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Pre-supernova neutrino emission from massive stars and their detection

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Pre-supernova neutrino emission from massive stars and their detection

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Abstract. Recent progress of neutrino detectors makes it possible to detect pre-SN neutrinos, which are emitted from the core of massive stars before supernova explosions. Pre-SN neutrino observations will become an alarm for supernovae. We hence calculate the number luminosity and energy spectra of pre-SN neutrinos from the 15 $M_\odot$ progenitor based on the state-of-the-art calculations of massive stars. We find that the number luminosity of ν_e's is $L_N^\nu \sim 10^{55}, 10^{57}$ s^{-1} before core collapse and core bounce, respectively, whereas that of $\bar{\nu}_e$'s becomes largest around core collapse $L_N^\nu \sim 10^{53}$ s^{-1}. We then estimate the number of neutrino events at neutrino detectors taking neutrino oscillations into the obtained luminosities and spectra. We find that an alarm is issued a few days before the explosion by detecting $\bar{\nu}_e$'s at liquid-scintilation type detectors if the progenitor is located at 200 pc. Finally, we perform a systematic study of pre-SN neutrino emission for 7 progenitor models with different initial masses. We find that the difference of the number luminosities is ~ 1 order and the dependence of the initial mass have to be taken into the theoretical predictions of pre-SN neutrino observations.

1. Introduction

Neutrino astronomy has begun at the historical supernova event SN1987A. Neutrino detectors at that time detected 24 neutrinos for the first time [1] and we obtained the luminosity and average energy of supernova neutrinos $L_\nu \sim 5 \times 10^{52}$ ergs, $\langle E_\nu \rangle \sim$ 10-12 MeV [2]. They are consistent with theoretical predictions based on the neutrino heating mechanism, which is one of the favored mechanisms of core-collapse supernovae, and our understanding of supernova explosion has been developed greatly.

Neutrinos are efficiently emitted from the center of massive stars long before the supernova explosion, which are called pre-supernova (pre-SN) neutrinos. Massive stars with $M_{\mathrm{ZAMS}} >$

8 $M_\odot$ evolve synthesizing heavy elements by nuclear fusion at the core and form an onion-like strucure with a iron core. Pre-SN neutrinos take energy from the core and affect its thermodynamical evolution. Further nuclear burning does not proceed after a iron core is formed and matters begin to accrete toward the center because of electron captures by free protons and/or iron-group elements and photodissociations of irons (core collapse). The density and temperature increase during the core collapse until the core becomes stable owing to nuclear force at $\rho_c \sim 10^{14}$ g/cm^3. A shock wave is formed between the accretion and stable parts (core bounce) and propagates outward. If it reaches the stellar surface, the supernova explosion occurs. Neutrinos freely escape from the core before the core collapse, whereas they interact with nuclei more frequently and trapped inside the core during the core collapse ($\rho > 10^{11}$ g/cm^3). We have to hence adopt the different numerical treatments for calculating neutrino luminosities and spectra before and after the core collapse (see Section 2).

Pre-SN neutrinos have a lower energy ($<$ a few MeV) than that of supernova neutrinos and it seemed to be difficult to detect the former. Remarkable progress of neutrino detectors, however, makes it possible. We can hence exploit observations of pre-SN neutrinos to deepen our understanding of stellar evolutions, supernova explosions and neutrino physics. In this paper we focus on an alarm for supernovae by pre-SN neutrino observations. Pre-SN neutrinos may be observed firstly in the evolution of massive stars located at our vicinity and their detection will make us possible to surely observe the subsequent supernova explosions, which is referred to occur once per centry. It is hence strongly required to establish an alert system with pre-SN neutrinos.
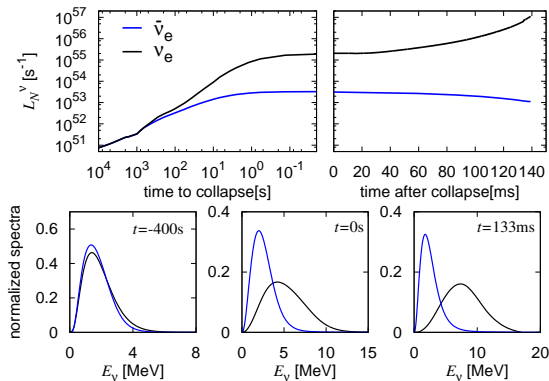

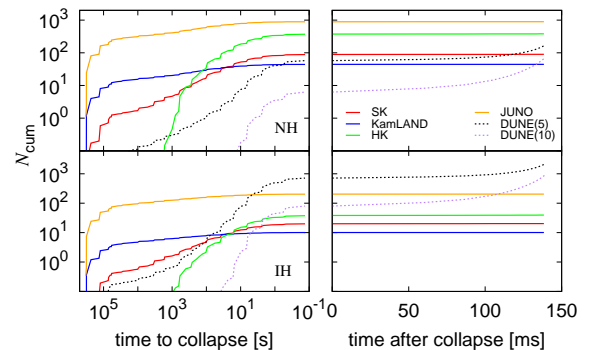**Figure 1.** The time evolution of number luminosities (top) and the snapshots of energy spectra (bottom) [3].

Figure 2. The time evolution of cumulative events at neutrino detectors [3].

2. Methods

In this section we explain about the calculation methods of number luminosities and spectra of pre-SN neutrinos. We ask readers to refer to our previous paper [4, 3] for the details. We devide the evolution of massive stars before the core bounce into two phases: quasi-static evolution and core-collapse phases as we explained before. The evolutions in the former phase are calculated by Takahashi *et al.* [5, 6]. Although the effects of neutrinos are included in these calculations, they miss energy spectra due to the numerical costs. We hence calculate the number luminosities and energy spectra of pre-SN neutrinos on static backgrounds derived from these calculations in the post processes. We, on the other hand, employ the 1-dimensional hydrodynamical code with a Boltzmann solver developed by Nagakura *et al.* [7, 8] to follow the evolution of the

core collapse. The luminosity and energy spectrum of electron neutrinos (ν_e's) in the collapse phase are obtained directly from the simulations whereas those for other neutrino species are calculated in the post processes.

3. Alert system with pre-SN neutrinos

The typical properties of pre-SN neutrinos are shown in Figure 1. Top panel shows the time evolution of number luminosity from the 15 $M_\odot$ progenitor model. The number luminosity of ν_e's (solid) is $L_N^\nu \sim 10^{55}, 10^{57}$ s^{-1} before core collapse and core bounce, respectively, and electron captures by free protons and heavy nuclei greatly contribute to it. In the case of $\bar{\nu}_e$'s (dotted), on the other hand, the number luminosity becomes largest around the core collapse $L_N^\nu \sim 10^{53}$ s^{-1}, because the number of positrons decreases due to the high degeneracy of electrons inside the core. The snapshots of energy spectra are shown in bottom panels. Average energy of ν_e's glow up to ~ 8 MeV before core bounce, whereas that of $\bar{\nu}_e$'s up to ~ 3 MeV. This is due to the difference of electron and positron degeneracies.

We estimate the number of neutrino events at current and future neutrino detecotrs, taking neutrino oscillations into the obtained luminosities and spectra. Figure 2 shows the time evolution of cumulative neutrino events for normal (top) and inverted (bottom) hierarchies. We consider inverse-β decay of protons and inverse electron captures of argons for neutrino detections. If the progenitor is located at 200 pc, the liquid-scintillation detectors, JUNO and KamLAND, can detect $\bar{\nu}_e$'s almost 6 days before the explosion first for both hierarchies, because they have the lowest energy thresholds. These events becomes an alarm for the supernove explosions. Following that, the water-cherenkov detectors, Super-Kamiokande (SK) and Hyper-Kamiokande (HK), detect $\bar{\nu}_e$'s with the increase of neutrino energy. A large number of ν_e's, on the other hand, are detected during the core collapse at DUNE, especially for inverted hierarchy.
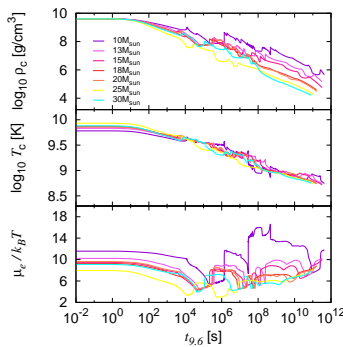

Figure 3. The time evolutions of central density (top), temperature (middle) and electron degeneracy (bottom) for 7 progenitor models.
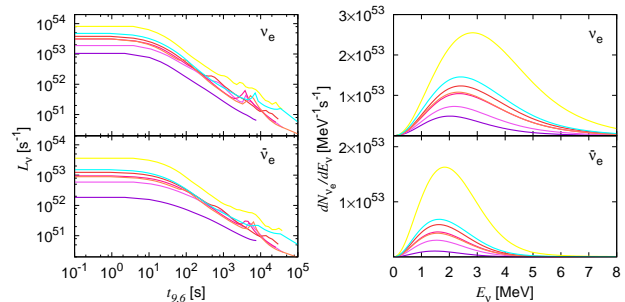
Figure 4. The time evolution of number luminosities (left) and the snapshots of energy spectra at $t_{9.6} = 0$ s (right) for 7 progenitor models.

4. Systematic study of pre-SN neutrino emission

It is expected that the observable distance for pre-SN neutrinos is < 1 kpc [9] and there are 39 candidates for the detection of pre-SN neutrinos [10]. Their initial masses are theoretically predicted to be from 9 to 25 $M_\odot$ and stellar evolutions highly depend on them. We hence perform a systematical study of pre-SN neutrino emission before the core collapse for 7 progenitor models with $M_{\mathrm{ZAMS}} = 10, 13, 15, 18, 20, 25$ and 30 $M_\odot$ [6].

Figure 3 shows the time evolution of central density, temperature and electron degeneracy. We define $t_{9.6} = 0$ s, where the central density becomes $\rho_c = 10^{9.6}$ g/cm^3. We find that the

low-mass progenitors have lower central temperature and higher degeneracy than the high-mass ones. The central temperature in the 25 $M_\odot$ progenitor model is, however, higher than that in the 30 $M_\odot$ progenitor model exceptionally. This is supposed to be due to the efficient mass-loss from the stellar surface.

We calculate the number luminosity and spectra of ν_e's (top) and $\bar{\nu}_e$'s (bottom) in Figure 4. The luminosity increases not with the initial mass but with the central temperature and the 25 $M_\odot$ progenitor has the largest number luminosity among 7 progenitor models. The difference of number luminosities is within 1 order for both flavors and the dependence of the initial mass have to be taken into the theoretical predictions of pre-SN neutrino observations. The peak energies of neutrino spectra are almost same for ν_e's from 2-3 MeV, whereas for $\bar{\nu}_e$'s 1-2 MeV (See right panels of Fig. 4).

5. Summary and future works

Recent progress of neutrino detection makes it possible to detect pre-SN neutrinos, which are emitted from the core of massive stars before core bounce. Pre-SN neutrinos may be observed firstly in the evolution of massive stars located at our vicinity and their detection becomes an alarm for the subsequent supernova explosion. It will make us possible to surely observe the next galactic supernova and contribute to deepen our understanding of supernova explosions. It is hence strongly required to establish an alert system with pre-SN neutrinos.

We calculate number luminosities and energy spectra of pre-SN neutrinos from the 15 $M_\odot$ progenitors based on the state-of-the-art calculations of massive stars. The number luminosity of ν_e's is $L_N^\nu \sim 10^{55}, 10^{57}$ s^{-1} before core collapse and core bounce, respectively, whereas that of $\bar{\nu}_e$'s becomes largest around the core collapse $L_N^\nu \sim 10^{53}$ s^{-1}. We estimate the number of neutrino events at neutrino detecotrs, taking neutrino oscillations into the obtained number luminosities and spectra. If we assume the progenitor is located at 200 pc, we find that an alarm is issued a few days before the explosion by detecting $\bar{\nu}_e$'s at liquid-scintilation type detectors.

In our vicinity there are 39 candidates with various initial masses for the detection of pre-SN neutrinos. We hence perform a systematic study of pre-SN neutrino emission for 7 progenitor models with $M_{\rm ZAMS} = 10, 13, 15, 18, 20, 25$ and 30 $M_\odot$ and find that the number luminosities increase not with the initial mass but with the central temperature. The difference of number luminosities is ~ 1 order for both flavors and the dependence of the initial mass have to be taken into the theoretical predictions of pre-SN neutrino observations. We have a plan to apply this systematic study to the predicions of pre-SN neutrinos from nearby red-super giants.

6. References

[1] Hirata K, Kajita T, Koshiba M, Nakahata M, Oyama Y, Sato N, Suzuki A, Takita M, Totsuka Y and Kifune T *et al* 1987 *Phys. Rev. L* **58** 1490–1493
[2] Sato K and Suzuki H 1987 *Phys. Rev. L* **58** 2722–2725
[3] Kato C, Nagakura H, Furusawa S, Takahashi K, Umeda H, Yoshida T, Ishidoshiro K and Yamada S 2017 *Astrophys. J.* **848** 48
[4] Kato C, Delfan Azari M, Yamada S, Takahashi K, Umeda H, Yoshida T and Ishidoshiro K 2015 *Astrophys. J.* **808** 168
[5] Takahashi K, Yoshida T and Umeda H 2013 *Astrophys. J.* **771** 28
[6] Yoshida T, Takiwaki T, Kotake K, Takahashi K, Nakamura K and Umeda H 2019 *Astropys. J.* **881** 16
[7] Nagakura H, Sumiyoshi K and Yamada S 2014 *Astrophys. J. Suppl.* **214** 16
[8] Nagakura H, Iwakami W, Furusawa S, Okawa H, Harada A, Sumiyoshi K, Yamada S, Matsufuru H and Imakura A 2018 *Astrophys. J.* **854** 136
[9] Asakura K *et al.* (KamLAND) 2016 *Astrophys. J.* **818** 91
[10] Nakamura K, Horiuchi S, Tanaka M, Hayama K, Takiwaki T and Kotake K 2016 *MNRAS* **461** 3296–3313