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Neutrino signal of supernova shock wave propagation: MSW distortion of the spectra and nucleosynthesis

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We try to limit the neutrino oscillation parameters from the supernova neutrinos by studying the MSW matter effect. The supernova neutrinos are generated in the core and propagate through the envelope. It is pointed out that shock wave propagation has strong influences on the supernova neutrino oscillation through the change of density profile.

Using an implicit Lagrangian code for general relativistic spherical hydrodynamics (Yamada,1997), we succeeded in calculating propagation of shock waves which are generated by adiabatic collapse of iron cores and pass into the stellar envelopes for more than ∼5s.

We examined how the influence of the shock wave appears in the neutrino spectrum, using density profile obtained in our calculation. We confirmed that the influence of the shock wave appears from low-energy side and moves toward high-energy side according to the shock propagation. In addition, we calculated the neutrino signal that will be observed on the earth, and found that this manner of the neutrino signal depends remarkably on the neutrino oscillation parameters. Therefore, there is a possibility of constraining the neutrino oscillation parameters from the supernova neutrino spectrum. Moreover, there is a possibility of finding the influence on the nucleosynthesis by changing the neutrino spectrum.

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1. Introduction

There are still a lot of mysteries on the mechanism of the core-collapsed supernova and nature of supernova neutrinos. They have been studied by numerical simulations in worldwide [1, 2, 3, 4, 5]. The neutrino oscillation has been studied in various experiments[6, 7]. But, even if the recent results from many experiments are taken into account, one cannot determine the remaining three neutrino oscillation parameters, i.e. the sign of mass difference(Δm_{13}), the mixing angle(θ_{13}) and the CP violating phase(δ).

Since most of the supernova neutrinos are released for about 10 s after the core bounce, it was initially thought that the shock wave hardly influences the neutrino oscillation of supernova neutrinos[8]. However 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 mass eigenstate of the neutrino changes according to the density profile of the star and there are two resonance points on the way[9]. The high density side is called H-resonance and the low density side L-resonance. When the evolution of neutrinos passes into adiabatic condition at the resonance point, the mass eigenstates are being kept. On the contrary, when it passes into non-adiabatic condition, the mass eigenstates flip. The effect of the shock wave manifests as a decrease in average energy of ν_e in the case of normal mass hierarchy (or $\bar{\nu_e}$ in the case of inverted mass hierarchy) at stellar surface[10]. If $\sin^2 2\theta_{13}$ is large, the average neutrino energy as a function of time decreases according to shock propagation[11]. The expected event rates of neutrino detection depend on the magnitude of θ_{13} [12]. The time structure of the expected of event rates in a specific energy range was calculated for various θ_{13} values[13, 14]. They use simplify parametrized shock-wave profiles.

Therefore, it is worthwhile to study the shock wave propagation for a longer time scale $\sim$10 s, which is generated by adiabatic collapse is our theoretical calculations using hydrodynamic code. For our realistic density profile, we can reexamine the dependence on of time evolution of the supernova neutrinos on the undetermined neutrino oscillation parameters.

2. Numerical Method

2.1 Supernova Model

In order to calculate the detailed density profile, we use the one dimensional simulation result of the supernova for the studies of the MSW effect of supernova neutrinos. We model the supernova explosion using an implicit Lagrangian code for general relativistic spherical hydrodynamics[15]. As the first step, we perform simplified calculations of core collapse and bounce by letting them follow adiabatic collapse with fixed electron fraction. This is because we intend to construct an approximate model of prompt explosion in order to follow shock wave propagation for a long time scale $\sim$10 s[16]. We adopt the presupernova model of $15M_\odot$ star provided by Woosley and Weaver (WW95) [17]. The numerical tables of Shen's relativistic equation of state (EOS)[18] and Timmes's EOS[19] are adopted for the high and low density matters, respectively. We calculate the region from the central core ($\sim 10^{15}$g/cm^3) through the stellar envelope ($\sim$ 1 g/cm^3) simultaneously in a single numerical code.

Having the extended EOS table, we succeeded in the calculation of propagation of shock for more than 10 s, which is generated by adiabatic collapse of iron core passing through the stellar envelope consistently[20]. In the following sections we discuss how the shock propagation affects the oscillation of the supernova neutrinos.

2.2 Neutrino Oscillation

The calculation of neutrino oscillations requires the solution of the time evolution of the neutrino wave function along the density profile of our supernova model[21]. The neutrino oscillation parameters are taken from the analysis of the various observations, except for θ_{13} [22]: $\sin^2 2\theta_{12}$=0.84, $\sin^2 2\theta_{23}$=1.00, Δm^2_{12}=8.1$\times$10^{-5}eV^2 and Δm^2_{13}=2.2$\times$10^{-3}eV^2. 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 which will be observed on the earth are calculated by multiplying the survival probability by original neutrino spectra that change in time[23]. The expected event rate of neutrino detection in water Cherenkov detector can be expressed as

$$\frac{d^2N}{dE_e dt} = N_{tar}\cdot\eta_{(E_e)}\cdot\frac{1}{4\pi d^2}\cdot\frac{d^2N_\nu}{dE_\nu dt}\cdot\sigma(E_\nu)\cdot\frac{dE_\nu}{dE_e}, \tag{2.1}$$

where N is the detection number of neutrinos, E_e[MeV] is the energy of electron/positron, E_ν[MeV] is the energy of neutrino, N_{tar} is the target number, $\eta_{(E_e)}$[MeV] is the efficiency of the detector, d[m] is the distance from the supernova, $\frac{d^2N_\nu}{dE_\nu dt}$[/s /MeV] is the neutrino spectrum and σ[cm^2] is the cross section[9]. We assume detection at the Super-Kamiokande. The fiducial mass of Super-Kamiokande is 32000 ton and the solvent is water. The reaction $\bar{\nu}_e p \to e^+ n$ mainly contributes to neutrino detection at the Super-Kamiokande because the cross section of this reaction is largest. The finite energy resolution of the detector was neglected here. The event rate is integrated over the angular distribution of the events. The energy of the electron is assumed to be $E_e = E_\nu + m_p - m_n - m_e$ for $\bar{\nu}_e p \to n e^+$, and $E_e = E_\nu - \frac{m_e}{2}$ for $\nu e \to \nu e$. To make the estimate, we assumed as follows: $\eta_{(E_e)} = 0$ for $E_e < 7$ [MeV], and $\eta_{(E_e)} = 1$ for $E_e \geq 7$ [MeV]. We also assumed that the supernova appears near the center of the Milky Way (d=10[kpc]). We neglect the earth effect[24].

3. Result

In our simulation the shock wave reaches the H-resonance point in about 2 s[25]. The electron number density at the resonance point is

$$n_{e,res} \equiv \frac{1}{2\sqrt{2}G_F}\frac{\Delta m^2}{E}\cos 2\theta, \tag{3.1}$$

where G$_F$ is Fermi coupling constant, Δm^2 is the mass squared difference, θ is the mixing angle, and E is the neutrino energy. Δm^2 and θ correspond to Δm^2_{13} and θ_{13} at H-resonance and to Δm^2_{12} and θ_{12} at L-resonance, respectively. As the shock wave propagates outward, the density at the shock front decreases progressively and the resonance condition is satisfied for higher energy neutrinos. Therefore, the influence of the shock appears at first in low-energy region (see Eq.(3.1)) and moves toward high-energy region as the time passes by with the shock wave propagation[25].

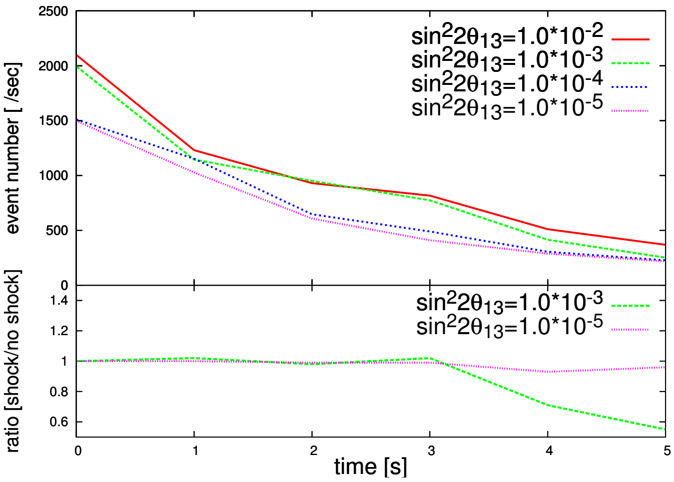

Figure 1: The upper part shows expected event rate of $\bar{\nu}_e$ at the Super-Kamiokande as a function of time, in the case of the inverted mass hierarchy. The lower part shows the ratio of event rate of $\bar{\nu}_e$ with and without shock.

The upper part of Figure 1 shows the expected event rate in the Super-Kamiokande as a function of time after bounce in the case of inverted mass hierarchy. The observation of neutronization ν_e burst at Super-Kamiokande can determine the time at bounce. When $\sin^2 2\theta_{13}$ is large, a lot of $\bar{\nu}_e$ events are expected. We found that there is a difference by about 500 events at most, but the detail depends on the parameter θ_{13}. In the case of the inverted mass hierarchy, the adiabaticity of ν_e is not influenced by the shock wave because ν_e has no relation with the H-resonance. Therefore, the event rate of ν_e is almost the same because the spectrum of ν_e does not change independently of parameter values. It is to be noted that the constraint on θ_{13} is imposed by all event rate over the for whole energy range[14]. In the case of the normal mass hierarchy, H-resonance relate ν_e to ν_x. Therefore, behavior of ν_e is similar to the case of $\bar{\nu}_e$ though the absolute event rate is different.

The lower part of Figure 1 shows the ratio of the event rate with and without shock in the case of inverted mass hierarchy. The dashed and dotted lines show the cases of $\sin^2 2\theta_{13} = 10^{-3}$ and 10^{-5}, respectively. The shock front does not reach H-resonance point before for 3 s. In the cases of $\sin^2 2\theta_{13} = 10^{-3}$ after 3 seconds, the event rate with shock is smaller than that without shock. This is because the influence of the shock appears mainly for high-energy neutrinos as the shock propagates. On the other hand, in the case of $\sin^2 2\theta_{13} = 10^{-5}$, the difference is not clearly seen at any time. Therefore, we conclude that the influence of the shock wave appears at late times only if $\sin^2 2\theta_{13}$ is large.

4. Summary and discussion

We calculated the propagation of shock wave in the adiabatic collapse of iron core and the stellar envelope in order to study the shock effect on neutrino oscillation. We followed the shock wave propagation for long time ∼10 s after core bounce and used more realistic density profile. We calculated the expected event rate of neutrino detection at Super-Kamiokande. The time evolution of the event rate of $\bar{\nu}_e$ was calculated for various θ_{13} values. Depending on the parameter θ_{13}, the observed event rate of $\bar{\nu}_e$ is found to be different in the case of the inverted mass hierarchy, while the event rate of ν_e is different in the case of the normal mass hierarchy. We point out that the constraint on θ_{13} can be inferred by the integrated event rate over the whole energy range. When $\sin^2 2\theta_{13} = 10^{-3}$, the influence of the shock wave appears after 3 s in the observation of $\bar{\nu}_e$. Therefore, observing the time evolution of the event rate would limit the mixing parameter θ_{13}.

The interaction between neutrinos might be important because of their huge flux immediately after they have come out of the proto-neutron star. This could change initial neutrino spectrum from what we assumed in an exponential decay model of the present study. Balantekin et al. [26] discussed that it virtually makes several interesting effects on the neutrino signal, the r-process nucleosynthesis, and the neutrino-process nucleosynthesis. However, we enjoy a success in modeling these nucleosynthesis processes by using the exponential decay model [27, 28, 29] so that the calculated elemental abundances can reproduce the observed data of r-process elements and LiB which are produced in core-collapse supernovae. We therefore interpret that the neutrino-neutrino interaction does not strongly destroy these results although it may change explosion models which provide environmental condition for the nucleosynthesis. We will consider this effect in more realistic calculations of the neutrino signal in the future.

If the detailed information of supernova neutrinos is obtained in future supernova events, it would reveal the effect of the propagation of the shock wave through the comparison between observation and theoretical predication. Moreover, it might feed back to the construction of the theoretical modeling of detailed explosion mechanism, and to tie with more detailed mechanism clarification. Moreover, there is a possibility of finding the influence on the nucleosynthesis in supernova by changing the neutrino spectrum[28].

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