DYNAMICS AND NEUTRINO SIGNAL OF BLACK HOLE FORMATION IN NONROTATING FAILED SUPERNOVAE. II. PROGENITOR DEPENDENCE

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ABSTRACT

We study the progenitor dependence of black hole formation and its associated neutrino signal due to the gravitational collapse of a nonrotating massive star, following on our previous study of a single progenitor model. We aim to clarify whether the dynamical evolution toward black hole formation occurs in the same manner for different progenitors and to examine whether the characteristic of neutrino bursts having short duration and rapidly increasing average energies is a general one. We perform numerical simulations using general relativistic neutrino radiation hydrodynamics to follow the dynamical evolution from the collapse of 40 and 50 $M_\odot$ presupernova models to black hole formation via contracting proto–neutron stars. For the three progenitor models studied in this paper, we find that black hole formation occurs $\sim$0.4–1.5 s after core bounce through an increase of the proto–neutron star mass, accompanied by a short and energetic neutrino burst. The density profile of the progenitor is important in determining the accretion rate onto the proto–neutron star and, therefore, the duration of the neutrino burst. We compare the neutrino bursts of black hole–forming events from different progenitors and discuss whether they can be used to probe clearly the progenitor and the dense matter.

Subject headings: black hole physics — equation of state — hydrodynamics — neutrinos — stars: neutron — supernovae: general

Online material: color figures

1. INTRODUCTION

The final fate of massive stars is a key issue in stellar physics as well as astrophysics. Stars more massive than $\sim 8 M_\odot$ are the origin of compact objects, neutron stars and black holes, as the result of gravitational collapse at the end of their lives. They also contribute to the production of heavy elements through explosive nucleosynthesis and to high-energy phenomena by giving off bursts of electromagnetic radiation and neutrinos, which in turn play important roles in the evolution of galaxies. Massive stars in the wide range between $\sim$8 and $\sim$100 $M_\odot$ produce various explosive phenomena such as core-collapse supernovae, hypernovae (or gamma-ray bursts), and failed supernovae (Heger et al. 2003). Such energetic phenomena depend on the properties of the progenitor, such as mass, rotation, and profiles—for example, as in the mass limit for ordinary supernovae and the branching between hypernovae and failed supernovae as a function of mass (Maeda & Nomoto 2003). We focus here on the fate of nonrotating massive stars, as an extreme example of failed supernovae, in the mass range $\sim$40–50 $M_\odot$.

The death of such massive stars has attracted attention recently, since it is a possible channel for black hole formation and is characterized by unique neutrino signals (Liebendörfer et al. 2004; Sumiyoshi et al. 2006, 2007) of short duration and with average energies and luminosities increasing over time. This is in contrast to the neutrinos from ordinary supernovae, whose emission from the nascent proto–neutron star lasts for $\sim$20 s with a gradual decrease of average energy and luminosity (Burrows 1988; Suzuki 1994). Black hole formation is inevitable for stars more massive than $\sim 40 M_\odot$, the value estimated by Fryer (1999), with large uncertainties, to be the threshold for black hole formation. The dynamical collapse to a black hole is triggered by intense accretion of matter onto the proto–neutron star. Note that this is different from so-called delayed black hole formation by a proto–neutron star of fixed mass (Keil & Janka 1995; Baumgarte et al. 1996a; Pons et al. 1999) owing to the termination of accretion after the successful launch of a shock wave. It should be also emphasized that the neutrino signal may be used as a probe into the equation of state of nuclear matter (Sumiyoshi et al. 2006) and exotic matter (Nakazato et al. 2008) in a different way from the delayed collapse of proto–neutron stars (Pons et al. 2001a, 2001b).

This is the second paper, following Sumiyoshi et al. (2007, hereafter Paper I), in a series studying black hole formation associated with short bursts of energetic neutrinos. In Paper I, the evolution toward black hole formation from the gravitational collapse of a 40 $M_\odot$ star was examined, taking into account the dependence on the equation of state. By solving the equations of general relativistic neutrino radiation hydrodynamics, we followed the dynamics up to the moment of black hole formation and the neutrino distribution over the course of the evolution to ascertain the details of the neutrino emission. These simulations showed that black hole formation occurs $\sim$1 s after core bounce via proto–neutron star evolution but depends crucially on the
equation of state (EOS) of dense matter. The EOS controls the timing of the recollapse from proto–neutron star to black hole, since it determines the maximum mass. The mass of the proto–neutron star increases as a result of the accretion of material in the situation of a failed shock wave, and dynamical collapse is triggered when the mass reaches a critical value. We note that the 40 $M_{\odot}$ progenitor model from Woosley & Weaver (1995) has been adopted in our and other studies of such massive stars (e.g., Liebendo¨rfer et al. 2004).

In Paper I, the associated neutrino burst was shown to be a unique way to identify black hole formation and to probe the properties of dense matter. The burst is terminated by formation of the black hole, and the average neutrino energies increase toward the end because of the high temperature realized in the collapsing proto–neutron star. These features are again sensitive to the properties of the EOS, which determines the duration of the burst and the properties of the compressed matter in the neutrino-emitting region. Such neutrino bursts can, in principle, be detected at terrestrial neutrino detector facilities (Ikedo et al. 2007) and can be used as a marker of black hole formation and a probe of dense matter (Sumiyoshi et al. 2006). Moreover, if a massive star collapses in a nearby galaxy, the event may be observed—for example, in the survey for the disappearance of massive stars proposed by Kochanek et al. (2008)—making it possible to obtain information on the progenitor. However, one has to constrain the detailed features of the neutrino bursts by taking care of uncertainties in the progenitor models, in addition to the models of dense matter, if one wants to use them as templates in such a search.

In this study, we make a first attempt to see whether the features of black hole formation reported in Paper I carry over to different progenitors. We adopt three stellar models as the initial conditions for the numerical simulations to compare with the evolution from the modeling in Paper I. In addition to the 40 $M_{\odot}$ stellar model from Woosley & Weaver (1995), we employ models from Hashimoto (1995) and from Tominaga et al. (2007). As a case with different mass, we adopt a 50 $M_{\odot}$ star from Tominaga et al. (2007), who studied the evolution of metal-poor, massive stars. We chose the model with zero metallicity among their series of different metallicities. This is the limiting case for metal-poor massive stars without mass loss. For a model with the same mass (40 $M_{\odot}$) but from a different method of stellar evolutionary calculation, we adopt a 40 $M_{\odot}$ star from Hashimoto (1995). The comparison between the different models enables us to explore the dependence of the numerical results on the uncertainties in the stellar evolution.

Investigating the progenitor dependence is important in order to utilize neutrino bursts as a probe of the equation of state. If the bursts are quite different depending on the progenitor, it becomes difficult to distinguish the differences produced by the EOS. Using two different equations of state (Lattimer & Swesty 1991; Shen et al. 1998a, 1998b), it was shown in Sumiyoshi et al. (2006) that the burst duration can differ by a factor of $\sim 2$ depending on the softness of the EOS. If the various progenitor models produce large differences, they may smear out the EOS difference, which we want to use as a probe.

Our aim in the paper is, therefore, to make a first exploration of the dependence on the progenitor by adopting a small number of stellar models and to show that the dynamics approaching black hole formation is in common among massive stars having a large central iron core. We also aim to demonstrate that the neutrino signal has similar features once we set the EOS.

We analyze how the evolution is related to the density profile of the progenitor, which determines the accretion rate. We discuss the characteristics of neutrino bursts obtained for different progenitors with two sets of equation of state for possible detection in the future.

The plan of the paper is as follows: We briefly explain the numerical simulations in § 2. We compare the progenitors adopted for the initial models and discuss the differences in § 3. We report the numerical results on the dynamics in §§ 4.1 and 4.2 for two models through a comparison with the previous result. We describe the accretion rates and the temperature and density profiles during the evolution in §§ 4.3 and 4.4 to explain the differences among the models. We discuss the characteristics of the neutrino signals in the models to distinguish the progenitor and the EOS in § 4.5. Implications of this work and a summary are presented in §§ 5 and 6.

2. NUMERICAL SIMULATIONS

The numerical simulations are performed with a numerical code for general relativistic neutrino radiation hydrodynamics under spherical symmetry (Yamada 1997; Yamada et al. 1999; Sumiyoshi et al. 2005). This code has been applied to the gravitational collapse of massive stars to study supernova explosions (Sumiyoshi et al. 2005) and black hole formation (Sumiyoshi et al. 2006, 2007; Nakazato et al. 2006, 2007). A detailed description of the numerical simulations of the gravitational collapse toward black hole formation can be found in Paper I, which also reports the results for a 40 $M_{\odot}$ progenitor (Woosley & Weaver 1995). We adopt the same number of grid points for the Lagrangian mass coordinate and variables in the neutrino distributions for $\nu_e$, $\bar{\nu}_e$, $\nu_{\mu}/\tau$, and $\bar{\nu}_{\mu}/\tau$. The mesh for the mass coordinate is optimized for each progenitor model to follow the accretion phase with enough resolution using a rezeroing method.

Using a fully implicit method for the neutrino radiation hydrodynamics enables us to follow the extended evolution for over $\sim 1$ s toward black hole formation. The exact treatment of neutrino transfer together with the hydrodynamics under general relativity permits a detailed evaluation of the neutrino fluxes from the contracting proto–neutron stars until black hole formation. We identify the latter by finding the apparent horizon, as explained in Nakazato et al. (2006) and Paper I.

We treat the microphysics in the same manner as in Paper I to facilitate comparison of the new results with the previous result for a 40 $M_{\odot}$ progenitor. We use two sets of equations of state for the supernova simulations to assess the influence of the EOS on different progenitors. The EOS from Shen et al. (1998a, 1998b; hereafter the “Shen EOS”), which is obtained in the relativistic mean field framework with data on unstable nuclei, is rather stiff, having a maximum neutron star mass of 2.2 $M_{\odot}$. The EOS from Lattimer & Swesty (1991; the “LS EOS”) is obtained through an extension of the compressible-liquid model, taking a density dependence of energy based on the Skyrme interaction. We have chosen the case with an incompressibility of 180 MeV among the three options in the LS EOS as representative of a soft EOS, having a maximum neutron star mass of 1.8 $M_{\odot}$. The same set of weak interaction rates as in Paper I is adopted for the current simulations, by implementing the standard formulation of Bruenn (1985) and several extensions (Sumiyoshi et al. 2005).

3. INITIAL MODELS

We adopt three different profiles from the presupernova models of massive stars as initial models. We have picked massive stars around 40 $M_{\odot}$, which are massive enough to form black holes without a successful explosion. The choice of progenitor models in the current study is meant as a first and small-scale trial exploration and does not reflect the possible great variety
of massive stars. We use the central part of the presupernova profiles, up to 3 \( M_\odot \) in baryon mass coordinate, and set the density, electron fraction, and temperature distributions as initial configurations for the simulations.

As a baseline model, we adopt a 40 \( M_\odot \) star from the set of massive stars by Woosley & Weaver (1995). This model has been used for our previous calculations of black hole formation, and the details of the numerical results can be found in Paper I. We call this model W40 and use it as a reference to examine the new results. The size of the iron core in this model is 1.98 \( M_\odot \). As an example of another type of massive star, we adopt a case with 50 \( M_\odot \) and zero metallicity (\( Z = 0 \)) from a series of massive stars having low metallicity (Umeda & Nomoto 2005; Tominaga et al. 2007). These zero-metal stars do not experience mass loss during stellar evolution and remain as massive as in the initial stage (Umeda et al. 2000). This choice is meant to explore the dependence of the phenomena on the progenitor mass and the stellar evolution. The size of the iron core in this model is 1.88 \( M_\odot \). We call this model H40.

We compare the profiles of the three adopted models in Figure 1. One can see quantitative differences among the three, although the profiles look similar at first glance. The density in models T50 and H40 are higher than that of W40 in the central region, whereas the trend reverses in the outer region. This difference in profile gradients from the center to the outer part is related to different accretion rates onto the proto-neutron star. In fact, the densities at baryon mass coordinate \( M_b = 2-3 \ M_\odot \), which covers the range of maximum proto-neutron star masses, are crucial to determining the final stage of the accreting proto-neutron star through the free-fall timescale \([1/(G\rho)^{1/2}]\).

4. NUMERICAL RESULTS

We present the numerical results for models T50 (§ 4.1) and H40 (§ 4.2) through a comparison with the baseline model W40. We add a letter, S or L for Shen or LS, respectively, to denote the choice of EOS. The calculated models are summarized in Table 1. We discuss the differences among the three models and their implications in §§ 4.3–4.5.

4.1. 50 \( M_\odot \) Star from Tominaga et al.

We show the radial trajectories of mass elements as a function of time after core bounce for models T50S and T50L in Figures 2 and 3, respectively. The trajectories are plotted every 0.02 \( M_\odot \) in mass coordinate. Thicker lines denote the trajectories for 0.5, 1.0, 1.5, 2.0, and 2.5 \( M_\odot \). The thick dashed line represents the position of the shock wave.

The general features of the evolution are similar to the corresponding W40 models. After core bounce, a shock wave is launched out to \( \sim 150 \) km in 0.1 s and then recedes gradually toward the surface of the central object. The nascent neutron star shrinks as a result of the mass increase, slowly in T50S and quickly in T50L, due to the intense accretion. Dynamical collapse occurs when the proto-neutron star’s mass exceeds a critical value, which depends on the stiffness of the EOS, and a black hole is formed.

The time from core bounce to black hole formation is 1.51 s and 0.51 s for models T50S and T50L, respectively, reflecting the difference between the Shen and LS EoSs. The duration in T50S is slightly longer than that in W40S, while the duration in T50L is slightly shorter than that in W40L. This is because the

### Table 1: Summary of Calculated Models

| Model     | Progenitor | \( M_{\text{Fe}} \) (\( M_\odot \)) | \( M_{\text{Fe}} \) (\( M_\odot \)) | \( M_{\text{max}} \) (\( M_\odot \)) | \( M_{\text{max}} \) (\( M_\odot \)) | \( t_{\text{BH}} \) (s) |
|-----------|------------|-----------------------------------|-----------------------------------|-----------------------------------|-----------------------------------|----------------------|
| W40S...... | WW95       | 40                                | 1.98                              | 2.66                              | 2.38                              | 1.35                 |
| W40L...... | WW95       | 40                                | 1.98                              | 2.10                              | 1.99                              | 0.57                 |
| T50S...... | TUN07      | 50                                | 1.88                              | 2.65                              | 2.33                              | 1.51                 |
| T50L...... | TUN07      | 50                                | 1.88                              | 2.11                              | 2.01                              | 0.51                 |
| H40L...... | H95        | 40                                | 1.88                              | 2.17                              | 2.08                              | 0.36                 |

Notes.—\( M_{\text{Fe}} \) and \( M_{\text{max}} \) are the mass of the progenitor and the iron core, respectively; \( M_{\text{max}} \) and \( M_{\text{max}} \) are the masses of the proto-neutron star just prior to the recollapse in baryon and gravitational masses, respectively; \( t_{\text{BH}} \) is the time to the black hole formation, measured from core bounce.

\* (WW95) Woosley & Weaver 1995; (TUN07) Umeda & Nomoto 2005, Tominaga et al. 2007; (H95) Hashimoto 1995.
accretion rate is different between models T50 and W40 in a time-dependent manner, as we will see in § 4.3.

The duration of the neutrino burst is determined by the time to black hole formation. In Figures 4 and 5, we display the time evolution of the average energies and luminosities of neutrinos emitted during the evolution described above. The corresponding results with the same EOS but using the W40 progenitor model are shown by thin lines to illustrate the progenitor dependence. In general, the features of the neutrino emission for T50 resemble those for W40. The average energies for all species show the tendency of increasing after core bounce. Among these, the persistent increase for $\nu_\mu\tau$ is remarkable. Looking more closely, small differences appear at late phases (after $\sim$0.4 s). The luminosities for T50S become clearly lower than those for W40S in the late phases. This is related to a lower accretion rate in T50 than in W40 at $\sim$1 s after bounce (see Fig. 8 below).

We note that a rapid decrease of neutrino energies due to gravitational redshift expected in the terminal phase has not been observed yet in the current simulations. One would have to follow the evolution further (\leq 20 ms) after the formation of the apparent horizon. For that purpose, however, a singularity-avoiding scheme (Baumgarte et al. 1996b) should be implemented. We note also that some of the wiggles and jumps seen in Figures 4 and 5 are numerical artifacts caused by insufficient numerical resolution in the final phase of the simulations.

4.2. 40 $M_\odot$ Star from Hashimoto

We display the radial trajectories of mass elements as a function of time after core bounce for model H40L in Figure 6. The line styles are the same as in Figure 2. In this case, the evolution is much quicker than in models W40L and T50L. The time to black hole formation is 0.36 s in H40L. Since the accretion rate in H40 is larger than those in W40 and T50, the proto–neutron star reaches the critical mass earlier (see § 4.3). The contraction of the central object is accordingly quick, and therefore, the interior density and temperature reach high values early on. It can be seen that the position of the shock wave behaves in a
different manner than in the other cases, staying around 100 km after initial launch instead of receding. This is mainly because of the high neutrino luminosity, due to the high accretion rate.

We show the time evolution of the average neutrino energies and luminosities in Figure 7. The duration of the neutrino burst is clearly shorter than that of W40L. The average $\nu_\mu\tau$ energy is larger and increases much faster than that of W40L, reflecting the different temperatures, whereas those of $\nu_e$ and $\bar{\nu}_e$ behave similarly. The neutrino luminosities of all species in model H40L are higher than those in W40L. The $\nu_e$ and $\bar{\nu}_e$ luminosities are proportional to the accretion luminosity ($\dot{M}M/r$) and are high because of the high accretion rate ($\dot{M}$) and a more massive object ($M$) at the center. The high $\nu_\mu\tau$ luminosity originates from the high temperature in the massive object. The fact that the luminosity reflects the behavior of the accretion luminosity has also been seen for the neutrino emission at shock breakout in the core collapse of 11–20 $M_\odot$ stars (Thompson et al. 2003). The larger accretion rates found in the current study of 40–50 $M_\odot$ stars lead to a more rapid increase of luminosity than for less massive stars.

4.3. Accretion Rate

As discussed above, the accretion rate is a key factor to determine the behavior in the approach toward black hole formation. In other words, the rate of increase of the proto–neutron star’s mass is crucial to determining the growth time to critical mass. We show in Figure 8 the baryon mass of the central object (corresponding to the proto–neutron star) as a function of time after bounce. We define here the central object, which is quasi-hydrostatic, as the region inside the position of the shock wave. Note that the time derivative (i.e., the gradient) of the mass curve
is the accretion rate. After core bounce, the central object acquires $\sim 1.5 M_\odot$ within 50 ms. The proto–neutron star, with a typical mass, is formed immediately after the core bounce. This feature is common to all models of black hole–forming collapse and is different from the case of ordinary supernovae, for which the proto–neutron star ($\sim 1.5 M_\odot$) formation takes place over $\sim 0.3$ s (Burrows 1988; Suzuki 1994). The mass increases gradually toward the critical value in each model, and the dynamical collapse to a black hole occurs at the end point. The end point depends on the adopted progenitor and the EOS.

Amazingly, the mass increase is similar in models W40 and T50. Although the masses for T50 are slightly larger up to 0.6 s after bounce, their gradients (the accretion rate) are the same, judging from the parallel curves between T50S and W40S (and T50L and W40L). This similarity is the reason why the evolution of T50 and W40 and the resulting neutrino signals are quite similar. Adopting the LS EOS, black hole formation occurs around the same time ($\sim 0.5$ s) in the cases of T50L and W40L. For the Shen EOS, however, there is a difference of about 0.2 s between T50S and W40S. This is due to a smaller late-phase accretion rate in T50 ($\lesssim 0.6$ s after bounce) than in W40, as can be seen from the crossing of the curves for T50S and W40S. We note that the small accretion rate at late phases is related to the density profile of the outer layers in the adopted progenitor.

It is remarkable that the behavior of H40L is different. The mass of the central object for H40L increases faster than in any other model. This means that the accretion rate is highest among the models and leads to the shortest neutrino burst. Since the mass becomes large soon after bounce, the density and temperature inside the proto–neutron star become high and cause the quick rise of average energies and luminosities discussed above. This behavior is in accord with the analysis by Liebendo¨rfer et al. (2004) for their numerical results on the collapse of a 40 $M_\odot$ star.

### 4.4. Density and Temperature Profiles

We next examine the profiles of the three models during their evolution to discuss the origin of differences in the black hole formation and the neutrino signal. In order to clarify the origin of the different accretion-rate histories, we compare the density profiles for W40L, T50L, and H40L at the time when the central density reaches $10^{11}$ g cm$^{-3}$ and also at 30 ms after bounce in Figure 9. In the top panel, we see the same profiles at the center
when compared at the same central density during the collapse, although we have seen the differences among the initial models as a whole in Figure 1. This similarity implies similar dynamics around core bounce. In fact, the density profiles in the central parts \((M_b \lesssim 1 \, M_\odot)\) at 30 ms after bounce are quite similar, as can be seen in the bottom panel of Figure 9. We note that the profiles of temperature and electron fraction are also similar in the central region.

It is remarkable to see the differences in density in the outer parts \((M_b \gtrsim 1 \, M_\odot)\) among the three models. Since the density at each point determines the timescale of free fall \([-1/(G\rho)^{3/2}]\) onto the central object, the accretion rate \((M = 4\pi r^2 \rho v)\) is proportional to \(\rho^{5/2}\); therefore, the density difference is the origin of the different accretion rates. In Figure 9, the higher density in the outer profile for model H40L informs us that the accretion rate is higher up to the point at which \(M_b \sim 2.4 \, M_\odot\), where there is a crossing with the two other models. The T50L and W40L profiles are rather similar to each other, although there are slight differences and a crossing at \(M_b \sim 2.1 \, M_\odot\).

The difference in the densities in the outer layers persists during the evolution of the proto–neutron star up to black hole formation and leads to the different curves for the proto–neutron star masses, as we have seen in Figure 8. At 30 ms after bounce, proto–neutron stars of \(\sim 1.4 \, M_\odot\) (in baryon mass) have formed and the rest of the outer layers accrete onto them in the free-fall time. Eventually, the baryon mass of the H40L proto–neutron star becomes larger than those of models W40L and T50L because of the higher accretion rate. The cases of W40L and T50L in Figure 8 are almost the same because of the similarity of the density profiles. For the Shen EOS, models W40S and T50S in Figure 8 behave similarly to each other for the same reason. The increase in T50S at \(\sim 1 \, s\) slows relative to that in W40S, reflecting a crossing in the density profiles similar to the one discussed above.

In Figure 10, we compare the density and temperature profiles at 300 ms after bounce for models W40L, T50L, and H40L. The central density for H40L is higher than those for W40L and T50L, as a result of the larger baryon mass in the H40L proto–neutron star, as seen in Figure 8. The corresponding temperature for H40L is higher than the others’ because of a more compact proto–neutron star profile. We note that the kink at \(\sim 100 \, \text{km}\) in the density profile for H40L corresponds to the shock position in the accreting matter. The profiles of W40L and T50L are similar to each other, although T50L’s is slightly more compact, having higher density and temperature than W40L.

The compact profile for H40L leads to higher average neutrino energies and luminosities than in the two other models. The higher average \(\nu_\mu, \tau\) energy in this model arises from the higher temperature. The higher luminosities in H40L are also caused by the higher temperature and the compactness of the central object. Since the accretion luminosities of \(\nu_e\) and \(\bar{\nu}_e\) are determined by...
the energy liberated in the gravitational potential of the central proto–neutron star, a more massive and compact object leads to higher luminosities. In contrast, the neutrino energies and luminosities in W40L and T50L are similar to each other because of the similar accretion histories and the resulting evolution of their proto–neutron stars. The same argument applies for the comparison between W40S and T50S, in which the average energies are very close. The luminosities in T50S are somewhat smaller, corresponding to the lower accretion rate in the late phase, ≥0.6 s after bounce.

To summarize, the density profile of the progenitor determines the accretion rate in black hole–forming collapse and affects the evolution of the proto–neutron star on its way toward black hole formation. The difference in proto–neutron star profiles in turn leads to different features of neutrino emission. The characteristics of the neutrino emission reflect minute differences in the density profiles of the progenitors, while the influence from the EOS is more significant.

4.5. Differences in Neutrino Signal

Here we discuss the characteristics of the neutrino bursts in the five calculated models, aiming to discriminate between the effects from the progenitors and the EOSs. We summarize the numerical results regarding the black hole formation in Table 1.

In order to probe the EOS, the duration of the neutrino burst is decisive. If the accretion rate of the progenitor can be determined, measurement of the burst duration enables one to infer the critical mass of the proto–neutron star and to extract the stiffness of the EOS. In this study, the Shen EOS is stiff and provides large critical masses of \(~2.7 M_\odot\) in baryons \((2.3 M_\odot)\) in gravitational mass; see Table 1) for the accreting proto–neutron stars. This large mass corresponds to a time to black hole formation of over 1.3 s and is significantly longer than the case of the LS EOS, as seen from Figure 8. For the soft LS EOS, the critical mass is \(~2.1 M_\odot\) in baryons \((2.0 M_\odot)\) in gravitational mass. The duration in this case is \(~0.5 s\) with a weak dependence on the progenitor among models T50L, H40L, and W40L. If one can time the burst duration accurately, the critical mass can be inferred through the calculated curves of mass increase. For example, if we assume that the duration of the neutrino burst is 0.3 s, the critical mass is between 1.8 and 2.1 \(M_\odot\), as estimated from the range between W40L and H40L in Figure 8. Therefore, one can estimate the critical mass with an error of \(~0.3 M_\odot\) from the burst duration given the uncertainty in the density profiles of the progenitors. It should be noted that the critical masses for proto–neutron stars, which contain abundant neutrinos at finite temperature, are different from the maximum masses for neutrinoless and cold neutron stars.

To reveal the differences due to the progenitor, it is necessary to examine the details of the average energies and luminosities. When the Shen EOS is adopted, one has to wait until \(~1 s\) to discern differences between models W40S and T50S. For the LS EOS, it is rather difficult to distinguish any differences between the progenitors, since the burst duration is too short. The neutrino signals in W40L and T50L are too similar to discriminate. H40L is different from W40L and T50L, on the other hand, and may be distinguishable if data on the average \(\nu/\bar{\nu}\) energy or accurate luminosities are available.

In Figure 11, we compare the energy spectra of the emitted neutrinos 300 ms after bounce for models H40L and W40L. The shapes of the \(\nu_\ell\) and \(\bar{\nu}_\ell\) spectra are similar between H40L and W40L; however, the peak values are higher in H40L. The peak position for \(\nu/\bar{\nu}\) in H40L is shifted to higher energy, although the peak value is close to that for W40L. These differences appear as higher luminosities of all species and higher average \(\nu/\bar{\nu}\) energy (but similar average energies for \(\nu_\ell\) and \(\bar{\nu}_\ell\)) in H40L, as seen at 300 ms in Figure 7. We also compared the energy spectra at 300 ms after bounce for T50L and W40L (not shown). They are similar aside from slightly higher peak values for \(\nu_\ell\) and \(\bar{\nu}_\ell\) in T50L.

We note here that the discussion of neutrino signals so far does not address neutrino oscillations. One should take into account the changes in the spectra during the propagation of the neutrinos in the outer layers. The observational aspects of the current numerical results considering the effects of neutrino oscillations are now under investigation and will be published elsewhere.

5. DISCUSSION

In this section, we discuss the prospects of the current work regarding the progenitors and the equation of state. We also remark upon the chances of observing such neutrino bursts and the implications regarding astrophysical phenomena associated with such black holes.

This study relies on the presupernova configurations of massive stars. Further studies with updated progenitor models are definitely warranted. A necessary condition for this type of phenomenon is an appropriate density distribution to cause intense accretion. In the three models adopted in the current study (T50, H40, and W40), the size of the iron core is large \((~2 M_\odot)\) and the dense region extends out to \(M_\odot \sim 3 M_\odot\). This is different from the case of the 15 \(M_\odot\) star analyzed by Woosley & Weaver (1995), in which the iron core is smaller and the density slope is already steep at \(M_\odot \sim 1.5 M_\odot\), for example. It is necessary to study further the density profiles of various progenitors and the profile’s relation to the accretion in order to determine whether the size of the iron core is essential. It may be enough to have a flat density profile such that the density remains high \((~10^{10}\ g\ cm^{-3})\) at \(M_\odot \sim 2–3 M_\odot\), which corresponds to the critical proto–neutron star mass. If the density profile is steep and the density too low at the corresponding region in 40–50 \(M_\odot\) stars, black hole formation may take much longer \((~10–100\ s)\) than in the current case. Such events with longer neutrino bursts may look similar to ordinary supernovae from \(~15 M_\odot\) stars in terms of neutrino signal.

Regarding the uncertainty in the progenitors, one should attend to mass loss as well as rotation. The models of Woosley & Weaver (1995) and Hashimoto (1995) were obtained by considering presupernova evolution without mass loss. The inclusion

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**Figure 11.** Energy spectra at 300 ms after bounce as a function of neutrino energy (\(\nu_\ell\), solid lines; \(\bar{\nu}_\ell\), dashed lines; \(\nu/\bar{\nu}\), dash-dotted lines) for models H40L (thick lines) and W40L (thin lines). [See the electronic edition of the Journal for a color version of this figure.]
of mass loss leads to a smaller mass at the precollapse stage, even from a large initial value (e.g., 50 $M_\odot$) at the main sequence. The mass of the iron core and the density distribution may end up being similar to those in progenitors of about 20 $M_\odot$. In this regard, massive metal-poor stars are more likely to be the progenitors of black hole formation as studied in the current work. In fact, model T50 adopted here is the one with zero metallicity that forbids the mass loss. Its large central core results in the necessary intense accretion, which in turn leads to quick black hole formation with a short neutrino burst. Whether a change of evolution toward solar metallicity might suppress the current scenario remains to be seen, along with systematic studies of the metallicity dependence of progenitors and careful studies of the mass loss.

We have studied the black hole formation under spherical symmetry. This geometric assumption limits us to nonrotating massive stars. One should note, however, that spherical symmetry is a good approximation if the rotation is not significantly fast. It is challenging to study the collapse of rapidly rotating massive stars, which are possible progenitors of hypernovae and gamma-ray bursts. Fully general relativistic calculations in multiple dimensions are required in order to follow the evolution toward black hole formation. Such challenges have been met in numerical simulations of general relativistic hydrodynamics, but with simple treatments of neutrino transfer, microphysics (e.g., EOS), and progenitors (Shibata & Sekiguchi 2005; Sekiguchi & Shibata 2005, 2007). Multidimensional simulations with a proper treatment of neutrino transfer are awaited to predict the features of neutrino emission.

Rotational collapse to a black hole and the subsequent evolution are also interesting from the perspective of nucleosynthesis. In the context of the collapsar scenario, the ejection of neutron-rich material in a jet from the surroundings of the black hole and the neutrino-driven winds from the accretion disk around the black hole have been proposed as possible sites for heavy-element production, including $r$-process elements (Surman et al. 2006; Fujimoto et al. 2007). Although our numerical simulations were performed in the limit of no rotation, one may use the results to guess the time until black hole formation and the accretion rate of material, which are influential in the scenario of nucleosynthesis. The duration obtained in the current work is a lower limit, since the maximum mass of a rotating proto-neutron star is larger than that of a nonrotating one (Sumiyoshi et al. 1999) and the rotation supports accreting material away due to the centrifugal force. The accretion rate in the current study is an upper limit, accordingly. Large accretion rates in the disk formed around the black hole, which are assumed in studies of $r$-process nucleosynthesis (Surman et al. 2006), may be limited by the density profile of the progenitor, as we have pointed out.

The possibility of observing neutrino bursts due to black hole formation by massive stars deserves to be mentioned. The occurrence rate of the phenomenon (nonrotating black hole formation and its short neutrino burst) in this scenario is proportional to the fraction of stars massive enough to have intense accretion without significant rotation. This depends on the initial mass function and the rotation rates with large uncertainties, but such stars make up a certain fraction ($\sim$30%) of massive stars, which can be estimated from the Salpeter (1955) initial mass function with an assumption regarding the mass threshold ($\sim$25 $M_\odot$) for black hole formation. Kochanek et al. (2008) estimated from the observations performed to date that the rate of black hole formation could be comparable to the rate of normal core-collapse supernovae. Observational analyses of explosion energies and Ni production for various supernovae indicate that at least several faint events (e.g., SN 1997D and SN 1999br) have been observed from stars more massive than 20 $M_\odot$ lacking significant rotation, which may be akin to the events considered in this paper (Nomoto et al. 2007).

The planned survey of the disappearance of massive stars within a distance of 10 Mpc (Kochanek et al. 2008) will find both dim supernovae and collapses with no optical display that lead to black hole formation. If one of these occurs in the Galaxy or nearby galaxies, information on the progenitor can be obtained from the optical records before it disappeared. In addition, thousands of neutrinos will be detected at terrestrial facilities. Neutrino data combined with optical data will provide us with information on the dynamics of black hole formation and also constrain the properties of dense matter and the progenitors. In the search for supernova neutrinos by the Super-Kamiokande detector, neither neutrinos associated with black hole formation nor ordinary supernova neutrinos were detected during the survey period, unfortunately (Ikeda et al. 2007).

Our numerical results for the massive star with zero metallicity (model T50) suggest that black hole formation in the current scenario may occur for Population III stars in the early universe (see also Nakazato et al. 2006, 2007). Since massive stars become more populous in the metal-poor epoch, the neutrinos from black hole formation in the early stage of galaxies may contribute to the relic signal as background neutrinos. Although the signal is brief, higher energies and luminosities may help to enhance this contribution, and they might not be negligible. This argument again depends on the fraction of massive stars that result in the current scenario through the evolution of galaxies.

Before we close the discussion, we comment on the choice of equation of state. Although the density and temperature can become high enough to introduce new degrees of freedom such as hyperons and quarks during the evolution toward black hole formation, we have adopted two EOSs within the nucleonic degree of freedom in the current study to assess the progenitor dependence. Studies of the modifications to the evolution of black hole formation and the neutrino signal due to hyperon mixtures and the appearance of the quark phase are now under way and will be reported in separate papers (Nakazato et al. 2008).

6. SUMMARY

We have studied black hole formation and the associated neutrino emission from the gravitational collapse of massive stars in order to clarify the dependence on the progenitor model, following the basic study of these phenomena in the first paper of this series. We performed sets of numerical simulations of general relativistic neutrino radiation hydrodynamics under spherical symmetry to follow the collapse of massive (40 and 50 $M_\odot$) stars, adopting different models for the presupernova evolution. We have clarified that the characteristics of the evolution of the proto-neutron stars toward black hole formation and the associated short burst of neutrinos are similar in the simulations for the three progenitor models.

We find that different progenitor models may result in different rates of matter accretion onto the proto-neutron star born in the collapse of a massive star. These different accretion rates can lead to different histories of mass increase of the proto-neutron star to the critical value and to different durations until black hole formation. In order to extract the properties of the equation of state from the resultant neutrino burst, as proposed in previous studies (Sumiyoshi et al. 2006, 2007), it is necessary to constrain the uncertainty from progenitor models. In the comparison of the three progenitors studied, the change in duration is not as large as...
the difference originating from the two sets of equations of state. The change in time profile of the average neutrino energies and luminosities due to the progenitor is found to be minor as well. Note, however, that this is a first, trial exploration and more systematic investigations are obviously necessary to see whether our conclusion is generic or not.

We demonstrated that there is a relation between the density profile of the progenitor and the accretion history that causes a difference in black hole formation. A higher density at $M_b = 2.0–3.0 M_\odot$ in the progenitor results in a shorter free-fall time and a higher accretion rate. A flat core density profile in massive stars is a key factor to cause rapid black hole formation (in ~1 s) together with the characteristic neutrino burst. When the density gradients are different, as in the comparison between our models W40L and H40L, the density profiles may be distinguishable with detailed information from neutrino detections. This relation between the density profile of the progenitor and the accretion rate is helpful in discussing the postcollapse evolution of massive stars in other stellar models and may be useful to infer the accretion dynamics of rotational collapse to black hole formation and associated explosive phenomena such as collapsars. Further studies of the collapse of rotating massive stars with intense accretion are called for in order to clarify whether the outcome may lead to possible success in modeling gamma-ray bursts or the nucleosynthesis of heavy elements.

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