PROCEEDINGS OF SCIENCE

Effects of collective neutrino oscillations in multiple core-collapse supernova models

PoS(NIC XIII)107

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We investigate possible impacts of collective oscillations and MSW matter effects on neutrino signals from core-collapse supernovae (CCSNe). Using results of spherically-symmetric and three-dimensional radiation-hydrodynamics CCSN simulations for multiple progenitors (11.2, 13, 15, 27 and 40 $M_{\odot}$), we estimate the neutrino signals, in which both of the collective oscillations and the MSW effects are taken into account. As previously identified, the collective oscillations are unlikely to impact the revival of a stalled supernova shock for most of the progenitors, while we find that they could potentially affect the subsequent evolution of the revived shock in a lighter progenitor model ($11.3M_{\odot}$). Neutrinos emitted from a nascent proto-neutron star (PNS) change its flavor typically twice in propagating out to the stellar mantle due to the collective oscillations and the MSW effects. As a result, the spectrum of anti-electron type neutrinos ($\bar{\nu}_e$) becomes relatively close to those emitted from the PNS. For a variety of the progenitor models, we estimate the event numbers in Super-Kamiokande and discuss how the behaviors of the signals are sensitive to the employed progenitors.

XIII Nuclei in the Cosmos,
7-11 July, 2014
Debrecen, Hungary

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1. Introduction

There are a lot of unresolved problems regarding the mechanism of core-collapse supernova (CCSN) explosions and the neutrino signatures. Due to the development of numerical schemes, a number of neutrino-radiation hydrodynamics models have been reported recently [1, 2]. These self-consistent models have revealed many interesting natures of the supernova neutrinos, which provides an important probe into the still uncertain explosion mechanism (e.g., [3] for collective references therein).

In addition to the currently running observatories suitable for detecting supernova neutrinos (e.g., [4] for a review), the Megaton-class detectors are being proposed [5]. These next-generation detectors are expected to permit observations of the CCSN neutrinos from nearby galaxies in the Mega-parsec distant scales on a yearly basis [6]. Important parameters of the neutrino oscillations, to which the behaviors of the flavor mixtures of the CCSN neutrinos are very sensitive (e.g., [7] for a review), have been determined by various neutrino experiments [8] except for $|\Delta \mathrm{m}^2_{31}|$. Due to such rapid progress both in theory and observation, neutrino astronomy of the CCSNe is expected to become a reality in the coming decade.

In order to quantitatively evaluate the supernova neutrino signals, it is indispensable to include the effect of the collective neutrino oscillation (e.g., [9, 10, 11], see [12] for a review) and the MSW matter effect [13, 14, 15] inside the star. The collective oscillation becomes important in the vicinity of the PNS ($\sim 10^{12}\,\mathrm{g/cm^3}$), whereas the MSW effects occur far outside the iron core ($\sim 10^3\,\mathrm{g/cm^3}$). As pointed out by (e.g., [16, 17]), both of these effects should be included in a reliable modeling of the supernova neutrino signals.

Joining in these efforts, we explore in this contribution the effects of the collective neutrino oscillations and the MSW matter effects on the supernova neutrino signals using the results of spherically-symmetric (1D) and three-dimensional (3D) CCSN simulations of multiple progenitor models. For a variety of the progenitor models, we estimate the event numbers in Super-Kamiokande and discuss how the behaviors of the signals are sensitive to the employed progenitors.

2. Supernova Model and Numerical Method

We use several supernova models based on new sets of radiation-hydrodynamics simulations for 11.2, 13, 15, 27 and 40 $M_\odot$ progenitor stars using the IDSA transport scheme [18]. In these simulations, three flavor neutrinos are taken into account. Left and right panels of Fig.1 show the time evolutions of the average energy and the luminosity of each flavor neutrinos obtained through these simulations.. In Fig.1, the progenitor mass is 13, 15 and 27 $M_\odot$ from top to bottom. The time evolution of the average energy and the luminosity is quantitatively different in each models, however these qualitative behaviours are rather similar to previous studies (e.g., [19]). For each of the models, we calculate the neutrino spectra at the neutrino sphere (PNS) using these average energies and luminosities (e.g., [14, 15]).

The neutrinos are influenced by two effects in the star, one is the collective oscillation, and the other is MSW matter effects. Following the method proposed by [20], we calculate the neutrino survival probability considering the two effects, in which a single-angle approximation is taken for

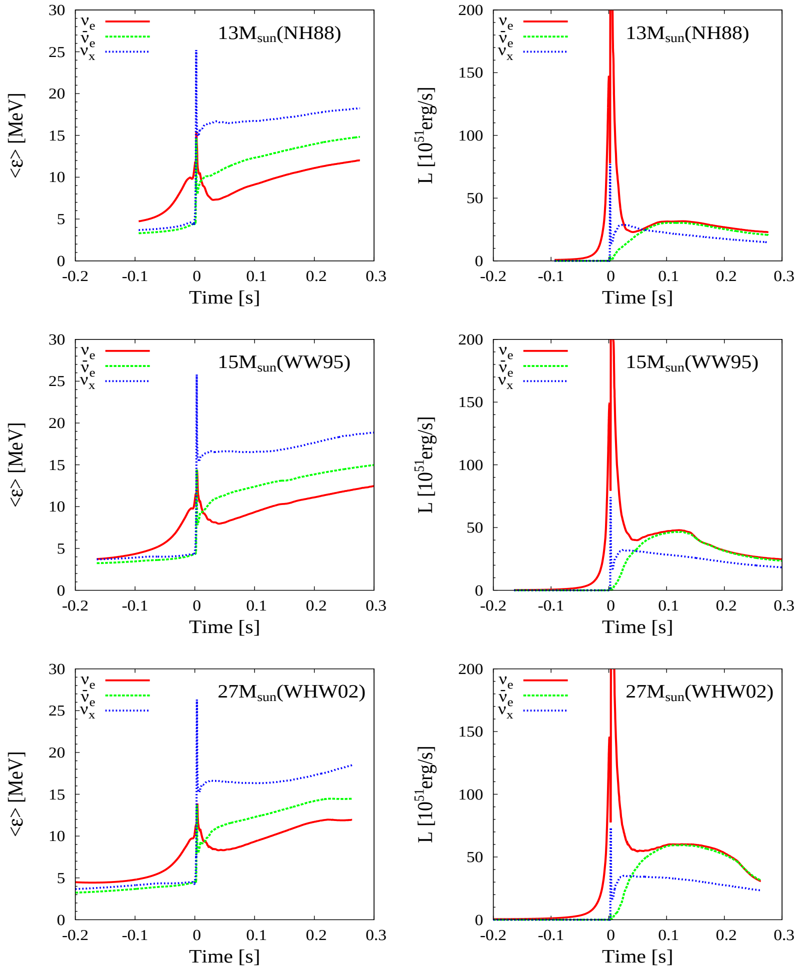

Figure 1: Time evolutions of the luminosity and the average energy. Left and right panels show the time evolutions of the average energy, and the luminosity of each flavor neutrinos. The progenitor mass is 13, 15, and 27 $M_\odot$ from top to bottom.

the collective oscillations of (three-species) neutrinos. We use the neutrino oscillation parameters as follows; $\sin^2 2\theta_{23} = 0.84$, $\sin^2 2\theta_{12} = 1.0$, $\sin^2 2\theta_{13} = 0.098$, $\Delta m^2_{21} = 7.6 \times 10^{-5}$, $|\Delta m^2_{31}| = 2.5 \times 10^{-3}$ [8]. We assume the inverted mass hierarchy.

3. Results

Fig. 2 shows comparison of the collective oscillation radius to shock radius in the case of 13 $M_\odot$ model computed either in 1D (left panel) or 3D (right panel) hydrodynamics [18]. In both of the panels, the shock radius is shown by red line, and the radii where the collective oscillations begin ($r_{\rm sync}$) and end ($r_{\rm end}$) are represented by green and blue line, respectively.

In 1D, our results are in agreement with the work by [9] who showed that collective oscillations do not affect the revival of the stalled shock because the collective oscillation starts and ends far outside the shock. But in the corresponding 3D model in which the shock-revival is obtained

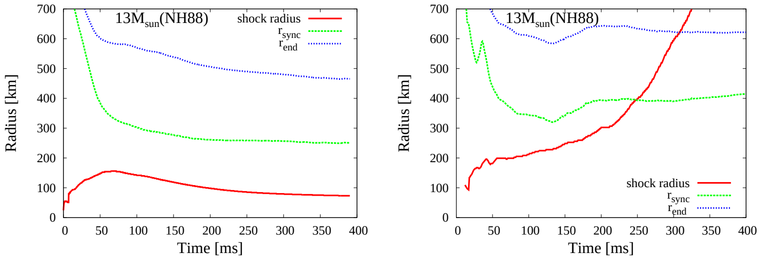

Figure 2: Comparison of the collective oscillation radius to shock radius in the case of 13 $M_\odot$ model. Left figure shows the 1D simulation result, and right shows the 3D simulation result.

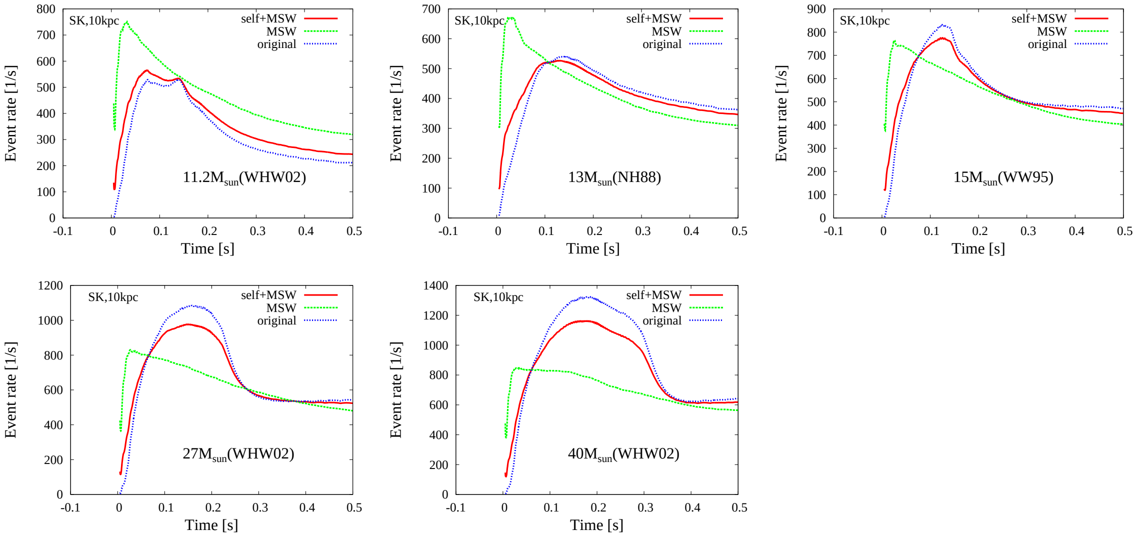

Figure 3: The event rate of $\overline{\nu}_e$. Top panels are the event rate of 11.2, 13 and 15 $M_\odot$ from left to right, and bottom panels are of 27 and 40 $M_\odot$. Red line shows the event rate taking account of the collective oscillation and the MSW effect. Green and blue lines show the event rate taking account of only MSW effect, and the event of original neutrinos (at PNS).

(after $\sim$ 250 ms postbounce, see red line in the right panel), the collective oscillation occurs inside the expanding shock (same as for the 11.2 $M_\odot$ model). We point out that this might affect the subsequent evolution of the shock and also nucleosynthetic yields in the high entropy hot bubbles in the neutrino-driven wind phase. We plan to study this in more detail using 2D and 3D models that are trending toward an explosion.

Fig. 3 shows the event rate of $\overline{\nu}_e$ detected by Super-Kamiokande from a source at the distance of 10 kpc. Top panels of Fig.3 are the event rate of 11.2, 13 and 15 $M_\odot$ from left to right, and bottom panels are of 27 and 40 $M_\odot$. Red line shows the event rate taking account of the collective oscillation and the MSW effect. Green line shows the event rate taking account of only MSW effect, and blue line shows the event of original neutrinos (at PNS). As shown in Fig. 3 , the $\overline{\nu}_e$ signals become relatively close to those emitted from the PNS. This is because the $\overline{\nu}_e$ change its flavor typically twice under the influence of the collective oscillations and the MSW effect.

Table 1: The total event number of $\bar{\nu}_e$ by Super-Kamiokande for a Galactic CCSN event.

progenitor mass [$M_\odot$]	11.2	13	15	27	40
collective+MSW	3600	4120	5400	6740	8340
MSW	4400	4200	5360	6320	7000

Table1 shows the (extrapolated) total event number of $\bar{\nu}_e$, in which we assume that neutrino emission continues for the next 10 s after the simulation time (e.g., [14]). Depending on the progenitor mass, the effect of the collective oscillations on the event number varies, i.e., the event numbers decrease and increase for lighter (11.2 and 13 $M_\odot$ models) and heavier progenitor models (15, 27 and 40 $M_\odot$), respectively. It is recently demonstrated that the compactness of progenitors is a key to characterise the neutrino signatures [21]. Using such results relying on hundreds of multi-D models for multiple progenitors, we plan to perform the more systematic survey, aiming to clarify the connection between the progenitor structures and the neutrino signatures in the presence of both the collective oscillations and the MSW effects.

4. Summary

We explored the effect of the collective neutrino oscillations and the MSW matter effects on the neutrino signals using the results of 1D and 3D CCSN simulations of multiple progenitor model. Using the 3D model of a 13$M_\odot$ star that is trending towards explosion, we pointed out that the collective oscillations could influence the subsequent evolution of the shock after the shock-revival. Assuming the inverted mass hierarchy and using the neutrino oscillation parameters that are consistent with experiments, our results show that the neutrinos change its flavor typically twice under the influence of the collective oscillations and the MSW effects. We could get the information of the anti-electron type neutrinos which would be helpful in extracting the information of the long-veiled explosion mechanism via the next nearby CCSN event.

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