

# Shock wave propagation in prompt supernova explosion and the MSW effect of neutrino

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**Abstract.** The MSW effect of supernova neutrino is one of foci of recent neutrino astrophysics. It is still an open question how the shock wave propagation affects the neutrino oscillation. Using an implicit Lagrangian code for general relativistic spherical hydrodynamics, we succeeded in numerical simulations of breakout of shock wave propagation through the stellar envelope. We first discuss our successful result of shock wave propagation which is generated by adiabatic collapse of iron core, and compare with non-adiabatic models. Secondly, we apply our model to the neutrino oscillation and calculate survival probabilities of three light-neutrino families. We discuss how the flux and energy spectrum of each neutrino species can change due to the MSW effect.

## 1. Introduction

There still exist a lot of mysteries of the mechanism of the supernova explosion. Most of previous simulations of supernova explosion were carried out so that the shock wave propagations through the iron core and the stellar envelope were separately solved. An artificial initial condition is often given to the inner core when the outside layer is calculated. Therefore, in order to remove such a defeat, we try to carry out numerical simulations of the explosion throughout the core to the envelope consistently in a unified manner.

The supernova neutrinos have very interesting nature. 99% of the gravitational energy for the core collapse is released as neutrinos. The average energies of various species of supernova neutrino are different from one another. These differences make some very interesting and important effects on neutrino oscillations.

The supernova neutrinos are generated in the core, and they propagate through the envelope. Therefore, it is necessary to consider matter effect of the neutrino oscillations. It is known that the shock wave influences the resonance area of neutrino oscillations [1]. With our numerical simulation, we thus study how and where the influence of the shock wave appears in neutrino oscillations.

## 2. Numerical Method

We use an implicit Lagrangian code for general relativistic spherical hydrodynamics [2]. As the first step, we perform simplified calculations of core collapse and bounce by following adiabatic collapse with fixed electron fraction, because we intend to construct an approximate model of prompt explosion. We adopt the presupernova model of  $15M_{\odot}$  star provided by Woosley and Weaver (WW95) [3] and calculate the region of the iron core and the stellar envelope simultaneously. The tables of Shen's relativistic EOS [4] and Timmes's EOS [5] are adopted for the high and low density matters, respectively.

We investigate how the shock propagation affects the neutrino oscillation for the supernova neutrinos. We solved numerically the time evolution equation of the neutrino wave function along the density profile of our supernova calculation [6]. The neutrino oscillation parameters are taken from various analysis of the observations, except  $\theta_{13}$ :  $\sin^2 2\theta_{12} = 0.84$ ,  $\sin^2 2\theta_{23} = 1.00$ ,  $\sin^2 2\theta_{13} = 6 \times 10^{-4}$ ,  $\Delta m_{12}^2 = 7.3 \times 10^{-5} \text{eV}^2$ , and  $\Delta m_{13}^2 = 2.5 \times 10^{-3} \text{eV}^2$ . If  $\theta_{13}$  is large, neutrino oscillation might be affected by the shock wave. The influence appears in neutrino spectra for normal mass hierarchy, and in anti-neutrino spectra for inverted mass hierarchy [7]. Using the density profile obtained from our calculation, we calculated the neutrino survival probabilities and neutrino fluxes.

## 3. Result and Discussion

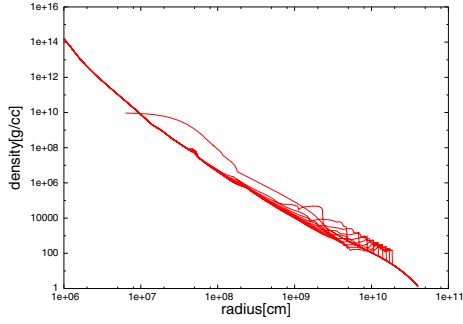
We succeeded in calculating propagation of shock wave which is generated by adiabatic collapse of iron core and passes into the stellar envelope in single simulation. Figure 1 shows the density profiles as functions of radius for every 2 seconds after the core bounce. But the density behind the shock wave hardly decreases because we neglect neutrino cooling in the protoneutron star in the present study. Extended calculation including this effect is now underway.

Figure 2 shows the survival probabilities of electron neutrinos as functions of neutrino energy for normal mass hierarchy. The survival probability of the electron type neutrinos becomes negligibly small when there is no shock. However, due to the shock propagation, the survival probability becomes appreciably different from zero. This effect appears from low-energy side and moves toward high-energy side according to the shock wave propagation. The electron number density at the resonance point is  $n_{e,res} \equiv (2\sqrt{2}G_F)^{-1}\Delta m^2 E^{-1} \cos 2\theta$ , where  $G_F$  is Fermi coupling constant,  $\Delta m^2$  is the mass squared difference,  $\theta$  is the mixing angle, and  $E$  is the neutrino energy.  $\Delta m^2$  and  $\theta$  correspond to  $\Delta m_{13}^2$  and  $\theta_{13}$  at H-resonance and to  $\Delta m_{12}^2$  and  $\theta_{12}$  at L-resonance, respectively. This is because, as shock wave propagates outward, the density at the shock front decreases and the resonance condition is satisfied for higher energy neutrinos.

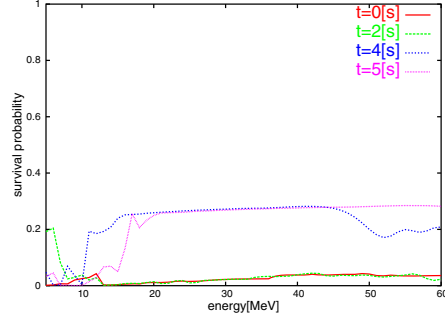
Figure 3 depicts the fluxes of three flavor neutrinos as functions of the neutrino energy at four different times of 0, 2, 4 and 5 s after the core bounce for normal mass hierarchy. We use the energy spectra of  $\nu_e$ ,  $\nu_{\mu}$  and  $\nu_x$  of the numerical supernova model [8]. Compared with  $t=0$  s, only a low energy part of  $\nu_e$  increases slightly at  $t=2$  s. At later times, the effect moves toward higher energy. The influence of the shock wave in the flux moves from the low-energy side to the high-energy side for the reason discussed in the previous paragraph.

## 4. Conclusion

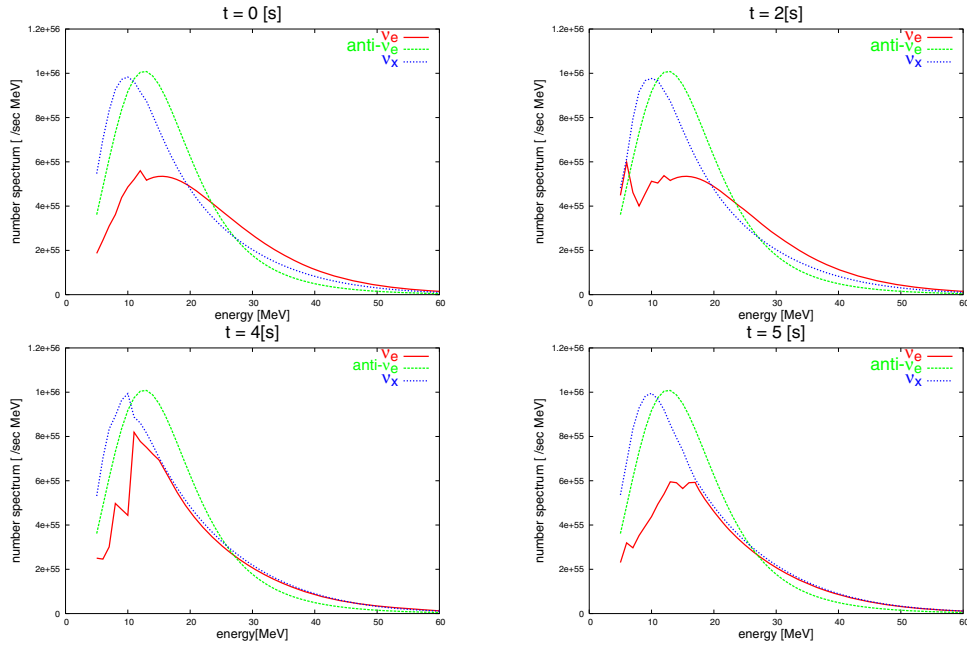
We succeeded in the calculation of propagation of shock wave which is generated by adiabatic collapse of iron core passing through the stellar envelope consistently. Using our calculation, we confirmed that the MSW effect appears from low-energy side and moves toward high-energy side according to the shock wave propagation. There is a possibility of finding the movement of the shock wave inside the star as such supernova neutrino signal. However, in our simulations, the density behind the shock wave hardly decreases because we neglected neutrino cooling of the protoneutron star. We need several improvements. Detailed studies of  $\theta_{13}$  dependence and the cooling effect of the protoneutron star are underway.



**Figure 1.** The density profiles as functions of radius for every 2 second after the core bounce.



**Figure 2.** The survival probabilities of electron neutrinos as functions of neutrino energy.



**Figure 3.** The neutrino spectra as functions of neutrino energy at different times 0, 2, 4 and 5 s after the core bounce, respectively. Spectra for  $\nu_e$ ,  $\bar{\nu}_e$  and  $\nu_x$  are displayed by red, green and blue curves, respectively.

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