Constraints on oscillation parameters through the MSW effect of supernova neutrinos

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Abstract. We try to constrain the neutrino oscillation parameters by studying the MSW matter effect on supernova neutrinos. Using an implicit Lagrangian code for general relativistic spherical hydrodynamics (Yamada,1997), we calculate the propagation of shock waves passing through the stellar envelopes over dozens of seconds, which is based on modeling the adiabatic collapse of iron core.

We study how quantitatively the influence of the shock propagation appears in the deformation of neutrino energy spectrum. In addition, we are able to examine the dependence of time evolution of the neutrino detection rates at SK. Using our supernova model, we found that the MSW effect appears, at first, from low-energy region and moves toward high-energy region as the shock wave propagates. We find that the shock propagation has strong influence on the supernova neutrino oscillation through the evolution of density profile induced by the shock propagation.

1. Introduction

There are still a lot of mysteries on the mechanism of the core-collapsed supernovae and the nature of supernova neutrinos. 99 % of the gravitational energy for the core collapse is released as neutrinos. The neutrino oscillation has been studied in various experiments [1] But, we cannot determine the remaining three neutrino oscillation parameters, i.e. the sign of mass difference ($\Delta m_{13}$), the mixing angle ($\theta_{13}$) and the CP violating phase ($\delta$).

It has recently been found that the shock wave changes the density profile around the resonance point in a few seconds after the core bounce. The effects of the shock wave appear as a decrease in average energy of $\nu_e$ in the case of normal mass hierarchy (or $\bar{\nu}_e$ in the case of inverted mass hierarchy) at stellar surface [2]. If $\sin^2 2\theta_{13}$ is large, the average neutrino energy as a function of time decreases according to shock propagation [3]. The neutrino event number is found to be different according to the $\theta_{13}$ value (large or small)[4]. The time dependence of the event rates was calculated in various cases of $\theta_{13}$ [5] and they discussed the influence of the shock wave on the neutrino event rate for a specific energy. They however used simplification of parameterized shock-wave profiles.
In contrast, we followed the shock wave propagation for a long time numerically, which is generated by a model of adiabatic collapse adopted in our hydrodynamics calculation, and obtained more realistic density profile. Then we apply the profile to the neutrino oscillation phenomena in order to examine the $\theta_{13}$ dependence of time evolution of the neutrino event rate in all energy ranges from 5MeV to 60MeV.

2. Numerical Method
As the first step, we intend to construct an approximate models of prompt explosion using an implicit Lagrangian code for general relativistic spherical hydrodynamics [6], we perform simplified calculations of core collapse and bounce by following adiabatic collapse with fixed electron fraction. We adopt the presupernova model of $15M_\odot$ star provided by Woosley and Weaver [8]. The numerical tables of Shen’s relativistic equation of state (EOS) [9] and Timmes’s EOS [10] are adopted for the high and low density matters, respectively. We succeeded in calculating propagation of shock waves which are generated by adiabatic collapse of iron cores and pass into the stellar envelopes[14]. In our simulation, the density behind the shock wave hardly decreases because we neglected neutrino cooling of the proto-neutron star. Detailed study of the cooling effect of the proto-neutron star is underway.

In order to calculate neutrino oscillation effect on the spectrum, we have to solve the time evolution of the neutrino wave function along the density profile of our supernova interior [11]. We here put the CP violating phase $\delta$ equal to zero in the CKM matrix. The neutrino oscillation parameters are taken from the analysis of the various observations [12], except for $\theta_{13}$: $\sin^2 2\theta_{12}=0.84$, $\sin^2 2\theta_{23}=1.00$, $\Delta m^2_{12}=8.1\times10^{-5}$eV and $\Delta m^2_{23}=2.2\times10^{-3}$eV. Using four values of $\sin^2 2\theta_{13} = 10^{-2}, 10^{-3}, 10^{-4}$ and $10^{-5}$, we calculate the neutrino survival probabilities. The neutrino energy spectra from supernova are obtained by multiplying the survival probability by original neutrino spectra that change in time [13], We assume detection at the Super-Kamiokande (SK) and Sudbury Neutrino Observatory (SNO). SK is filled with 32,000 ton pure water, and SNO is filled with 1,000 ton heavy water. The finite energy resolution of the detector was neglected here. The event number is obtained by integrating over the angular distribution of the events. We assumed a supernova at the center of the Milky Way (10[kpc]) and neglected the Earth effect.

3. Result and Discussion
Figure 1 show the expected event rates of $\bar{\nu}_e$ in the case of inverted mass hierarchy. The upper part shows the expected event rates in the SK as a function of time. This figure shows that the behavior of event rate is roughly divided into two features. When $\sin^2 2\theta_{13}$ is large, large $\bar{\nu}_e$ event rate is expected. When $\theta_{13}$ is large, the $\bar{\nu}_e$ neutrinos pass into the H-resonance in adiabatic condition, and $\nu_\mu$ and $\nu_x$ completely convert to each other. The average energy of neutrino is different ($E_{\nu_e} < E_{\nu_x} < E_{\nu_x}$). Therefore, the average energy of $\nu_e$ becomes higher, and the event rate of $\bar{\nu}_e$ of large $\theta_{13}$ is larger than the event rate of $\bar{\nu}_e$ of small $\theta_{13}$. The lower part of Figure 1 shows the ratio of the event rates of $\bar{\nu}_e$ with and without shock in the case of the inverted mass hierarchy. The shock front does not reach H-resonance point before 3 seconds. The event rate with shock is smaller than that without shock after 3 seconds. This is because the influence of the shock wave appears mainly for high-energy neutrinos as the shock propagates, and the number of high energy $\bar{\nu}_e$ decreases. On the other hand, in the case of small $\theta_{13}$, the difference is not clearly seen at any time. We hence confirm that the influence of the shock wave appears at late times only if $\sin^2 2\theta_{13}$ is large. In the case of the inverted mass hierarchy, the adiabaticity of $\bar{\nu}_e$ is influenced by the shock wave, because $\nu_e$ is related to the H-resonance [15]. On the other hand, the expected event rates of $\nu_e$ in the SK hardly change in the case of the inverted mass hierarchy.
The upper part shows the expected event rates of $\nu_e$ in the case of inverted mass hierarchy in the SNO as a function of time, and the lower part shows the ratio of event rate with shock and without shock.

Figure 2 is the same as Figure 1, but the expected event rates of $\nu_e$ in the case of normal mass hierarchy in the SNO. The upper part shows the expected event rates of $\nu_e$ as a function of time and the lower part shows the ratio of event rate with shock and without shock. This figure shows similar behavior to Figure 1. In the case of normal mass hierarchy, the adiabaticity of $\nu_e$ is influenced by the shock wave, because $\nu_e$ is related to the H-resonance. Therefore, the behavior of Figure 2 is almost the same as the Figure 1.

We point out that the constraint on $\theta_{13}$ can be inferred by the integrated event rate over the whole energy range. When $\sin^2 2\theta_{13}$ is large, the influence of the shock wave appears after a few seconds in the observation. It is time that the shock wave reached H-resonance. Therefore, observing the time evolution of the event, we would limit $\sin^2 2\theta_{13}$ and know the propagation of shock wave inside the star for large $\sin^2 2\theta_{13}$. If the detailed information of supernova neutrinos are obtained in future supernova events, it may reveal the appearance of the propagation of the shock wave by comparing the observation with our theoretical predication. Moreover, it is possible to feed back to the construction of the theoretical model of supernova explosion and to tie with clarification of more detailed explosion mechanism.

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