PROCEEDINGS OF SCIENCE

Neutrino oscillations in non-spherical supernova explosions

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Over the last decades, it has been observationally suggested that the core-collapse supernovae are generally aspherical. On the other hand, most of the previous studies about the neutrino oscillation with the predictions of the neutrino spectra have been concerned with the spherically symmetric supernova explosions. Here we study how the explosion anisotropy affects the neutrino spectra through the neutrino oscillation in the non-spherical supernova envelope.

In order to clarify the dependence of the neutrino spectrum in the direction, we calculate the neutrino spectra in two typical directions of the equator and the pole, and compared them with each other. Moreover, we predict the event rates of the supernova neutrinos to be observed in the Super-Kamiokande by assuming a supernova at the center of Milky Way. We find that the survival probabilities and neutrino spectra are different from one another depending on the direction from the axis for asymmetric Type-Ic supernova explosion. The event rate of the polar direction decreases when the shock wave is propagating the H-resonance ($\sim 10^3$ g/cm^3). If we obtain the inclination from axis of the supernova by optical observation, we can find the asymmetric diverse of core explosion from the neutrino observation, and the explosion mechanism in detail.

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1. Introduction

There are a lot of unresolved problems concerning to the mechanism of core-collapsed supernova explosions and supernova neutrinos. Since 99 % of the gravitational energy of the collapsed core is released as neutrinos, it is expected that the neutrinos are important keys to solve how supernova explosions succeed. The neutrino oscillation was discovered in various neutrino experiments [1]. However, it is still very difficult to determine three neutrino oscillation parameters of the mass difference between 1-3 mass eigenstates, Δm^2_{13}, the 1-3 mixing angle, θ_{13}, and the CP violating phase, δ.

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 ν_e in the case of normal mass hierarchy (or $\overline{\nu}_e$ 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 time dependence of the event rates was calculated in various case of θ_{13} (e.g., [4]). However, most of the previous studies about the supernova neutrino oscillation have been concerned with the spherically symmetric supernova explosions. On the other hand, it has been observationally and theoretically suggested that the most core-collapse supernovae explode to non-spherical symmetry (e.g., [5, 6]). Therefore, we study how the explosion anisotropy affects the neutrino spectra through the neutrino oscillation in the non-spherical supernova envelope. In order to clarify detailed dependence of the supernova neutrinos in the non-spherical supernova envelope, we calculated the event rates of the supernova neutrinos in the equatorial and polar directions to be observed with the Super-Kamiokande.

2. Numerical Method

2.1 Supernova model

We use the explosion model of a Type-Ic supernova which was calculated by using the 2D magnetohydrodynamic simulation adopted a 25 $M_\odot$ rotating presupernova model as the initial model of the explosion (Takiwaki *et al.* 2008) . Initial magnetic field strength of center of core is 10^{12}G. Figures 1 (a) and (b) are the density profiles as a function of the distance for the center in the equatorial and the polar directions, respectively. The density profile in the polar direction changes greatly as the time passes by, and the shock wave reaches the H-resonance ($\sim O(10^3)$g/cm^3) in the very early stage after the core bounce. On the other hand, the density profile in the equatorial direction is almost unchanged except for a local structure near the shock front.

2.2 Neutrino oscillation

We solve the time evolution of the neutrino wave function [7] using the density profiles of 2D simulation result. We put the CP violating phase equal to zero. The neutrino oscillation parameters are taken from the analysis of the various observations [8] ; $\sin^2 2\theta_{12}$=0.84, $\sin^2 2\theta_{23}$=1.00, $\Delta m^2_{12}=8.1\times10^{-5}$eV^2 and $|\Delta m^2_{13}|=2.2\times10^{-3}$eV^2. We assumed $\sin^2 2\theta_{13}=1.00\times10^{-3}$ and the case of inverted mass hierarchy. Using these values, we calculate the neutrino survival probabilities.

The neutrino energy spectra from supernova are obtained by multiplying the survival probability by original neutrino spectra [9]. The original neutrino spectra is assumed to decay exponen-

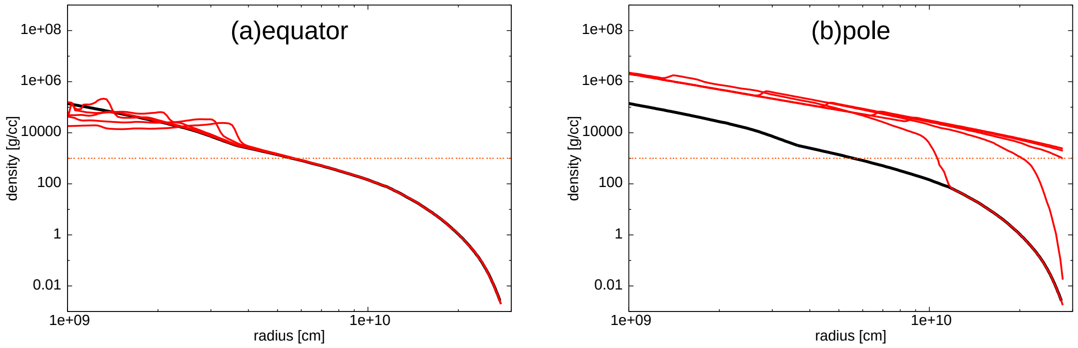

Figure 1: The density profile every 1 sec as a function of radius. Left figure (a) and right figure (b) are the equatorial and the polar direction, respectively. The horizontal line shows approximately density of the H-resonance.

tially with the decay time of 3 sec. The integrated our spectra are corresponding to a model of the Lawrence Livermore group [7]. We calculated the expected event rate of neutrino. We consider the Super-Kamiokande(SK) detector which is filled with 32000 ton pure 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. As for the efficiency of the detector, we assumed as follows for simplicity $\eta_{(E_e)} = 0$ at $E_e < 7$ [MeV] and $\eta_{(E_e)} = 1$ at $E_e \geq 7$ [MeV]. We assumed a supernova at the center of Milky Way (d=10[kpc]), and we neglected the Earth effect.

3. Result

3.1 Detection of neutrinos

Figure 2 shows the event rate of $\bar{\nu}_e$ in the case of inverted mass hierarchy and $\sin^2 2\theta_{13} = 10^{-3}$ as a function of time. Solid line and dotted line are the event rates in the polar and equatorial directions, respectively. The event rate in the polar direction is different from that in the equatorial direction. In the polar direction, the shock wave reaches H-resonance in the early stage after core bounce. Therefore the neutrinos in the polar direction are strong influenced by the shock wave. As a result, the events of high energy neutrinos decrease. On the other hand, the shock wave in the equatorial direction does not reaches H-resonance until 5sec after core bounce. Therefore, the neutrinos in the equatorial direction is less influenced by the shock wave.

3.2 Time-dependent event rates for high energy and low energy neutrinos

Figure 3 shows the time evolution of $\mathrm{R}(t)$ which is defined by the following equation,

$$\mathrm{R}(t) \equiv \frac{\text{event number for neutrinos of } 20 < E < 60\text{MeV}}{\text{event number for neutrinos of } 5 < E < 20\text{MeV}} \tag{3.1}$$

The solid and dotted lines of Figure 3 are $\mathrm{R}(t)$ in the polar and equatorial directions, respectively. Although $\mathrm{R}(t)$ in the polar direction is 4.75 until 0.4 sec, it decreases to ~ 3.40 in 0.4 - 2 sec. This decrease is due to the change of the adiabaticity of H-resonance according to the shock wave

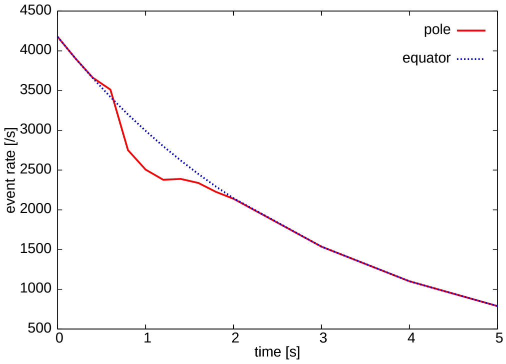

Figure 2: The expected event rate of $\overline{\nu}_e$ in the case of inverted hierarchy and $\sin^2 2\theta_{13} = 10^{-3}$. Solid line and dotted line are the event rates in the polar and the equatorial directions, respectively.

propagation. The neutrino is in the state of adiabatic before the shock arrival to the resonance. However, the neutrinos become in the state of non-adiabatic while the shock wave propagates through the resonance, and the events of the high energy neutrinos decrease. We can see that the shock wave influences the neutrinos in 0.4 - 2 sec, which is the time when the shock wave passes over H-resonance. Therefore, the time evolution of $\mathrm{R}(t)$ is a very important observable to find the effects of shock propagation in supernova.

4. Summary and Discussions

We calculated the event rates of the supernova $\overline{\nu}_e$ neutrinos by SK with the assumption that the supernova explodes at the center of the Milky Way. We showed that the neutrino event rate in the polar direction suffers strong influence of the shock wave from very early time. On the other hand, the neutrinos in the equatorial direction which and suffer little influence of shock wave.

Moreover, we consider the time evolution of ratio, $\mathrm{R}(t)$. In the equatorial direction, $\mathrm{R}(t)$ keeps the same value. On the other hand, $\mathrm{R}(t)$ in the polar direction greatly changes with time. This change is due to the change of the adiabaticity of H-resonance according to the shock propagation. The time when the influence of the shock wave appears in neutrino is early because shock propagation is very rapid, and the period that the shock wave influences neutrinos is short. Therefore, we can know that the shock wave in the polar direction reaches H-resonance very early, and passes through H-resonance in a very short period of time. In other words, we can find the effects of shock propagation in supernovae through $\mathrm{R}(t)$. If the influence of the shock wave is seen very early in the observation of the supernova neutrinos, like the polar direction result, we would be able to find that the shock wave reaches to H-resonance very early. Therefore, we would be able to expect that this explosion is a strong explosion. If the influence is seen, but is not very early, we would be able to expect that this explosion is not strong or we can see this explosion from about the equatorial direction. Moreover, the appearance of the influence of the shock wave in the neutrinos means large θ_{13} and the inverted mass hierarchy.

The nonlinear neutrino self-interactions might be important because of their huge flux immediately after they have come out of the proto-neutron star. This could change initial neutrino

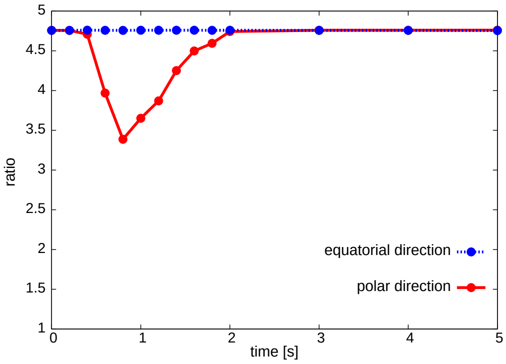

Figure 3: The ratio for high energy and low energy neutrino event, $\mathrm{R}(t)$. Solid line and dotted line are the ratio in the polar and equatorial directions, respectively.

spectra from what we assumed in an exponential decay model of this paper. We will consider this effect in more realistic calculations of the neutrino signal in the future. In the present study, we calculated only the model of $\sin^2 2\theta_{13} = 10^{-3}$ in the inverted mass hierarchy. We also assumed the Super-Kamiokande for the anti-neutrino detector system. Extended studies using other parameter values in both normal and inverted mass hierarchies for various detectors are now underway.

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