

## Neutrino Signals from the Formation of a Black Hole: A Probe of the Equation of State of Dense Matter

K. Sumiyoshi,<sup>1,2,\*</sup> S. Yamada,<sup>3</sup> H. Suzuki,<sup>4</sup> and S. Chiba<sup>5</sup>

<sup>1</sup>Numazu College of Technology, Ooka 3600, Numazu, Shizuoka 410-8501, Japan

<sup>2</sup>National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan

<sup>3</sup>Science & Engineering and Advanced Research Institute for Science and Engineering, Waseda University, Okubo, 3-4-1, Shinjuku, Tokyo 169-8555, Japan

<sup>4</sup>Faculty of Science and Technology, Tokyo University of Science, Yamazaki 2641, Noda, Chiba 278-8510, Japan

<sup>5</sup>Advanced Science Research Center, Japan Atomic Energy Research Institute, Tokai, Ibaraki 319-1195, Japan

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The gravitational collapse of a nonrotating, black-hole-forming massive star is studied by  $\nu$ -radiation-hydrodynamical simulations for two different sets of realistic equation of state of dense matter. We show that the event will produce as many neutrinos as the ordinary supernova, but with distinctive characteristics in luminosities and spectra that will be an unmistakable indication of black hole formation. More importantly, the neutrino signals are quite sensitive to the difference of equation of state and can be used as a useful probe into the properties of dense matter. The event will be unique in that they will be shining only by neutrinos (and, possibly, gravitational waves) but not by photons, and hence they should be an important target of neutrino astronomy.

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Massive stars of  $\geq 10$  solar masses ( $M_{\odot}$ ) end their lives when the iron core is formed at the center [1]. For the mass range of  $\sim(10\text{--}20)M_{\odot}$ , the spectacular optical display known as the supernova explosion occurs following the gravitational collapse of iron core and the launch of shock wave by the bounce of core at high densities. The successful explosion produces a proto-neutron star that emits a bunch of neutrinos for  $\sim 20$  s during the formation and cooldown [2], which was vindicated in SN 1987A [3,4].

Stars more massive than  $\sim 20M_{\odot}$  may have different fates. They have larger iron cores and will be intrinsically too massive to produce a neutron star via the supernova explosion. Then, the outcome will be a black hole. The gravitational collapse of these massive stars is currently attracting great interest. This is mainly because they are supposed to be associated with gamma ray bursts with long durations, one of the most energetic explosions in the universe. Although the central engine and possible simultaneous production of hyperenergetic Type Ic supernova (sometimes referred to as hypernova in the literature) are remaining to be a mystery, many researchers believe that the collapse of *rapidly rotating* massive stars and the subsequent formation of black hole are responsible for the phenomenon [5].

Not all the massive stars may not be rotating so rapidly, though. According to recent analysis of light curves of supernovae and nucleosynthetic yields by Nomoto and his collaborators [6], there appears to be a subset of supernovae with a progenitor mass of  $\sim 20\text{--}25M_{\odot}$ , which produce a markedly smaller amount of  $^{56}\text{Ni}$  and, as a consequence, are substantially underluminous. They suggest that these faint supernovae are slow rotators. If this is the case, it is highly likely that there exist essentially *nonrotating* massive stars that cannot produce even a dim

optical display and form a black hole. They are the target of this Letter.

Such a nonrotating, black-hole-forming collapse will be no less faint in neutrinos than the rotational counterpart. Following the core bounce and shock launch as in the ordinary supernova, there will be a phase of hyperaccretion through the stalled shock onto the proto-neutron star, lasting for  $\sim 1$  s before black hole formation. As shown below, as many neutrinos as in the ordinary supernova will be emitted during this period with distinctive characteristics in luminosities and spectra. Then the emission will be terminated rather abruptly after a black hole is formed. These features will be an unmistakable indication of black hole formation. The event will be unique in that they will be bright predominantly by neutrinos. Hence they should be an important target of neutrino astronomy.

In fact, this channel of black hole formation (failed supernova), in particular, its neutrino signal, has not been studied in detail with hydrodynamical simulations so far. Most of the previous papers were concerned with quasi-static evolutions of mass-accreting proto-neutron stars [7] or the so-called delayed collapse of proto-neutron stars [8–13] that is supposed to occur after a *successful* supernova explosion, triggered by some phase transitions during its cooling phase. [Note we do not consider supermassive or intermediate-mass black holes [14] in this Letter.] In some other papers [15,16], long term hydrodynamical simulations of failed explosion similar to ours were performed but their foci were different from ours. Hence this is the first serious and quantitative investigation into the phenomenon.

The most important findings in this Letter are the fact that the neutrino signals from the gravitational collapse of nonrotating massive stars are highly sensitive to the differ-

ence of equation of state (EOS) and can be used as a useful probe into the properties of hot and dense hadronic matter. EOS of dense matter is one of the most important ingredients in high energy astrophysics but is arguably difficult to obtain from first-principle calculations and, as a result, the theoretical predictions are subject to uncertainty. Hence many attempts have been made over the years to obtain some constraints on EOS. We propose in this Letter to add a new item to this attempt list, that is, the detection of neutrino signals from the hyper-accretion phase preceding the black hole formation in the nonrotating collapse of massive stars.

A number of such events is admittedly highly uncertain but might be a substantial fraction (20%–40%) of that of the ordinary supernovae, depending on the mass range for the event and the initial mass function of massive stars. Then this event will be as important a target for neutrino astronomy as the ordinary supernova is currently thought to be. It is, therefore, a very urgent task to provide theoretical predictions for luminosities and spectra of neutrinos.

*Models.*—We adopt the presupernova model of  $40M_{\odot}$  by Woosley and Weaver [17]. The model contains the iron core of  $1.98M_{\odot}$ , which is larger than the ordinary size of  $\sim 1.4M_{\odot}$  and warrants the black hole formation without explosion as its fate. We use the profile of central part of this model up to  $3.0M_{\odot}$  in baryon mass coordinate to describe the accretion of envelope matter for a long time.

We follow the dynamical evolutions by a general relativistic  $\nu$ -radiation-hydrodynamical code that solves the Boltzmann equation for neutrinos ( $\nu_e$ ,  $\bar{\nu}_e$ ,  $\nu_{\mu/\tau}$ , and  $\bar{\nu}_{\mu/\tau}$ ) together with Lagrangian hydrodynamics under spherical symmetry [18–20]. The general relativity is especially crucial in the current study, since the recollapse is triggered by general relativity. We assume the spherical symmetry, targeting the massive-end objects of the faint supernova branch, which are supposed to be rotating slowly.

In order to assess the influence of EOS, we employ two sets of realistic EOS by Lattimer and Swesty (LS-EOS) [21] and by Shen *et al.* (SH-EOS) [22]. They have been used in most of recent studies of the ordinary supernovae [20] and are the current standard in the society. The subroutine of LS-EOS is based on the compressible liquid drop model for nuclei immersed in dripped nucleons. The data table of SH-EOS is relatively new and constructed in the relativistic nuclear many body frameworks [23] with the nuclear interactions constrained by the properties of unstable nuclei [24] that are available recently in radioactive nuclear beams facilities. The two sets of EOS are, as a result, different from each other in stiffness at high densities and symmetry energy in neutron-rich environment [25]. For example, the incompressibilities are 180 MeV and 281 MeV and the maximum masses of cold neutron star are  $1.8M_{\odot}$  and  $2.2M_{\odot}$  for LS-EOS and SH-EOS, respectively.

It should be noted here that both sets of EOS take into account only the nucleonic degrees of freedom and ignore possible existence of other constituents such as hyperons, pion- and kaon-condensations, and deconfined quarks. We do not intend to justify the negligence [see, e.g., [8–13] for their importance in the proto-neutron star cooling]. It is, however, mentioned that this is essentially the first attempt to explore the EOS dependence of the neutrino signals from the nonrotating collapse of massive stars leading to the black hole formation. Considering also the inherent uncertainties in the theories of these constituents other than nucleons, we think it is reasonable to start with the most basic EOS with nucleons alone, which will also serve as a reference for the future work with other degrees of freedom taken into account.

The weak interaction rates for neutrinos are implemented by following the formulation of Bruenn [26]. In addition, included are the plasmon process and the nucleon-nucleon bremsstrahlung process which is calculated consistently with the effective nucleon mass in the EOS table [20]. The other recent developments of neutrino-matter interactions [27] and electron-capture rates [28] are not included in the current computations to facilitate the comparison with the previous study on  $15M_{\odot}$  star [20]. It has been demonstrated that the electron captures are important to determine the mass of the bounce core and the improvement may give a difference of  $\sim 0.1M_{\odot}$  [28]. The implementation of these reaction rates and more consistent treatments of reactions with EOS will be an important issue for the future work. We think, however, the basic scenario from the core bounce and shock stall through the hyperaccretion onto the proto-neutron star and then to the final collapse to black hole would not be changed substantially.

*Results.*—We start the description of numerical results by presenting the radial position of shock wave as a function of time after the core bounce ( $t_{\text{pb}}$ ) in Fig. 1. In both models, the launched shock wave reaches the maximum radius and then turns into recession around  $t_{\text{pb}} \sim 100$  ms owing to the ram pressure of falling matter. The size of bounced core is similar in two models and does not give

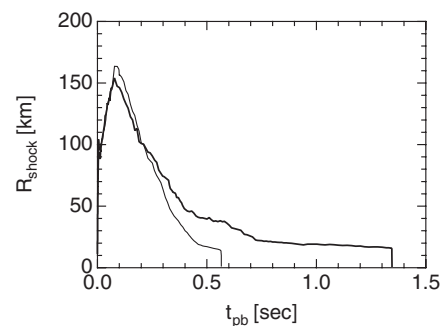


FIG. 1. Position of shock wave as a function of time after bounce in models LS (thin line) and SH (thick line).

much difference in the early dynamics of shock wave. Clear differences appear in the recession of shock wave and the shrinkage of central core after  $t_{\text{pb}} = 100$  ms when the hyper-accretion phase sets in. It should be noted that the accretion rate for the present model of  $40M_{\odot}$  ( $\sim 1M_{\odot}/\text{s}$  at  $t_{\text{pb}} = 0.4$  s) is considerably higher than that ( $\sim 0.2M_{\odot}/\text{s}$ ) for the canonical  $15M_{\odot}$  model for supernovae. This fact results in much faster contraction of central cores in the former.

In model LS, the shock wave recedes quickly down to  $\sim 20$  km. The central core contracts rapidly as its mass increases toward the maximum value for hot and lepton-rich configurations in stable equilibrium. At  $t_{\text{pb}} = 0.56$  s, a dynamical collapse finally sets in and the central core shrinks on a dynamical time scale. By this time, the enclosed baryon mass and gravitational mass inside the shock wave reach  $2.10M_{\odot}$  and  $1.99M_{\odot}$ , respectively. Within the next  $\sim 8$  ms, the central core becomes compact enough to form an apparent horizon at  $\sim 5$  km, which marks the formation of black hole.

In model SH, on the other hand, the shock wave recedes rather slowly over  $\sim 1$  s. The dynamical collapse starts when the enclosed baryon mass reaches  $2.66M_{\odot}$  (gravitational mass  $2.38M_{\odot}$ ) at  $t_{\text{pb}} = 1.34$  s. This remarkable difference in the durations of the hyper-accretion phase preceding the black hole formation is worth particular emphasis. It originates mainly from the difference in the maximum mass of the hot and lepton-rich core in stable equilibrium and, to lesser extent, from the difference in the accretion rates. Hence, if observed, this will provide us with invaluable information on the stiffness of EOS.

This novel difference is most clearly reflected in the duration of neutrino emissions as demonstrated in Fig. 2,

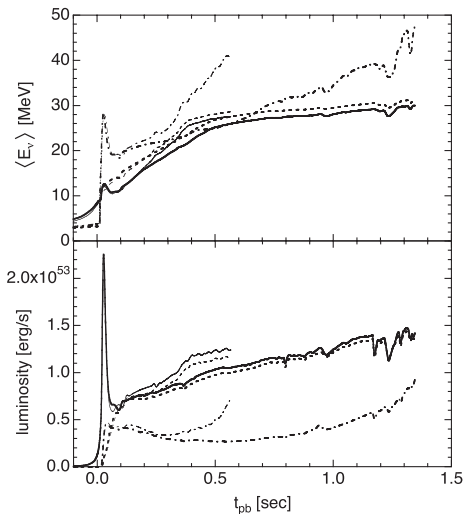


FIG. 2. Average energies (upper) and luminosities (lower) of  $\nu_e$  (solid line),  $\bar{\nu}_e$  (dashed line), and  $\nu_{\mu/\tau}$  (dot-dashed line) as a function of time ( $t_{\text{pb}}$ ) in two models LS (thin line) and SH (thick line).

where the average energies and luminosities of neutrinos are shown as a function of time ( $t_{\text{pb}}$ ). The end points in the figure correspond to the formations of apparent horizon, i.e., the births of black hole. Note, however, that the major decline of neutrino emission will occur a fraction of millisecond later when the neutrino sphere is swallowed by the horizon and will be recognized at the boundary ( $\sim 6000$  km) another  $\sim 20$  ms later, when neutrinos outside the neutrino sphere have traversed the distance at the light velocity. Unfortunately, we cannot follow this termination of neutrino emission owing to numerical problems. We will have to implement a scheme to avoid both coordinate and real singularities to handle this problem [see, e.g., [9,10]]. However, it is stressed that this problem does not matter in this Letter. The point here is that the longer-term neutrino emissions during the hyper-accretion phase is more revealing.

The time profile of luminosities right after bounce is similar to the ones in ordinary supernovae having the neutronization burst of  $\nu_e$  and the rise of  $\bar{\nu}_e$ ,  $\nu_{\mu/\tau}$ , and  $\bar{\nu}_{\mu/\tau}$ . Luminosities afterward are dominated by the contributions from the accreted matter, which is heated up by the shock wave and further by compression onto the proto-neutron star surface. Since the accreted matter contains a lot of electrons and positrons, they annihilate with each other to create pairs of neutrino and antineutrino of all species. They are also captured by nucleons to produce electron-type neutrinos and antineutrinos. These latter processes are responsible for the dominance of  $\nu_e$  and  $\bar{\nu}_e$  as well as their similarity in the luminosity.

The difference in the reactions also leads to the difference in the radial positions of neutrino sphere and, hence, to the hierarchy of average energies shown in Fig. 2. The average energy of  $\nu_{\mu/\tau}$  and  $\bar{\nu}_{\mu/\tau}$  is particularly a good indicator of the difference of temperatures in two models, having, for example, a higher average energy at  $t_{\text{pb}} \sim 0.5$  s in model LS owing to the faster contraction. It is remarkable that the luminosities and average energies increase by a factor of 2 or more toward the formation of black hole,

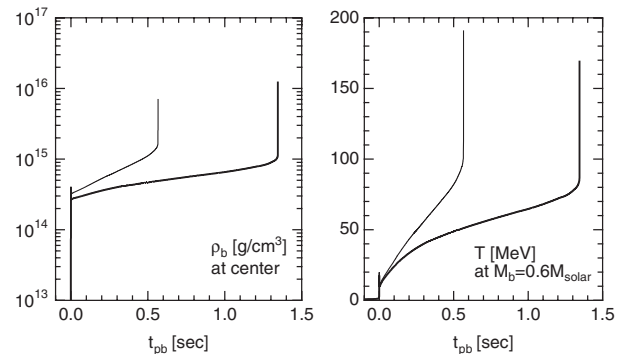


FIG. 3. Baryon mass density at center (left) and temperature at off-center (right) as a function of time ( $t_{\text{pb}}$ ) in models LS (thin line) and SH (thick line).

which will be utilized for diagnosis of the present channel of black hole formation.

The earlier contraction of proto-neutron star and formation of black hole in LS apparently comes from the softness of the EOS, which gives a smaller maximum mass of neutron star. In Fig. 3, we display the evolution of central density as a function of time ( $t_{pb}$ ). Right after a small peak at bounce, the central density in model LS rises very quickly toward the final collapse in contrast to the much slower increase in model SH. Since the contraction of proto-neutron star proceeds almost adiabatically, the temperature inside becomes enormously high owing to the compression. The peak temperature is attained off center near the inner core surface thanks to the shock heating. We show in Fig. 3 the time evolution of temperature at  $0.6M_{\odot}$  in baryon mass coordinate, which is near the temperature peak. The temperature reaches around 100 MeV at the beginning of recollapse and exceeds much over 100 MeV for both models while it rises much slower before recollapse in model SH.

It is to be noted that we have used LS-EOS and SH-EOS in very high density and temperature regimes that they may not have been originally meant for. (We have extended the SH-EOS table using the original framework for the current simulations.) This will certainly be an oversimplification. Exotic phases such as meson condensations, hyperons, or deconfined quarks are expected to appear at certain densities and temperatures. The current models will serve as a reference for comparison. If, for example, a new phase emerges at a certain point in evolution, the softening of EOS will cause immediately a dynamical collapse to black hole just like the ordinary delayed collapse. Hence the present simulations provide upper limits to the duration of neutrino emission before black hole formation. It should be emphasized again that the difference in EOS is already remarkable in the neutrino signals without these exotic constituents, which is in good contrast to the proto-neutron star cooling.

The current generation of neutrino detectors will detect thousands of neutrinos from the above-discussed events in our galaxy. Simultaneous observations of different neutrino flavors, from the initial burst of  $\nu_e$  through the rise of luminosity and hardening of spectra up to the termination, at Super-Kamiokande, SNO and other facilities together with an appropriate consideration of neutrino oscillation are indispensable to claim the black hole formation through the channel of current interest. The neutrino signal may be a complex folding of a couple of factors in addition to EOS. It is of urgent importance to provide more detailed theoretical predictions, particularly the dependence not only on EOS but also on the mass and structure of progenitor, which we are currently doing systematically.

In summary, we computed neutrino signals from the collapse of a nonrotating massive star of  $40M_{\odot}$  and found

that they are remarkably sensitive to the difference of EOS and, hence, can be utilized as a novel probe into the properties of hot and dense matter. The terrestrial detection of such events in the future will reveal the quantitative details of the accretion and contraction of proto-neutron star deep inside the star leading to black hole formation, and will give a new constraint on EOS at high density and temperature.

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\*Electronic address: sumi@numazu-ct.ac.jp

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