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Observations of presupernova neutrinos relating to the final evolution of massive stars

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Abstract. We investigate neutrino events from presupernova stars at the distance of 200 pc detected by current and future neutrino observatories. The spectrum evolution of neutrinos emitted from presupernova stars of 12, 15, and 20 M_{\odot} after the O burning until the core collapse is evaluated. The expected $\bar{\nu}_e$ events are several to more than ten for KamLAND and are hundreds for JUNO and Hyper-K. The time evolution of the $\bar{\nu}_e$ events could reveal the evidence for the change of burning processes during the final evolution of massive stars. We propose the detection of presupernova neutrinos by Gd-loaded Super-K and Hyper-K using the delayed γ -ray signals of Gd(n, γ) reaction. Gd-loaded Super-K and Hyper-K have a possibility for the detection of hundreds and thousands neutrino events, respectively. We also estimate the time for supernova alarms using presupernova neutrinos. KamLAND, JUNO, and other neutrino detectors could send supernova alarms using presupernova neutrinos several hours to one day before a supernova explosion. Multiple observations of presupernova neutrinos will raise the reliability of the supernova alarm.

1. Introduction

When a supernova (SN) explodes at the distance of hundreds pc, neutrinos emitted from the presupernova (preSN) star are expected to be detected by current and future neutrino observatories (e.g., [1, 2, 3, 4]). If hundreds of neutrinos are observed, we could extract the information of the final evolution of massive stars from the time evolution of the neutrino events. Further, preSN neutrinos can be a precursor of a SN explosion. An alarm of a SN explosion can be sent using the preSN neutrinos [3]. We investigate the time evolution of the neutrino events from preSN stars before the SN explosions detected by current and future neutrino observatories. We discuss the relation of the time evolution of the detected neutrino events to the final evolution of massive stars. We also discuss the SN alarm based on preSN neutrino events by KamLAND and JUNO. Details for this study have been shown in [4].

2. Presupernova neutrino events

We calculate the stellar evolution of 12, 15, and 20 M_{\odot} solar-metallicity stars until the core-collapse using the stellar evolution code in [5]. Then, we evaluate the evolution of the number spectra of neutrinos emitted through pair neutrino process from the stars after the O burning. The neutrino emission rate and the average energy increase with time for most of time. However, they decrease for a while at the ignition of O and Si shell burnings.



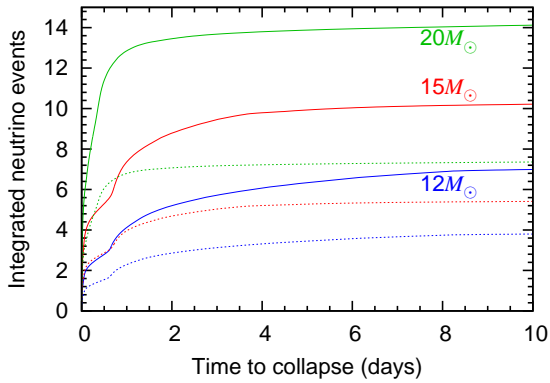


Figure 1. Integrated $\bar{\nu}_e$ events of the 12 (blue lines), 15 (red lines), and 20 M_\odot (green lines) preSN stars by KamLAND. Solid and dashed lines indicate the normal and inverted mass hierarchies.

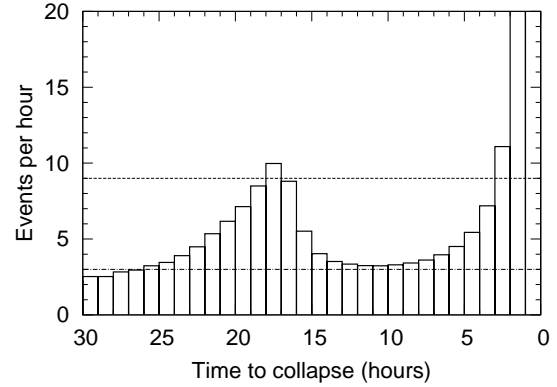


Figure 2. Time evolution of the $\bar{\nu}_e$ events of the 15 M_\odot preSN star per hour by JUNO in the normal mass hierarchy. Dotted and dash-dotted horizontal lines indicate the 3σ background in high and low reactor phases.

2.1. Time evolution of the neutrino events from presupernova stars

We investigate the time evolution of the neutrino events from the preSN stars at the distance of 200 pc detected through $\bar{\nu}_e + p \rightarrow e^+ + n$ by KamLAND [3], JUNO [6], and Hyper-Kamiokande (Hyper-K). The neutrino events by other detectors are shown in [4]. Figure 1 shows the integrated $\bar{\nu}_e$ events detected by KamLAND. The detection efficiency is assumed to be average efficiency [4]. We expect that 7–14 and 4–7 neutrino events will be observed in KamLAND for seven days before the SN explosion in the normal and inverted mass hierarchies. JUNO is also a liquid scintillation neutrino detector and has a fiducial volume about 20 times as large as KamLAND. We expect that 232–480 and 126–251 $\bar{\nu}_e$ events will be observed in JUNO. For Hyper-K, we assume the $\bar{\nu}_e$ threshold energy as 4.79 MeV. At this time, we expect that 134–406 and 80–233 $\bar{\nu}_e$ events will be observed in the normal and inverted mass hierarchies. The observed $\bar{\nu}_e$ events strongly depend on the threshold energy. If the threshold energy is higher, the expected event number becomes much smaller.

We expect hundreds of preSN $\bar{\nu}_e$ events in JUNO and Hyper-K. In this case, the time evolution of the $\bar{\nu}_e$ events will also be observed. Figure 2 shows the expected time evolution of the $\bar{\nu}_e$ events of the 15 M_\odot preSN star per hour by JUNO in the normal mass hierarchy. We see the increase in the $\bar{\nu}_e$ events with time until seventeen hours before the explosion. However, the events decrease in 17–10 hours. This time evolution relates to the change of the burning process from the Si core burning to the O shell burning of the star. When the $\bar{\nu}_e$ events increase, the Si core burning proceeds or the central core gradually collapses and the central temperature gradually increases. On the other hand, when the $\bar{\nu}_e$ events decrease, the O shell burning ignites and the central temperature decreases for a while. When the Si shell burning ignites in several ten minutes before the explosion, the decrease in the $\bar{\nu}_e$ event rate also could be observed by JUNO and Hyper-K [4]. The observation of the $\bar{\nu}_e$ events could reveal the change of the burning processes during the final evolution of the star.

Gd-loaded Super-K and Hyper-K detect $\bar{\nu}_e$ through the prompt signal by $p(\bar{\nu}_e, e^+)n$ and the delayed signal by the γ -rays emitted by the neutron capture of Gd [7]. For preSN neutrinos, the detection of the prompt signal is difficult because of the low energy of preSN neutrinos. However, the detection of the delayed γ -ray signal is promising. We propose the detection of preSN neutrino events through the delayed γ -rays by Gd-loaded Super-K and Hyper-K. We expect that 146–302 and 79–158 $\bar{\nu}_e$ events will be observed in Gd-loaded Super-K in the normal

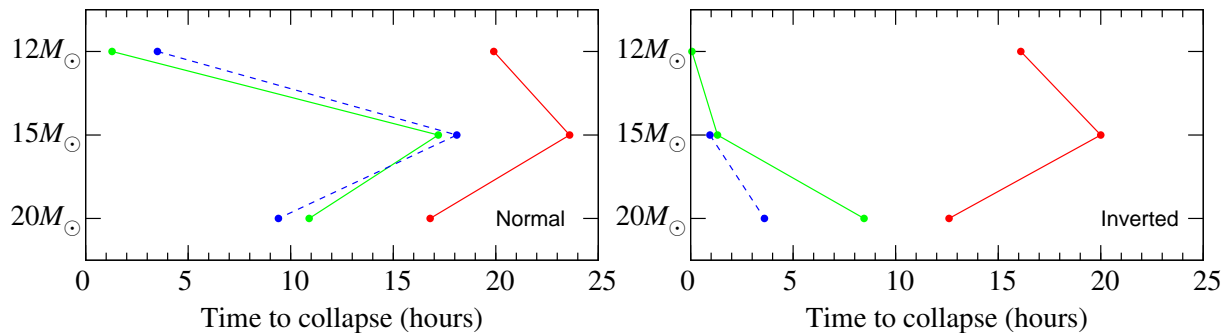


Figure 3. Estimated SN alarm time using preSN neutrinos in the normal (left panel) and inverted (right panel) mass hierarchies. Red and green lines indicate JUNO in the low and high reactor phases. Dashed blue lines indicate KamLAND in three events for 48 hours.

and inverted mass hierarchies. Here, we assume 50 % detection efficiency for simplicity. In Gd-loaded Hyper-K, we expect 2466–5106 and 1342–2666 $\bar{\nu}_e$ events. When thousands $\bar{\nu}_e$ events are observed, we will obtain detailed time evolution of the events. This observation will show the evidence for the O shell burning and the Si shell burning before the SN explosion.

2.2. Supernova alarms using presupernova neutrinos

The SuperNova Early Warning System (SNEWS) is a project to send a prompt alert of a SN explosion to astronomical community when SN neutrinos are detected [8]. If neutrinos from a preSN star are detected, the neutrinos can also become a preSN neutrino alarm. We investigate the time of preSN neutrinos of the preSN stars in accordance with the procedure in [3].

Figure 3 shows the estimated SN alarm time of KamLAND and JUNO using preSN neutrinos. We consider that a SN alarm is sent from KamLAND when three $\bar{\nu}_e$ events are detected for 48 hours, corresponding to the events 3.7σ and 2.1σ significance in the low and high reactor phases [3]. For JUNO, we consider that a SN alarm is sent when nine (three) events are detected for one hour, corresponding to the events more than 3σ significance in the high (low) reactor phase. We expect that a SN alarm could be sent a few hours to one day before the SN explosion. The alarm time also depends on the detector condition, especially on the operation of reactor experiments. The alarm time of KamLAND with the low reactor phase is roughly same as the alarm time of JUNO with the high reactor phase. If reactor neutrino experiment is not operated, JUNO can send a SN alarm about one day before the SN. Other current and future neutrino detectors such as SNO+, RENO-50, Gd-loaded Super-K, and Gd-loaded Hyper-K also can send a SN alarm using preSN neutrinos. SN neutrino alarms from multiple individual neutrino observatories will raise the reliability of the SN neutrino alarms.

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