumed as a background of neutrino radiation, and we use their “accretion phase model II,” in which the neutrino transfer was solved in the background of a 150 ms postbounce model by way of a general relativistic simulation. The fitting parameters for their MC simulation is also summarized in Table 1. Unlike the previous two calculations, their result clearly shows that the average energy of $\nu_x$ is very close to that of $\bar{\nu}_e$. It also indicates that the equipartition among each flavor was not realized, but rather $L_{\nu_x} \simeq L_{\bar{\nu}_e} \simeq 2L_{\bar{\nu}_e}$. However, also in this case, since the totally time-integrated neutrino flux is unknown from such temporal information, we assume perfect equipartition, $L_{\bar{\nu}_e} = L_{\nu_x} = 5.0 \times 10^{52}$ ergs, as well as that the average energies are the same as those in Table 1.

2.4. Neutrino Spectrum after Neutrino Oscillation

The original $\bar{\nu}_e$ spectrum is different from what we observe as $\bar{\nu}_e$ at Earth, owing to the effect of neutrino oscillation. Since the specific flavor neutrinos are not mass eigenstates, they mix with other flavor neutrinos during their propagation. The behavior of flavor conversion inside the supernova envelope is well understood, because the relevant mixing angles and mass square differences are fairly well determined by recent solar, atmospheric, and reactor neutrino experiments. The remaining ambiguities concerning the neutrino oscillation parameters are the value of $\theta_{13}$, which is only weakly constrained ($\sin^2 2\theta_{13} \lesssim 0.1$; Apollonio et al. 1999), and the type of mass hierarchy, i.e., normal ($m_1 < m_2$) or inverted ($m_1 > m_2$). We first discuss the case of normal mass hierarchy as our standard model; in this case, the value of $\theta_{13}$ is irrelevant. The case of inverted mass hierarchy is addressed in § 5.3. In addition, other exotic mechanisms, such as resonant spin-flavor conversion (see Ando & Sato 2003b and references therein) and neutrino decay (Ando 2003), which possibly change the SRN flux and spectrum, might work in reality. However, we do not consider such possibilities in this study.

The produced $\bar{\nu}_e$ at the supernova core are coincident with the lightest mass eigenstate $\tilde{\nu}_1$ owing to the large matter potentials. Since this state $\tilde{\nu}_1$ is the lightest also in vacuum, there are no resonance regions in which one mass eigenstate can change into another state, and therefore $\bar{\nu}_e$ at production arrives at the stellar surface as $\tilde{\nu}_1$. Thus, the $\bar{\nu}_e$ spectrum observed by the distant detector is

$$\frac{dN_{\bar{\nu}_e}}{dE_{\bar{\nu}_e}} = |U_{e1}|^2 dN_{\tilde{\nu}_1} + |U_{e2}|^2 dN_{\tilde{\nu}_2} + |U_{e3}|^2 dN_{\tilde{\nu}_3}$$

$$= |U_{e1}|^2 \left( \frac{dN_{\tilde{\nu}_1}}{dE_{\tilde{\nu}_1}} + 1 - |U_{e1}|^2 \right) \frac{dN_{\tilde{\nu}_1}}{dE_{\tilde{\nu}_1}},$$ (7)

where the quantities with superscript 0 represent those at production, $U_{e1}$ is the mixing matrix element between the $\nu_e$-flavor state and the mass eigenstate, and observationally $|U_{e1}|^2 = 0.7$. In other words, 70% of the original $\bar{\nu}_e$ survives; on the other hand, the remaining 30% comes from the other component $\nu_x$. Therefore, both the original $\bar{\nu}_e$ and $\nu_x$ spectra are necessary for the estimation of the SRN flux and spectrum; since the original $\nu_x$ spectrum is generally harder than that of the original $\bar{\nu}_e$, as shown in Table 1, the flavor mixing is expected to harden the detected SRN spectrum.

3. Flux and Event Rate of Supernova Relic Neutrinos

3.1. Flux of Supernova Relic Neutrinos

The SRN flux can be calculated by equation (3) with our reference models given in § 2. Figure 2 shows the SRN flux as a function of neutrino energy for the three supernova models, LL, TBP, and KRJ. The flux of atmospheric $\bar{\nu}_e$, which becomes background events for SRN detection, is shown in the same figure (Gaisser, Stanev, & Barr 1988; Barr, Gaisser, & Stanev 1989). The SRN flux peaks at $\pm 5$ MeV, and around this peak, the TBP model gives the largest SRN flux because the average energy of the original $\bar{\nu}_e$ is considerably smaller than in the other two models but the total luminosity is assumed to be the same. On the other hand, the model gives a smaller contribution at high-energy regions, $E_{\nu} > 10$ MeV. In contrast, the high-energy tail of the SRN flux with the
The LL model extends farther than with the other models, and it gives flux more than 1 mag larger at $E_{\nu} = 60$ MeV. This is because the high-energy tail was mainly contributed by the harder component of the original neutrino spectrum; in the case of the LL calculation, the average energy of the harder component $\nu_x$ is significantly larger than that of the other two calculations, as shown in Table 1. We show the values of the SRN flux integrated over the various energy ranges in Table 2. (In the following, we refer only to the upper part of Table 2; the values in the lower part are discussed in § 5.3.) The total flux is expected to be 11–16 cm$^{-2}$ s$^{-1}$ for our reference models, although this value is quite sensitive to the shape of the assumed SFR, especially at high-$z$. The energy range in which we are more interested is high-energy regions such as $E_{\nu} > 19.3$ MeV and $E_{\nu} > 11.3$ MeV, because as discussed below, the background events are less critical and the reaction cross section increases as $\propto E^2_{\nu}$. In such a range, the SRN flux is found to be 1.3–2.3 cm$^{-2}$ s$^{-1}$ ($E_{\nu} > 11.3$ MeV) and 0.14–0.46 cm$^{-2}$ s$^{-1}$ ($E_{\nu} > 19.3$ MeV). Thus, the uncertainty about the supernova neutrino spectrum and its luminosity gives at least a factor 2–4 ambiguity to the expected SRN flux in the energy region of our interest.

Figure 3 shows the contribution by supernova neutrinos emitted from various redshift ranges. At high-energy region $E_{\nu} > 10$ MeV, the dominant flux comes from the local supernovae ($0 < z < 1$), while the low-energy side is mainly contributed by the high-redshift events ($z > 1$). This is because the energy of neutrinos that were emitted from a supernova at redshift $z$ is reduced by a factor of $(1+z)^{-1}$ reflecting the expansion of the universe, and therefore high-redshift supernovae only contribute to low-energy flux. We also show the energy-integrated flux from each redshift range in Table 2 in the case of the LL supernova model. From the table, it is found that in the energy range of our interest, more than 70% of the flux comes from local supernova explosions at $z < 1$, while the high-redshift ($z > 2$) supernova contribution is very small.

### 3.2. Event Rate at Water Cerenkov Detectors

The water Cerenkov neutrino detectors have greatly succeeded in probing the properties of neutrinos as elementary particles, such as neutrino oscillation. The SK detector is one of these detectors, and its large fiducial volume (22.5 kton) might enable us to detect the diffuse background of SRNs. Furthermore, much larger water Cerenkov detectors such as HK and UNO are being planned. SRN detection is most likely with the inverse $\beta$-decay reaction with protons in water.

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**TABLE 2**

| MODEL | REDSHIFT RANGE | TOTAL | $
E_{\nu} > 11.3$ MeV | $E_{\nu} > 19.3$ MeV | $E_{\nu} > 18$ MeV |
|-------|----------------|-------|--------------------|---------------------|-------------------|
| LL... | Total          | 11.7  | 2.3                | 0.46                | 2.3               |
|       | $0 < z < 1$*   | 4.1 (35.3) | 1.6 (70.9)      | 0.39 (85.2)         | 1.7 (77.5)        |
|       | $1 < z < 2$*   | 4.9 (42.0) | 0.6 (26.3)      | 0.06 (14.0)         | 0.5 (20.6)        |
|       | $2 < z < 3$*   | 1.8 (15.1) | 0.1 (2.5)       | 0.0 (0.7)           | 0.0 (1.7)         |
|       | $3 < z < 4$*   | 0.6 (5.3)  | 0.0 (0.2)       | 0.0 (0.0)           | 0.0 (0.1)         |
|       | $4 < z < 5$*   | 0.2 (2.1)  | 0.0 (0.0)       | 0.0 (0.0)           | 0.0 (0.0)         |
| TBP... | Total          | 16.1  | 1.3                | 0.14                | 0.97              |
| KRJ... | Total         | 12.7  | 2.0                | 0.28                | 1.7               |

Normal Mass Hierarchy with Large $\theta_{13}$

| MODEL | REDSHIFT RANGE | TOTAL | $E_{\nu} > 18$ MeV |
|-------|----------------|-------|-------------------|
| LL... | Total          | 9.4   | 3.1               |
| TBP... | Total         | 13.8  | 1.9               |
| KRJ... | Total         | 12.4  | 2.2               |

Notes.—Values in the upper part are evaluated for the case of normal mass hierarchy (or inverted mass hierarchy with sufficiently small $\theta_{13}$, i.e., $\sin^2 2\theta_{13} \simeq 10^{-3}$), which we use as our standard model. On the other hand, values in the lower part are applicable only when the value of $\theta_{13}$ is large enough to induce completely adiabatic resonance, i.e., $\sin^2 2\theta_{13} \simeq 10^{-3}$, in the case of inverted mass hierarchy.

* Contributions from each redshift range to the total ($0 < z < 5$) value are shown in parentheses as percentages.
$\bar{\nu}_e p \rightarrow e^n n$, and its cross section is precisely understood (Vogel & Beacom 1999; Strumia & Vissani 2003). In our calculation, we use the trigger threshold of SK-I (before the accident).

The expected event rates at such detectors are shown in Figures 4 and 5 in units of $(22.5 \text{ kton yr})^{-1} \text{ MeV}^{-1}$; with SK, it takes a year to obtain the shown SRN spectrum, while with HK and UNO, much less time [$1 \text{ yr} \times (22.5 \text{ kton}/V_{\text{fid}})$, where $V_{\text{fid}}$ is the fiducial volume of HK or UNO] is necessary because of their larger fiducial volume. Figure 4 compares the three models of the original supernova neutrino spectrum, and Figure 5 shows the contribution to the total event rate from each redshift range. In Table 2 we summarize the event rate integrated over various energy ranges for three supernova models. The expected event rate is $0.97–2.3 (22.5 \text{ kton yr})^{-1}$ for $E_\nu > 10 \text{ MeV}$ and $0.25–1.0 (22.5 \text{ kton yr})^{-1}$ for $E_\nu > 18 \text{ MeV}$. This clearly indicates that if the background events that hinder the detection are negligible, the SK has already reached the required sensitivity for detecting SRNs; with the future HK and UNO, a statistically significant discussion would be possible. This also shows that the current shortage of our knowledge concerning the original supernova neutrino spectrum and luminosity gives at least a factor of 2 ($E_\nu / C_{23} > 10 \text{ MeV}$) to 4 ($E_\nu / C_{23} > 18 \text{ MeV}$) uncertainty to the event rate at the high-energy range (actual detection range). We also summarize the contribution from each redshift range in the same table, especially for the calculation with the LL model. The bulk of the detected events will come from the local universe ($z < 1$), but the considerable flux is potentially attributed to the range $1 < z < 2$.

3.3. Comparison with Other Studies and Current Observational Limits

There are many past theoretical researches concerning the SRN flux estimation based on a theoretically/observationally modeled cosmic SFR (Totani et al. 1996; Malaney 1997; Hartmann & Woosley 1997; Ando et al. 2003). Here we briefly compare our results obtained in §§ 3.1 and 3.2 with these past analyses. Our basic approach in the present paper is the same as that in Ando et al. (2003), in which the LL supernova model was adopted. Thus the values for the LL model given in Table 2 are almost the same as those in Ando et al. (2003). Two other studies (Totani et al. 1996; Hartmann & Woosley 1997) also used a similar SFR-$z$ relation at low redshift, and therefore their results are very consistent with the present one (the LL model) at high-energy range ($E_\nu > 10 \text{ MeV}$). Since the SFR model adopted by Malaney (1997) gave a rather lower value at low redshift, the resulting SRN flux at high-energy regions was about a factor 2 smaller than our LL model or the other ones (Totani et al. 1996; Hartmann...
& Woosley 1997; Ando et al. 2003). Thus, our calculation with the LL supernova model gives values quite consistent with past studies within a factor of 2, but all of those studies used the supernova model that is very similar to the LL model. In fact, the present study is the first one to investigate the dependence on the adopted supernova models, by using the various original spectra of the different groups (LL, TBP, and KRJ). As already mentioned in § 3.1, it was found that the ambiguity concerning the original neutrino spectrum varies the resulting value of the flux by at least a factor of 2.

In addition, there are several other studies on the SRN flux (Totani & Sato 1995; Kaplinghat et al. 2000; Fukugita & Kawasaki 2003). As for Totani & Sato (1995), the authors used a constant supernova rate model in order to investigate the dependence on cosmological parameters; they gave a very large value (∼3 cm\(^{-2}\) s\(^{-1}\) at \(E_\nu > 19.3\) MeV), which is already excluded observationally, because they adopted a rather large supernova rate. Concerning the other two studies, since neither of them gives a specific value for the SRN flux, we cannot compare ours with theirs; they focused on giving a theoretical upper limit (Kaplinghat et al. 2000) or probing the cosmic SFR with the current observational upper limit by SK (Fukugita & Kawasaki 2003).

Observationally, the SK collaboration gave a very stringent upper limit to the SRN flux at \(E_\nu > 19.3\) MeV, i.e., 1.2 cm\(^{-2}\) s\(^{-1}\) (90% CL; Malek et al. 2003). This number can be directly compared with our predictions summarized in Table 2. Our predicted values are 0.46, 0.14, and 0.28 cm\(^{-2}\) s\(^{-1}\) for the LL, TBP, and KRJ models, respectively. Thus, the current SK upper limit is about a factor 2.5–8.5 larger than our predictions with the reference model for the cosmic SFR, depending on the adopted original neutrino spectrum.

3.4. Background Events against Detection

In § 3.2 we calculated the expected SRN spectrum at the water Čerenkov detectors on Earth, but the actual detection is quite restricted because of the presence of other background events. There are atmospheric and solar neutrinos, antineutrinos from nuclear reactors, spallation products induced by cosmic-ray muons, and decay products of invisible muons (for a detailed discussion of these backgrounds, see Ando et al. 2003). For the pure-water Čerenkov detectors, there is no energy window in which the flux of any backgrounds is much smaller than the SRN flux.

However, as proposed by Beacom & Vagins (2003), if we use Gd-loaded detectors, the range 10–30 MeV would be an energy window because we can positively distinguish the \(\bar{\nu}_e\) signal from other backgrounds such as solar neutrinos (\(\nu_e\)), invisible muon events, and spallation products; this is realized by capturing neutrons that are produced by the \(\bar{\nu}_e\)-p interactions. Above 30 MeV, the SRN flux becomes smaller than the flux of atmospheric \(\bar{\nu}_e\), as shown in Figure 2; because they are of the same flavor, it is in principle impossible to distinguish them from the SRN \(\bar{\nu}_e\). On the other hand, below 10 MeV the reactor neutrinos (\(\bar{\nu}_e\)) are the dominant background in the case of SK or HK; because the flux of reactor neutrinos strongly depends on the detector site, it may be possible to further reduce this lower energy cutoff (10 MeV) in the case of UNO.

The neutron capture efficiency by Gd is estimated to be 90% with the proposed 0.2% mixture by mass of GdCl\(_3\) in water (Beacom & Vagins 2003), and subsequently 8 MeV gamma cascade occurs from the excited Gd. The single-electron energy equivalent to this cascade was found to be 3–8 MeV by careful simulation (Hargrove et al. 1995), and with the trigger threshold adopted in SK-I, only about 50% of such cascades can be detected actually. However, it is expected that SK-III, which will begin operation in mid-2006, will trigger at 100% efficiency above 3 MeV, with good trigger efficiency down to 2.5 MeV (Beacom & Vagins 2003). In that case most of the gamma cascades from Gd will be detected with their preceding signal of positrons. From this point on, we assume 100% efficiency; even if we abandon this assumption, it does not affect our physical conclusion, since the relevant quantity representing the detector performance is (fiducial volume) \times (time) \times (efficiency), which we call effective volume.

4. MONTE CARLO SIMULATION FOR FUTURE DETECTOR PERFORMANCE

In this section we predict the expected signal at future detectors, such as Gd-SK, Gd-HK, and Gd-UNO, using the MC method with our reference models. These pseudodata are then analyzed using several free parameters concerning the SFR. Although we focus on how far the SFR can be probed by SRN observation, the uncertainty from the supernova neutrino spectrum would give a fair amount of error. However, this problem can be solved if a supernova explosion occurs in our Galaxy; the expected event number is about 5000–10,000 at SK, when supernova neutrino burst occurs at 10 kpc, and it will enable a statistically significant discussion concerning the neutrino spectrum from supernova explosions. Even if there are no Galactic supernovae in the near future, remarkable development of the supernova simulation can be expected with the growth of computational resources and numerical technique. With such developments, the supernova neutrino spectrum and luminosity may be uncovered, and the ambiguity is expected to be reduced significantly. Thus, in this paper we assume that the supernova neutrino spectrum is well understood and that our reference models are fairly good representatives of nature; we analyze the SFR alone with several free parameters.

The basic procedure of our method is as follows. (1) We simulate the expected signal (spectrum) at a Gd-loaded detector in the range 10–30 MeV, assuming that there are no background events. In that process, we use our reference models for the generation of the SRN signal (eq. [4] for the SFR and the LL model as neutrino spectrum). (2) Then we analyze the SRN spectrum using the maximum likelihood method with two free parameters of the SFR and obtain a set of the best-fit values for those parameters; they are concerned with the supernova rate as

$$R_{SN}(z) = \begin{cases} R_{SN}^0(1+z)^\alpha & z < 1, \\ 2^{\alpha} R_{SN}^0 & z > 1, \end{cases}$$

where \(R_{SN}^0\) represents the local supernova rate and \(\alpha\) determines the slope of supernova rate evolution. Although it is recognized that the SFR-z relation increases from \(z = 0\) to \(z = 1\) from various observations using light, the actual numbers for the absolute value and the slope of the SFR-z relation are still a matter of controversy and independent confirmation, such as ours, is needed. We assume that the comoving SFR is constant at \(z > 1\); even if we changed this assumption, the result would be the same because the bulk of the detected event comes from local supernovae. (3) We perform \(10^3\) such MC simulations and obtain \(10^3\) independent...
sets of best-fit parameters. Then we discuss the standard deviation of the distributions of such best-fit parameter sets and the implications for the cosmic SFR.

4.1. Performance of the Gd-loaded Super-Kamiokande Detector

In this subsection we discuss the performance of Gd-SK for 5 years, or an effective volume of 22.5 kton \( \times \) 5 yr. Because the expected event number is only \( \sim 10 \), the parameters \( R_{SN}^0 \) and \( \alpha \) cannot both be well determined at once. Therefore, we fix one of those parameters with some value inferred from other observations. First, the value of \( R_{SN}^0 \) was fixed to be \( 1.2 \times 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3} \), which was inferred from the local supernova survey (Madau et al. 1998a), and we obtained the distribution of the best-fit values of parameter \( \alpha \). Figure 6 shows the expected SRN spectrum; points with error bars represent the result of one MC simulation, and the dashed histogram is the spectrum with the best-fit parameter (\( \alpha = 2.97 \)). Thus, from one realization of the MC simulation, we obtain one best-fit parameter. The result of \( 10^3 \) MC simulations are shown in Figure 7 as a histogram of the distribution of best-fit parameters \( \alpha \) (solid histogram). The average value of these \( 10^3 \) values for \( \alpha \) is found to be 2.67, and the standard deviation is 0.80, i.e., \( \alpha = 2.67 \pm 0.80 \). A no-evolution (constant supernova rate) model would be excluded at the 3.3 \( \sigma \) level from the SRN observation alone with an effective volume of 22.5 kton \( \times \) 5 yr.

Then in turn, we fixed the value of \( \alpha \) to be 2.9 in order to obtain the distribution of best-fit values for the local supernova rate \( R_{SN}^0 \) from the SRN observation. The result of \( 10^3 \) MC generations and analyses in this case is shown in Figure 8. The average value for \( R_{SN}^0 \) is \( 1.2 \times 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3} \), and the standard deviation is \( 0.4 \times 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3} \), i.e., \( R_{SN}^0 = (1.2 \pm 0.4) \times 10^{-4} \text{ yr}^{-1} \text{ Mpc}^{-3} \).
and as the area between the two dashed curves for an effective volume of 22.5 kton and as the area between the two dotted curves for an effective volume of 440 kton.

Thus, we repeated the same procedure but without fixing the values of $\alpha$ or $R_{SN}^0$. The distribution of $10^3$ best-fit parameter sets of $(\alpha, R_{SN}^0)$ is shown in Figure 10 for a detector with an effective volume of 440 kton $\times$ 5 yr; the mean values and the standard deviations are $\alpha = 3.5 \pm 1.3$ and $R_{SN}^0 = (8.8 \pm 4.8) \times 10^{-5}$ yr$^{-1}$ Mpc$^{-3}$. Even though the effective volume is as large as 440 kton $\times$ 5 yr, it is still insufficient for determining both parameters at once. For another trial, we also carried out the same MC simulations, but using a hypothetical (and unrealistic) effective volume as large as 440 kton $\times$ 10$^4$ yr. In that case the free parameters are found to be quite well constrained at $\alpha = 3.68 \pm 0.03$ and $R_{SN}^0 = (7.11 \pm 0.09) \times 10^{-5}$ yr$^{-1}$ Mpc$^{-3}$.

We consider future megaton-class detectors such as Gd-HK or Gd-UNO. With these detectors, the effective volume that we consider, 440 kton $\times$ 5 yr, is expected to be realized in several years from the start of their operation. First we did the same analysis adopted in the previous subsection, i.e., we fixed one of relevant parameters, $\alpha$ or $R_{SN}^0$, and investigated the dependence on the remaining parameter. The values that we used for fixed parameters were the same as those given in the previous subsection. The result of these cases are also shown in Figures 7 and 8 as dashed histograms, which give $\alpha = 2.51 \pm 0.20$ and $R_{SN}^0 = (1.0 \pm 0.1) \times 10^{-4}$ yr$^{-1}$ Mpc$^{-3}$, respectively, and these values are also summarized in Table 3.

The statistical errors are considerably reduced compared with the case of 22.5 kton $\times$ 5 yr, because of the ~20 times larger effective volume. Thus, future megaton detectors will possibly pin down, within 10% statistical error, either the index of supernova rate evolution $\alpha$ or the local supernova rate $R_{SN}^0$ if the other is known in advance. The dashed curves in Figure 9 set the allowed region of the supernova rate at the 1 $\sigma$ level by the considered detectors, well reproducing the assumed model.

In principle, we can determine both parameters by SRN observation, because $R_{SN}^0$ is concerned with the absolute value of the flux alone but $\alpha$ is concerned with both the absolute value and the spectral shape; i.e., these two parameters are not degenerate with each other. Thus, we repeated the same procedure but without fixing the values of $\alpha$ or $R_{SN}^0$. The distribution of $10^3$ best-fit parameter sets of $(\alpha, R_{SN}^0)$ is shown in Figure 10 for a detector with an effective volume of 440 kton $\times$ 5 yr; the mean values and the standard deviations are $\alpha = 3.5 \pm 1.3$ and $R_{SN}^0 = (8.8 \pm 4.8) \times 10^{-5}$ yr$^{-1}$ Mpc$^{-3}$. Even though the effective volume is as large as 440 kton $\times$ 5 yr, it is still insufficient for determining both parameters at once. For another trial, we also carried out the same MC simulations, but using a hypothetical (and unrealistic) effective volume as large as 440 kton $\times$ 10$^4$ yr. In that case the free parameters are found to be quite well constrained at $\alpha = 3.68 \pm 0.03$ and $R_{SN}^0 = (7.11 \pm 0.09) \times 10^{-5}$ yr$^{-1}$ Mpc$^{-3}$.

5. DISCUSSION

5.1. Supernova Rate at High-Redshift Region

At the detection energy range 10–30 MeV that we have considered, the main contribution to the SRN event rate comes...
from low-redshift region $0 < z < 1$, as shown in Figure 5 and Table 2. However, if we can reduce the lower energy threshold $E_{th}$, we expect that the contribution of supernova neutrinos from high-redshift $z > 1$ becomes enhanced. The value of $E_{th}$ is restricted to 10 MeV because at energy regions lower than this, there is a large background of reactor neutrinos; its removal is impossible with the current detection methods. Since the SK and HK detectors are and will be located at Kamioka in Japan, they are seriously affected by background neutrinos from many nuclear reactors. If some large-volume detectors were built at a location free from such background, the lower threshold energy could be reduced, enabling us to probe the high-redshift supernova rate. In this subsection, thus, we discuss the detector performance as a function of the value of $E_{th}$.

In Figure 11a we show three toy models of comoving density of supernova rate as a function of redshift. These models exactly coincide with each other at $z < 1$ (and also with the previous reference model represented by eq. [4]) but seriously differ at $z > 1$. We calculate the expected event number for $E_{th} < E_c < 30$ MeV at a detector with an effective volume of 440 kton $\times$ 5 yr, using these toy models, the LL spectrum, and trigger threshold expected at SK-III. The result is shown in Figure 11b. As expected, the discrepancy among the three models becomes larger as we reduce the threshold energy. In particular, the model that produces larger numbers of supernovae at $z > 1$ (solid curve) is satisfactorily distinguishable in the case of sufficiently low $E_{th}$. This is because the larger supernova rate at high-redshift region $z > 1$ increases the fraction of its contribution to the SNR flux. On the other hand, the model with a lower supernova rate relatively increases the contribution from low-redshift region $z < 1$, and therefore the difference between constant (dotted curve) and decreasing model (dashed curve) is less prominent.

5.2. Probing Supernova Neutrino Properties

Until this point, we have assumed that the properties of supernova neutrinos, such as the average energy difference between flavors and luminosities of neutrinos of different flavors, will be quite well understood when future SNR detection comes within reach. However, this assumption itself is quite unclear because Galactic supernova explosions, which would give us rich information on the supernova neutrino spectrum and luminosity, may not occur by the time we are ready for the SNR detection. Furthermore, there is no assurance that the numerical experiments will succeed in obtaining the supernova explosion itself and predicting the supernova neutrino properties precisely by then. Thus, SNR observation might be the only probe of the supernova neutrino properties.

In this subsection, we discuss how far we can derive the supernova neutrino properties from SNR observation. We have already shown that even using data of 440 kton $\times$ 5 yr, at most only two free parameters can be satisfactorily constrained. Therefore, we now have to adopt another assumption such that the evolution of the supernova rate is quite well understood by future observations with the various planned satellites and telescopes. The procedure is basically the same as that of the previous section; i.e., we run $10^5$ MC simulations and analyze these pseudodata to obtain the best-fit values for two free parameters, $E_{\nu_e}$ and $E_{\nu_\mu}/E_{\nu_\tau}$. The values of $\beta_e$ and $L_p$ defined in equation (6) are assumed to be $\beta_e = 4.0$, $\beta_\mu = 2.2$, and $L_p = L_\tau = 5.0 \times 10^{52}$ ergs. As a result of such calculations, we obtain the distribution of the two parameters, which is characterized by $E_{\nu_e} = (15.9 \pm 1.3)$ MeV and $E_{\nu_\mu}/E_{\nu_\tau} = 1.5 \pm 0.4$, although this well reproduces the LL model, the errors are still very large. Considering that many uncertainties concerning the SFR estimate possibly remain even in future updated observations, the errors to these quantities would be much larger than the purely statistical ones given above.

5.3. Inverted Mass Hierarchy

Throughout the above discussion, we have assumed normal hierarchy of neutrino masses ($m_1 \ll m_2$). However, the case of inverted mass hierarchy has not been experimentally excluded yet, and we explore this possibility in this subsection. In this case, flavor conversions inside the supernova envelope change dramatically, compared with the normal mass hierarchy already discussed in $\S$ 2.4. Since $\bar{\nu}_1$ is the lightest, $\bar{\nu}_3$ are created as $\bar{\nu}_1$, owing to large matter potential. In that case, it is well known that at a so-called resonance point, there occurs a level crossing between $\bar{\nu}_1$ and $\bar{\nu}_3$ (for a more detailed discussion, see, e.g., Dighe & Smirnov 2000). At this resonance point, complete $\bar{\nu}_1 \leftrightarrow \bar{\nu}_3$ conversion occurs when the so-called adiabaticity parameter is sufficiently small compared to unity (it is said that resonance is "nonadiabatic"), while conversion never occurs when it is large (adiabatic resonance). The adiabaticity parameter $\gamma$ is quite sensitive to the value of $\theta_{13}$, i.e., $\gamma \propto \sin^2 2\theta_{13}$; when $\sin^2 2\theta_{13} \lesssim 10^{-3}$ ($\sin^2 2\theta_{13} \lesssim 10^{-5}$), the resonance is known to be completely adiabatic (nonadiabatic) (Dighe & Smirnov 2000). When the resonance is completely nonadiabatic (because of small $\theta_{13}$), the situation is the same as in the case of normal mass hierarchy already discussed in $\S$ 2.4 (because $\bar{\nu}_1$ at production become $\bar{\nu}_3$ at the stellar surface), and the $\bar{\nu}_3$ spectrum after oscillation is represented by equation (7). On the other hand, adiabatic resonance (due to large $\theta_{13}$) forces $\bar{\nu}_e$ at production to become

![Figure 11](https://example.com/figure11.png)

**Fig. 11.** (a) Three toy models for comoving density of supernova rate as a function of redshift. (b) Expected event number $N$ at $E_{th} < E_c < 30$ MeV as a function of $E_{th}$, for the fiducial volume of 440 kton $\times$ 5 yr. The line types correspond to those in (a). The upper and lower curves of each type represent $N + \sqrt{N}$ and $N - \sqrt{N}$, respectively; i.e., the area between the two curves is the allowed region at the 1$\sigma$ level.
\[ \frac{dN_{\nu_e}}{dE} = |U_{e\alpha}|^2 \frac{dN_{\nu_\alpha}}{dE} + \left(1 - |U_{e\alpha}|^2 \right) \frac{dN_{\nu_{\bar{\alpha}}}}{dE}, \quad (9) \]

The second equality follows from the fact that the value of \(|U_{e\alpha}|^2\) is constrained to be much smaller than unity from reactor experiments (Apollonio et al. 1999). Thus, equation (9) indicates that complete conversion takes place between \(\bar{\nu}_e\) and \(\nu_e\). When the value of \(\theta_{13}\) is large enough to induce adiabatic resonance (\(\sin^2 2\theta_{13} \gtrsim 10^{-3}\)), the obtained SRN flux and spectrum should be very different from ones obtained in \(\sin^2 2\theta_{13} \approx 0\) and \(3.2\). The SRN flux and event rate in this case were calculated with equations (3) and (9), and the results are summarized in the lower part of Table 2. The values (with the LL model) shown in this table are consistent with the previous calculation by Ando & Sato (2003a), in which numerically calculated conversion probabilities were adopted with some specific oscillation parameter sets (which include a model with inverted mass hierarchy and \(\sin^2 2\theta_{13} = 0.04\)), as well as realistic stellar density profiles.

The total flux becomes 9.4–14 cm\(^{-2}\) s\(^{-1}\), somewhat smaller than the values given in the upper part of the same table, because the total flux is dominated by the low-energy region. The fluxes at \(E_e > 19.3\) MeV are enhanced to be 0.30–0.94 cm\(^{-2}\) s\(^{-1}\), but this is still below the current 90% CL upper limit of 1.2 cm\(^{-2}\) s\(^{-1}\) obtained by the SK observation. The event rate at the future detectable energy range, \(E_e > 10\) MeV, is expected to become 1.6–3.8 yr\(^{-1}\), which is considerably larger than the values in the case of normal mass hierarchy, 0.97–2.3 yr\(^{-1}\). The increase (decrease) of the flux and event rate integrated over the high (total) energy region is due to the very high efficiency of the flavor conversion, \(\nu_e \rightarrow \bar{\nu}_e\), inside the supernova envelope; because the original \(\nu_e\) are expected to be produced with larger average energy, as shown in Table 1, the efficient conversion makes the SRN spectrum harder, which enhances the flux and event rate at the high-energy region. Thus, if the inverted mass hierarchy, as well as the large value for \(\theta_{13}\), were realized in nature, SRN detection would be rather easier, compared with the other cases. Although we do not repeat the MC simulations that were introduced in \(\S\) 4, the results can be easily inferred; the statistical errors in this case would be \((3.8/2.3)^{1/2} = 1.3\) times smaller than the values given in Table 3, because they are inversely proportional to the square root of the event number.

### 6. CONCLUSIONS

In the present paper, we have investigated the flux and event rate of SRNs and discussed their implications for the cosmic SFR. Since SRNs are diffuse neutrino background emitted from past core-collapse supernova explosions, they contain fruitful information not only on the supernova neutrino spectrum itself but also on the supernova rate in the past and present universe, which is quite difficult to estimate because, e.g., the problem of dust extinction is nontrivial. As reference models, we adopted the supernova rate model based on recent SFR observations (eq. [4]) and the supernova neutrino spectrum numerically calculated by three groups (LL, TBP, and KRJ).

As a result of our calculations, the flux integrated over the entire energy region was found to be 12–16 cm\(^{-2}\) s\(^{-1}\), depending on the adopted supernova neutrino spectrum (Table 2). Although there is no energy window for the SRN detection at present owing to various background events, in the near future, it is expected that the energy region of 10–30 MeV will be utilized for SRN detection. This is due to the technique of neutrino capture by dissolved Gd. In the detection energy range \(E_e > 10\) MeV, the SRN event rate was found to be 0.97–2.3 yr\(^{-1}\) at a detector with a fiducial volume of 22.5 kton (Table 2).

We also simulated the expected signal with one set of the reference models by using the Monte Carlo method and then analyzed these pseudodata with several free parameters, obtaining one set of best-fit values for them. MC simulations repeated \(10^3\) times gave \(10^3\) independent best-fit parameter sets, and we gave a statistical discussion using their distribution. First of all, we used parameterization such that \(R_{\text{SN}}(z) = R_{\text{SN}}^0(1+z)\alpha\), where \(R_{\text{SN}}^0\) and \(\alpha\) are free parameters, assuming that the supernova neutrino spectrum and luminosity are well understood by way of a future Galactic supernova neutrino burst or future development of the numerical supernova simulations. The obtained distribution for these two parameters was found to be represented by \(\alpha = 2.7 \pm 0.8\), \(\delta\alpha/\alpha = 30\%\) and \(R_{\text{SN}}^0 = (1.2 \pm 0.4) \times 10^{-4}\), \(\delta R_{\text{SN}}^0/(R_{\text{SN}}^0) = 28\%\) for a detector with an effective volume of 22.5 kton \(\times 5\) yr, and \(\alpha = 2.5 \pm 0.2\), \(\delta\alpha/\alpha = 7.8\%\) and \(R_{\text{SN}}^0 = (1.0 \pm 0.1) \times 10^{-4}\) Mpc\(^{-1}\), \(\delta R_{\text{SN}}^0/(R_{\text{SN}}^0) = 7.7\%\) for a detector with an effective volume of 440 kton \(\times 5\) yr, where one of the parameters is fixed (Figs. 7 and 8; Table 3). The parameterized supernova rate models with the obtained parameter values are compared with the assumed reference model in Figure 9, and we found that the fitting model well reproduced the reference model. On the other hand, if we fix neither value for these two parameters, the expected errors become rather large at \(\delta\alpha/\alpha = 37\%\) and \(\delta R_{\text{SN}}^0/(R_{\text{SN}}^0) = 55\%\), even with an effective volume of 440 kton \(\times 5\) yr.

In addition, we explored several other possibilities in \(\S\) 5. First, we discussed the dependence of the event number on the adopted lower cutoff energy. Although below 10 MeV there is a background of reactor neutrinos, their flux strongly depends on the detector sites, and the lower energy threshold \(E_\text{th}\) could possibly be reduced. We investigated the expected event number for \(E_\text{th} < E_e < 30\) MeV as a function of \(E_\text{th}\) in Figure 11 for various toy models of supernova rate and found that the model that produces larger number of supernovae at \(z > 1\) is satisfactorily distinguishable in the case of sufficiently small \(E_\text{th}\). Second, the SRN spectrum as a potential probe of the supernova neutrino spectrum itself was investigated, because such an approach might be very important if there are no Galactic supernova explosions in the near future or no successful numerical supernova simulations. We discussed using the same MC procedure, but assuming that the supernova rate is quite well understood. Although the obtained distribution reproduces properties of the LL spectrum, the errors were still found to be large, and considering the uncertainties concerning the SFR, these errors are only lower limits; the actual errors would be much larger. Finally, the case of an inverted mass hierarchy was investigated. We showed that only in the case in which \(\sin^2 2\theta_{13} \gtrsim 10^{-5}\) the values of the SRN flux should be modified. The results in the case of completely adiabatic resonance, which is realized when \(\sin^2 2\theta_{13} \gtrsim 10^{-3}\), are shown in the lower part of Table 2. In this case, it was found that the expected event rate would be enhanced to 1.6–3.8 yr\(^{-1}\), although these values are still below the current upper bound; SRN detection would be more probable in this case.

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