IMPACT OF ROTATION ON NEUTRINO EMISSION AND RELIC NEUTRINO BACKGROUND FROM POPULATION III STARS

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ABSTRACT

We study the effects of rotation on the neutrino emission from Population III (Pop III) stars by performing a series of two-dimensional rotational collapse simulations of Pop III stellar cores. Our results show that rotation enhances the neutrino luminosities and the average energies of emitted neutrinos. This is because the thermalized inner core, which is the dominant neutrino source from Pop III stars, can be enlarged, due to rotational flattening, enough to extend the inner core outside the neutrinospheres. This is in sharp contrast to the case of spherical collapse, in which the inner core shrinks deeper inside the neutrinospheres before black hole formation, which hinders the efficient neutrino emission. In the case of rotational core collapse, the emitted neutrino energies are found to become larger in the vicinity near the pole than those near the equatorial plane. These factors make the emergent neutrino spectrum broader and harder than the spherical collapse case. By computing the overall neutrino signals produced by the ensemble of individual rotating Pop III stars, we find that the amplitudes of the relic neutrinos, depending on their star-formation rates, can dominate over the contributions from ordinary core-collapse supernovae below a few MeV. A detection of this signal could be an important tool to probe star-formation history in the early universe.

Key words: hydrodynamics – methods: numerical – neutrinos – stars: rotation

Online-only material: color figures

1. INTRODUCTION

One of the most important goals in modern cosmology is to understand how the first stars formed at the end of the dark ages, and how they transformed the initially simple, homogeneous universe into a state of ever increasing complexity (e.g., Barkana & Loeb 2001; Bromm & Larson 2004; Loeb 2006). The first stars, so-called Population III (Pop III), are predicted to have been predominantly very massive with $M \gtrsim 100 M_\odot$ (e.g., Nakamura & Umemura 2001; Abel et al. 2002; Bromm et al. 2002; Yoshida et al. 2006; O’Shea & Norman 2007). During their evolution, the central core is thought to play an electron–positron pair creation instability after carbon burning, which reduces the thermal energy of the core and eventually triggers gravitational core collapse. For stellar masses less than $\sim 260 M_\odot$, rapid nuclear burning releases a large amount of energy sufficient to entirely disrupt the star as pair-instability supernovae (SNe). More massive stars, which also encounter pair instability, are so tightly bound that the fusion of oxygen is unable to reverse infall. Such stars are thought to collapse into black holes (BHs; Bond et al. 1984; Fryer et al. 2001), which we investigate in this paper. Information about the formation and evolution of the Pop III stars might be observationally obtained from re-ionization (Alvarez et al. 2006), the IR background (Dwek et al. 2005), nucleosynthesis yields (Heger & Woosley 2002; Iwamoto et al. 2005), gamma-ray bursts (Schneider et al. 2002; Bromm & Loeb 2006), and gravitational waves (Buonanno et al. 2005; Suwa et al. 2007a). However, at present, it is still unclear whether or not one can obtain clear information about Pop III stars directly from their observations.

Recently, neutrinos, which should have been emitted in large numbers at the phase of core collapse, are expected to be new eyes to unveil the mysteries of the first stars. Since direct detection is unlikely because of their large distances, a diffuse background of relic neutrinos could potentially be observable. In an analogous context, the relic neutrino background from ordinary core-collapse SNe has been studied elaborately (Bisnovatyi-Kogan & Seidov 1984; Totani et al. 1996; Hartmann & Woosley 1997; Kaplinghat et al. 2000; Ando et al. 2003; Ando & Sato 2004). Since the physics involved in relic neutrinos covers a very wide range of topics, e.g., cosmic star-formation rate and the collapse dynamics, detecting the relic neutrinos or even setting limits on their flux is expected to give us quite useful and unique implications not only for the understanding of the collapse physics itself, but also for various fields of astrophysics and cosmology.

The detectability of the relic neutrinos from Pop III stars has been discussed in several papers. Iocco et al. (2005) estimated the amplitudes of the relic neutrinos produced during the nuclear burning phases as well as the core-collapse phase, assuming a baryonic fraction of Pop III stars of $10^{-3}$ and monochromatic progenitors with a mass of $300 M_\odot$. Daigne et al. (2005) investigated the relic neutrino background produced by an early burst of Pop III stars taking into account a “normal mode” of the star formation at low redshift. The framework of hierarchical structure formation, on which their computation relies, is based on the cosmic star-formation histories, which are constrained by the observed star-formation rate at redshift $z \lesssim 6$, the observed chemical abundances in damped Lyman $\alpha$ absorbers, and in the intergalactic medium (IGM), and allow for an early re-ionization of the Universe at $z \sim 10 - 20$. Regardless of the differences in the treatment of the star-formation histories, these studies concluded that the typical energy of the relic neutrino background is lowered as low as MeV or sub-MeV due to the
cosmological redshift so that the detection is out of the question with presently known experimental techniques. However, it should be noted that, in their studies, the neutrino flux and energy emitted from the Pop III stars are set by hand with a simple spectrum based on the result of numerical simulation.

For more precise estimates of relic neutrinos from Pop III stars, we have to perform the hydrodynamical simulations. So far, there have been only a few simulations studying the gravitational collapse of Pop III stars with BH formation including appropriate microphysical treatment (Fryer et al. 2001; Nakazato et al. 2006; Suwa et al. 2007b). Nakazato et al. (2006) performed a spherically symmetric general relativistic simulation in a wide range of masses (300–10,000 M☉), in which the state-of-the-art neutrino physics is taken into account. Their detailed calculations revealed the properties of the emergent neutrino spectrum, and based on that they estimated the relic neutrino background and found that the detection for the spherically collapsing Pop III stars is difficult for the currently operating detectors. Meanwhile, current wisdom tells us that very metal-poor stars lose very small amounts of mass and angular momentum through radiatively driven stellar winds so that Pop III stars may collapse with a large angular momentum (Heger et al. 2003). Stellar rotation might vary the spectrum of emitted neutrinos and affect its potential observability, which is the motivation of this study. Fryer et al. (2001) investigated the collapse of a rotating Pop III star of mass 300 M☉ with gray-neutrino transport simulations and discussed effects of rotation on the emitted luminosities. They, however, investigated only one rotational model. Considering the uncertainty of the angular momentum distributions of the Pop III stars, a more broad study is required. More recently, we implemented a series of two-dimensional magnetorotational core-collapse simulations of Pop III stars (Suwa et al. 2007b), in which our interest was placed on the MHD effects on the formation of the jets.

In this study, we focus on the effects of rotation on the neutrino emission during the core-collapse phase of Pop III stars. For this purpose, we carry out two-dimensional simulations of rotational core collapse of Pop III stars, changing the initial strength of the angular momentum in a parametric manner. By doing so, we systematically investigate the dependence of the luminosity, the average energy, and the spectrum of neutrinos upon the rotation strength. We also pay attention to the anisotropy of the emergent neutrino energies, that is, the neutrino emission in the polar direction and in the equatorial plane. Using the spectrum of single Pop III stars, we calculate the number flux of the relic neutrino background by summing up the contribution from individual Pop III stars and discuss their detectability.

This paper is organized as follows: In the next section, we briefly introduce our numerical methods and the initial models. In Sections 3 and 4, we present the numerical results. We start with the outline of the dynamics and neutrino emission in the case of spherical collapse (Section 3) and then move on to discuss the effects of rotation on the dynamics and the neutrino luminosity (Section 4.1), the neutrino energies (Section 4.2), and the spectrum (Section 4.3). Section 5 is devoted to summary and discussion.

2. NUMERICAL TECHNIQUES AND INITIAL MODELS

For the hydro solver, we employ the ZEUS-2D code (Stone & Norman 1992) as a base and add major changes to include the microphysics appropriate for the simulation of Pop III stars. First, we have added an equation for the electron fraction in order to treat electron and positron captures and have approximated the neutrino transport by the so-called leakage scheme (Ruffert et al. 1996; Kotake et al. 2003; Rosswog & Liebendörfer 2003; Takiwaki et al. 2009). We consider three neutrino flavours: electron neutrinos, νe, electron anti-neutrinos, ν̄e, and the heavy-lepton neutrinos, νμ, ντ, ντ, which are collectively referred to as νX. Reactions of νX, pair, photo, and plasma processes are included using the rates by Itoh et al. (1989, 1996). As for the equation of state, we have incorporated the tabulated one based on relativistic mean field theory (see Shen et al. 1998). In our two-dimensional calculations, axial symmetry and reflection symmetry across the equatorial plane are assumed. Spherical coordinates (r, θ) are employed with logarithmic zoning in the radial direction and linear zoning in θ. One quadrant of the meridian section is covered with 300 (r) × 30 (θ) mesh points. We also calculated some models with 60 angular mesh points; however, there was no significant difference. Therefore, we report only the results obtained from the models with 30 angular mesh points. General relativistic gravity is taken into account approximately by an “effective relativistic potential” according to Marek et al. (2006), which is newly added in our code.

In this paper, we set the mass of the Pop III star to be 300 M☉. This is consistent with the recent simulations of the star-formation phenomena in a metal-free environment, providing the initial mass function peaked at masses 100–300 M☉ (see, e.g., Nakamura & Umemura 2001). We choose that value because we do not treat the nuclear-powered pair instability SNe (M ≲ 260 M⊙) and also to facilitate the comparison with the previous study, which employed the same stellar mass (Fryer et al. 2001).

We start the collapse simulations with a 180 M⊙ core for the 300 M⊙ star. The core, which is the initial condition of our simulations, is produced in the following way. According to the prescription in Bond et al. (1984), we set the polytropic index of the core to n = 3 and assume that the core is isentropic with ~10 k_B per nucleon (Fryer et al. 2001) with a constant electron fraction of Y_e = 0.5. We adopt a central density of 5 × 10^9 g cm^-3 at which the temperature of the central regions becomes high enough to photodisintegrate the iron (~5 × 10^8 K), thus initiating the collapse. Given the central density, the distribution of electron fraction, and the entropy, we numerically construct the hydrostatic structures of the core.

Since we know little about the angular momentum distribution in the cores of Pop III stars, we assume that the shellular rotation follows the initial rotation law

$$\Omega(r) = \Omega_0 \frac{r_0}{r^2 + r_0^2},$$

(1)

where Ω(r) is an angular velocity, r is a radius, and Ω₀ and r₀ are model parameters, which determine a total angular momentum and the degree of differential rotation, respectively. In this paper, we fixed the value of r₀ as 10^4 cm. Since the radius of the outer edge of the core is taken to be as large as 3.5 × 10^8 cm, the above profile represents a mildly differentially rotating core. Changing the initial rotational energies by varying the values of Ω₀, we compute eight models, namely, one spherical and seven rotational models. By doing so, we hope to see clearly how the dynamics and the neutrino emission deviate from those in the spherical case. We change the initial values of T/|W| from 0.01 to 2%, where T/|W| represents the ratio of the rotational to the gravitational energy. We take the model with T/|W| = 0.5% as the canonical rotating model. This is because the rotation rate is taken from the stellar-evolution calculations of extremely rapidly rotating cores of massive stars (Heger et al. 2000) as a
consequence of the study that Pop III stars could rotate rapidly due to insufficient mass loss in the main-sequence stage (Heger et al. 2003).

The shape of the neutrino spheres is important for analyzing the properties of neutrino emission. Following the common practice, we define the radius of the neutrinosphere, $R_\nu$, by the condition

$$\int_{R_\nu}^{\infty} \frac{dr}{\lambda} = \frac{2}{3},$$

where $\lambda$ is the mean free path of neutrinos. We perform the integration for each angular bin to obtain $R_\nu(\theta)$. It should be noted that the notion of a neutrinosphere is rather ambiguous. Neutrino reactions are highly energy dependent, and so the neutrinosphere should be as well. In theory, we should distinguish the last scattering surface from the surface of last energy exchange (Janka 1995). However, we stick to this approximate notion here for simplicity.

3. SPHERICAL COLLAPSE

We first outline the collapse dynamics in the case of spherical symmetry. In Figure 1, we show the time evolution of density (top left), temperature (top right), and radial velocity (bottom left) as a function of radius. Also shown is the radial velocity as a function of the mass coordinate (bottom right). We show the results for five time slices before BH formation (see Figure 1 for detail). As indicated in this figure, the core collapse of a very massive star can be divided into two phases: the infall phase ($\sim -24.1$ and $-10.1$ ms) and the accretion phase (from $-2.0$ to $0$ ms).

The infall phase sets in due to the gravitational instability induced by the photodisintegration of iron and the neutronisation that have the effect of reducing the pressure support at the core of the star, triggering a rapid collapse of the core just as an ordinary SNe progenitor. However, there are several important differences between the structures of very massive stars and ordinary SNe. As noted by previous works (e.g., Bond et al. 1984; Fryer et al. 2001; Nakazato et al. 2007), the entropy in the more massive core is larger and thus favors more complete photodisintegration of heavy elements and $\alpha$-particles so that the source of instability is reduced. This leads a thermally stabilized core.\footnote{The stability of the core depends on the adiabatic index. If the average adiabatic index is less than 4/3, the star is unstable (Shapiro & Teukolsky 1983). In the case of very massive stars, the pressure is dominated by radiation pressure, whose adiabatic index is 4/3. Since there are additional components such as the nonrelativistic nucleon, whose adiabatic index is 5/3, the mean adiabatic index is between 4/3 and 5/3 so that the core is mildly stabilized.}

This is quite different from what happens in ordinary SNe, in which the core is stabilized by nuclear forces. The core is divided into two distinct regions: the subsonic, “homologous” inner core and the supersonic outer core. The inner core becomes thermalized and stabilized.\footnote{In this paper, we define the surface of inner core as the location of maximum infall velocity.}

In the accretion phase, material in the outer core accretes onto the inner core after the thermal stabilization of the inner core, leading to the increase in mass of the inner core. We here note that the inner core continues to shrink after stabilization due to the accretion from the outer core. These features are seen in Figure 1. In the top panels and bottom left panel, the accretion shock can be seen at $\sim 2 \times 10^7$ cm for $t = 2.0$ ms and $\sim 1.5 \times 10^7$ cm for 0 ms before BH formation. The bottom right panel shows the increasing mass of the inner core. Because the outer core is out of sonic contact with its inner counterpart, an
accretion shock is formed between the two regions. It should be noted that the region just behind the accretion shock, that is the surface of the inner core, is the main source of neutrinos. This can be seen in Figure 2, which shows snapshots of the cooling rate of neutrinos, $Q_\nu$, as a function of the mass coordinate. Comparing with Figure 1, we find that the maximum cooling rate is just behind the accretion shock.

In the case of very massive stars, the inner core is more massive than the maximum mass of neutron stars so that these stars collapse to black holes directly. As for the nonrotating model, the initial mass of the BH is $\sim 5 M_\odot$. This is significantly smaller than our previous result, 20 $M_\odot$, for the nonrotating model in Suwa et al. (2007b), because of general relativistic effects that are newly implemented in this study. Although the core is stable in Newtonian gravity, the hot core is not stable when general relativistic effects are considered because the thermal energy also contributes to the gravitational potential. In our case, the temperature is so high that general relativistic effects become important because the critical temperature, above which the core becomes unstable, is $T_{\text{crit}} \sim 10^{12} \text{K}$ (see the discontinuity of the bottom right panel, $\sim 11 M_\odot$, in Figure 1 for core mass and the top right panel, $\sim 1.5 \times 10^7 \text{cm}$ for temperature). This instability drives further collapse of the inner part of the core, which can be seen in the radial velocity profile (see again the bottom panels in Figure 1). This feature is also seen in Nakazato et al. (2006), which is a fully general relativistic simulation (see Figure 2 in their result). Although the BH is smaller than the inner core at first, the inner core will be soon swallowed completely. Here we note that following Fryer et al. (2001) and Suwa et al. (2007b), BH formation is ascribed to the condition $\frac{\Delta m}{\Delta r} > r$, where $c$, $G$, and $m(r)$ are the speed of light, the gravitational constant, and the mass coordinate, respectively. This condition means that we assume that fluids cannot escape from the inner region below the radius of the marginally stable orbit of a Schwarzschild BH. When this condition is satisfied, we excise the region inside and then treat it as an absorbing boundary. Then, we enlarge the boundary of the excised region to take into account the growth from the mass infalling into the central region. Although it is not accurate at all to refer to the central region as a BH, we adhere to this simplification in order to follow and explore the dynamics later on.

Next, we mention the neutrino emission and its relation to dynamics. The time evolution of the neutrino luminosity, $L_\nu \equiv \int Q_\nu \: dV$, is shown in Figure 3. As the collapse proceeds, the density and temperature of the central region both increase, increasing the neutrino luminosity. As the density increases during core collapse, the opacity rises and the neutrinosphere is formed, in which the neutrino emission–absorption equilibrium is achieved. The relation of the radii of the inner core surface, $R_{\text{ic}}$, and neutrinosphere, $R_\nu$, is very important for the luminosity of neutrinos because the inner core is the main source of neutrino emission as already shown in Figure 2. Roughly speaking, if $R_{\text{ic}} \gtrsim R_\nu$, emissivity is the largest just behind the shock and, consequently, the luminosity is also large. On the other hand, the luminosity becomes small if $R_{\text{ic}} \gtrsim R_\nu$ because the emitted neutrinos cannot escape directly and interact with matter. In this case, the maximum value of the emissivity appears between the inner core surface and the neutrinosphere. In Figure 4, we show the evolution of radii of the inner core, neutrinospheres, and the BH as a function of time. The inner core surface goes down inside the neutrinospheres, which results in the peak in the evolution of luminosity shown in Figure 3 (see dots A and B in Figures 3 and 4). In addition, after BH formation the luminosity decreases due to the absorption of neutrino-emitting matter. Finally, the neutrinosphere gets swallowed by the BH and the emission of neutrinos almost terminates.

4. ROTATIONAL COLLAPSE

4.1. Features of Neutrino Luminosity

We now investigate how rotation affects the properties of the neutrino emission. The peak luminosity and total energy emitted by neutrinos for different values of the initial rotation rate, $T/|W_{\text{lim}}|$, are shown in Table 1. Interestingly, and maybe counterintuitively, it is found that the peak neutrino luminosity increases with the initial rotation rate (see Table 1).
This is because the inner core can partly extend outside the neutrinosphere, due to rotation, so that \( R_{ic} \gtrsim R_v \) is achieved, and the degree of the deformation becomes larger for more rapidly rotating models. In the following, we explain this feature in more detail.

Figures 4 and 5 show the time evolution of radii of neutrinospheres and the inner core for the nonrotating model and the rotating model with \( T/W_{\text{init}} = 0.5\% \), respectively. Note again that we set the model with \( T/W_{\text{init}} = 0.5\% \) to be the reference rotating model according to Heger et al. (2000, 2003). For the nonrotating model (Figure 4), the inner core becomes smaller than the surfaces of all of the neutrinospheres just before BH formation (see the evolutions after B in Figure 4). On the other hand, for the rotating model, the inner core is broadened in the equatorial plane due to the centrifugal forces (see left panel of Figure 5) and exists outside of the neutrinosphere of \( \nu_X \). Moreover, the inner core surface is located outside of the neutrinosphere of \( \nu_e \) along the polar axis (right panel). The above effects make the neutrino luminosities larger for the rotating models. In Figure 6, the global shapes of neutrinospheres of \( \nu_e \), and \( \nu_X \), and the inner cores just before BH formation for both the spherical model and the rotating models (with \( T/W_{\text{init}} = 0.1\% \) and \( 0.5\% \)) are presented. It is clearly seen from the comparison with the nonrotating model that neutrinospheres are more deformed for more rapidly rotating models. As the initial rotation rate becomes larger, the deformed inner core is shown to have larger surfaces approaching the neutrinospheres than the nonrotating model. As for the model with \( T/W_{\text{init}} = 0.5\% \), the inner core extends outside the neutrinosphere of \( \nu_X \) entirely.

The time evolution of the neutrino luminosity for models with different initial strengths of rotation is shown in Figure 7. For slow-rotation models (\( T/W_{\text{init}} \lesssim 0.1\% \)), the luminosity properties of \( \nu_e \) and \( \bar{\nu}_e \) are shown to not depend on the strength of rotation. On the other hand, the luminosity of \( \nu_X \) gets larger as the initial rotation gets faster. This is because the radius of the neutrinosphere of \( \nu_X \) is not shown in this figure because \( R_{\nu} \sim R_{ic} \).

### Table 1

| \( T/W_{\text{init}} \) (%) | \( L_{\text{peak}} \) (10^{54} \text{ erg s}^{-1}) | \( E_{\text{total}} \) (10^{53} \text{ erg}) |
|-----------------|--------------------|----------------------|
| 0               | 1.11               | 6.57                 |
| 0.01            | 1.17               | 6.78                 |
| 0.05            | 2.17               | 8.30                 |
| 0.1             | 4.19               | 11.3                |
| 0.3             | 7.55               | 22.2                |
| 0.5             | 8.22               | 29.6                |
| 1               | 8.64               | 40.8                |
| 2               | 8.44               | 52.4                |

**Notes.** \( T/W_{\text{init}} \) means the initial ratio of the rotational energy, \( T \), and the gravitational energy, \( W \). \( L_{\text{peak}} \) represents the peak total luminosity of neutrinos. \( E_{\text{total}} \) is the total energy emitted by neutrinos.
inner core. For slow-rotation models, only $\nu_X$ shows such a decrement because the neutrinosphere of $\nu_X$ is the smallest and it is consequently absorbed first and is inside the BH when the BH forms. On the other hand, the neutrinospheres of $\nu_e$ and $\bar{\nu}_e$ remain outside the BH at the onset of BH formation and are absorbed as the BH grows. The luminosity of $\nu_e$ and $\bar{\nu}_e$ decreases with the dynamical timescale ($\sim O(10)$ ms) of the region of the neutrinospheres. For fast-rotation models, all species show a drastic decrease because all neutrinospheres are partly or entirely in the BH region when it forms (see Figure 5 again) because the rapid rotation leads to a larger initial mass of the BH (see Suwa et al. 2007b).

We find that rotation enhances the total energy released by neutrinos. The total energy emitted in the form of neutrinos during the collapse is summarized in Table 1. It can be seen that for the nonrotating model the total radiated energy amounts to $6.6 \times 10^{53}$ ergs. This result is in good agreement with the simulation of Nakazato et al. (2006), who included neutrino transport during the collapse of a 300 $M_\odot$ Pop III star. They found a total energy output of $\sim 4 \times 10^{53}$ erg. The strong rotation models show larger energy emission. This is because rotation enhances the neutrino luminosity as already described. In addition, rotation delays BH formation by the centrifugal force, which leads to a longer duration of neutrino emission. These two effects account for the increase of radiated energy by neutrinos as the strength of rotation increases.

4.2. Features of Neutrino Energy

We discuss the effects of rotation on the emitted neutrino energies in this subsection. We consider the averaged neutrino energy, $\langle E_\nu \rangle \equiv \int Q_\nu \, dV \, dt / \int N_\nu \, dV$, where $N_\nu$ is the number density of emitted neutrinos. Figure 8 shows the difference of the average energy as a function of $T/|W|_{\text{init}}$. It can be seen that the average energies basically increase with the initial rotation rate, except for $\nu_X$ of the rapid-rotation model. It should be noted that the energy of $\nu_X$ is more sensitive to the rotation strength than that of the other species because the neutrinosphere of $\nu_X$ forms the deepest in the core. In fact, only $\nu_X$ is affected for relatively slow rotation ($T/|W|_{\text{init}} \lesssim 0.1\%$). As rotation becomes stronger, the energies of $\nu_e$ and $\bar{\nu}_e$ are gradually changed. Although the average energies of neutrinos basically follow the standard order sequence, namely $\langle E_{\nu_e} \rangle < \langle E_{\bar{\nu}_e} \rangle < \langle E_{\nu_X} \rangle$ as described in Iocco et al. (2005), $\langle E_{\nu_X} \rangle$ is found to be smaller than $\langle E_{\nu_e} \rangle$ for the model with $T/|W|_{\text{init}} = 2\%$. The strong centrifugal force interrupts the contraction of the inner part of the core, leading to the suppression of the releasable gravitational energy and thus smaller energy of neutrinos.

Next, we focus on the anisotropy of the neutrino energies and emission. The spatial distribution of the average energy of $\nu_e$ just before BH formation, with and without rotation, is depicted in Figure 9. It can be seen that due to the rotational flattening of the neutrinosphere (blue line) near the polar regions (right
Figure 7. Time evolution of neutrino luminosity for all models. $\nu_e$, $\bar{\nu}_e$, and $\nu_X$ are represented by solid, dotted, and dashed lines, respectively.

Figure 8. Total average energy of neutrinos, $\langle E_{\nu} \rangle \equiv \int dV Q_{\nu} dP_{\nu}/d\epsilon$, where $N_\nu$ is the number density of emitted neutrinos, as a function of $T/|W|_{\text{init}}$. The solid, dotted, and dashed lines represent $\nu_e$, $\bar{\nu}_e$, and $\nu_X$, respectively.

panel), the neutrinos achieve higher temperature just inside the neutrinosphere, leading to the emission of higher-energy neutrinos. In addition, the direction of anisotropy of the energies can be seen in the rotating model. In the polar direction, the inner core surface is almost coincident with the neutrinosphere (see Figures 5 and 6 again) so that neutrinos with high energy that are produced just inside the inner core can escape. On the other hand, the optical depth is $\sim 5$ at the inner core on the equatorial plane and a few neutrinos with high energies can escape. These effects, irrespective of the neutrino flavors, make the neutrino spectrum of the rotating model broader and harder than the nonrotating model, which will be useful for the discussion in the following subsection.

### 4.3. Neutrino Spectrum and Relic Background

In this subsection, we discuss the features of the neutrino spectrum and the effects of rotation. We calculate the neutrino luminosity spectrum as follows:

\[
\frac{dL_{\nu\alpha}}{d\epsilon'}(t) = \int dV Q_{\nu\alpha} \frac{dP_{\nu\alpha}}{d\epsilon'},
\]

where $Q_{\nu\alpha}$ is the emissivity for $\nu_{\alpha}$ ($\nu_{\alpha} = \nu_e, \bar{\nu}_e, and \nu_X$) and $dP_{\nu\alpha}/d\epsilon$ is the normalized Fermi-Dirac distribution,

\[
\frac{dP_{\nu\alpha}}{d\epsilon} = \frac{2}{3\zeta^3 T_{\nu\alpha}^3} \frac{\epsilon^2}{e^{\epsilon/T_{\nu\alpha}} + 1},
\]

where $\epsilon'$ is the energy of emitted neutrinos in the source frame and $T_{\nu\alpha} = 180\zeta_3 (\epsilon_{\nu\alpha}^e)/7\pi^4$ is the effective neutrino temperature with $\langle \epsilon_{\nu\alpha}^e \rangle$ being the local average energy of $\nu_{\alpha}$. Figure 10 shows the time-integrated energy spectrum, $\int dt (dL_{\nu\alpha}/d\epsilon')$, of $\nu_e$, $\bar{\nu}_e$, and $\nu_X$ for the model with $T/|W|_{\text{init}} = 0.5\%$. It can be seen that the spectrum of $\nu_X$ (dashed line) is harder than $\nu_e$ (solid line) and $\bar{\nu}_e$ (dotted line), as already described in the previous subsection. Figure 11 shows time-integrated energy spectrum of $\nu_e$ for models with $T/|W|_{\text{init}} = 0, 0.5, and 2\%$. It is obvious that the spectra of rotating models (dashed and thick dotted lines) are higher and harder than nonrotating model (solid line). In this figure, the thin dotted line represents a single temperature spectrum for comparison to the previous works. This spectrum is the Fermi-Dirac distribution calculated by the temperature $T_{\nu_e} = 180\zeta_3 \langle E_{\nu_e} \rangle / 7\pi^4$, with $\langle E_{\nu_e} \rangle$ being the
averaged neutrino energy of the model with $T/W_{\text{init}} = 0.5\%$. The normalization of the spectrum is determined by the total energy emitted by $\nu_e$. It can be seen that the calculated spectrum (thick dotted line) is harder than that with a single temperature. This is because the neutrino temperature is not a simple, single-temperature component, but rather consists of multiple-temperature components, depending on the time and position. It should be noted that the time evolution of the average energy of neutrinos from Pop III stars is drastic unlike the ordinary core-collapse SNe, which do not show a significant change in the temperature components, depending on the time and position. It is calculated by volume integration with the cosmic baryon–photon ratio, $\eta$, and the energy of neutrinos in the source frame, which appears in Equations (3) and (4), $f_{\text{III}}$ is the fraction of all baryons going through Pop III, $n_\gamma \simeq 410 \text{ cm}^{-3}$ is the cosmic microwave background photon density at redshift zero, $\eta \simeq 6.3 \times 10^{-10}$ is the cosmic baryon–photon ratio, $m_N$ is the nucleon mass, $M_{\text{III}}$ is the mass of Pop III stars, $\psi(z)$ is the normalized star-formation rate, and $dN_{\nu_e}/d\epsilon$ represents the number spectra at the source frame, which is also calculated by volume integration with the normalized Fermi–Dirac distribution (Equation 4). We assume that the star-formation rate is concentrated around a redshift $z \sim 10$, that is, $\psi(z) = \delta(z - 10)$. In addition, we assume that all Pop III stars have the same mass, $M_{\text{III}} = 300 M_\odot$. We used the result of the $T/W_{\text{init}} = 2\%$ model to calculate the relic neutrino flux. Since star-formation history is not observationally well-constrained at high $z$, we consider samples of $f_{\text{III}}$ as $10^{-1}$, $10^{-3}$, and $10^{-5}$. Figure 12 shows the calculated number flux spectrum of $\bar{\nu}_e$. If we adopt the largest value for $f_{\text{III}}$, the diffuse antineutrino flux from Pop III dominate those from ordinary SNe (dashed line) below $\sim 7$ MeV. The dotted line represents the flux from the model with $T/W_{\text{init}} = 0\%$ and $f_{\text{III}} = 10^{-3}$.

Figure 9. Average energy distribution of $\nu_e$ and the shape of neutrinosphere just before BH formation for models with $T/W_{\text{init}} = 0\%$ (left) and $0.5\%$ (right). The blue and green solid lines represent the position of the neutrinosphere and the inner core, respectively. The central black part corresponds to the region with the optical depth of neutrino being beyond ten, where neutrinos are almost trapped.

(A color version of this figure is available in the online journal.)

Figure 10. Energy spectra of neutrinos for the model with $T/W_{\text{init}} = 0.5\%$. The red solid, green dotted, and blue dashed lines represent $\nu_e$, $\bar{\nu}_e$, and $\nu_X$, respectively.

(A color version of this figure is available in the online journal.)

Figure 11. Energy spectrum of $\nu_e$ for model with different values of $T/W_{\text{init}}$. The red solid, green thick dotted, and blue dashed lines represent $T/W_{\text{init}} = 0$, 0.5, and 2%, respectively. The green thin-dotted line shows the spectrum with the single-temperature Fermi–Dirac distribution function (see Section 4.3 for discussion).

(A color version of this figure is available in the online journal.)
fraction of Pop III stars, the solid lines, we employed the result of the following: view of the neutrino luminosity and the average energy, and studied the deformation of neutrinospheres and investigated computed eight models, changing the initial strength of the an-

Comparing with the second solid line from the top, we can see the amplification of the relic neutrino flux by the stellar rotation.

5. SUMMARY AND DISCUSSION

We performed a series of two-dimensional hydrodynamic simulations of rotational collapse of Pop III stars. We computed eight models, changing the initial strength of the angular momentum in a parametric manner. We systematically studied the deformation of neutrinospheres and investigated the degree of anisotropic neutrino emission from the point of view of the neutrino luminosity and the average energy, and their impact on the neutrino spectrum. Then we found the following:

1. The neutrino luminosity increases for more rapidly rotating cores. This is because the inner core, which is the dominant neutrino source, is deformed due to rotation and can extend outside the neutrinospheres. In particular, \( \nu_Y \) is most sensitive to rotation because its neutrinosphere is located at the smallest radius and nearest to the inner core. The total energy emitted by neutrinos also increases with the strength of rotation.

2. The average energy of emitted neutrinos gets larger as rotation becomes faster. In addition, the energy is larger in the polar direction than in the equatorial plane due to rotation. The neutrino spectrum gets broader and harder for rotating models. As a result, the number spectrum of the relic neutrinos also gets harder so that the relic neutrinos from Pop III stars overwhelm those from an ordinary core-collapse supernovae (blue dashed line) according to Ando et al. (2003).

(A color version of this figure is available in the online journal.)

Figure 12. Calculated number flux of \( \nu_e \) (red solid lines). The employed baryon fraction of Pop III stars, \( f_{\text{B}} \), is \( 10^{-2} \), \( 10^{-3} \), and \( 10^{-5} \) from top to bottom. As for the solid lines, we employed the result of the \( T/W_{\text{lin}} = 2\% \) model. The dotted line represents the flux with the \( T/W_{\text{lin}} = 0\% \) model and \( f_{\text{B}} = 10^{-3} \). For comparison we show the diffuse flux from ordinary core-collapse supernovae (blue dashed line) according to Ando et al. (2003).

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