Neutrino oscillations in MHD supernova explosions

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Abstract. We calculate the neutrino oscillations numerically in magnetohydrodynamic (MHD) explosion models to see how asphericity has impacts on neutrino spectra. Magneto-driven explosions are one of the most attracting scenarios for producing large scale departures from spherical symmetric geometry, that are reported by many observational data. We find that the event rates at Super-Kamiokande (SK) seen from the polar direction (e.g., the rotational axis of the supernovae) decrease when the shock wave is propagating through H-resonance. In addition, we find that L-resonance in this situation becomes non-adiabatic, and the effect of L-resonance appears in the neutrino signal, because the MHD shock can propagate to the stellar surface without shock-stall after core bounce, and the shock reaches the L-resonance at earlier stage than the conventional spherical supernova explosion models. Our results suggest that we may obtain the observational signatures of the two resonances in SK for Galactic supernova.

1. Introduction
A large number of neutrinos are produced when a massive star undergoes a core-collapse supernova explosion. Such supernova neutrinos will carry valuable information from deep inside the core (e.g., [1]). Over the last decades, significant progress has been made in many neutrino detectors [2]. The neutrino detections are important to study not only the supernova physics but also the unknown neutrino oscillation parameters (e.g., [3, 4]). The supernova neutrinos interact with electrons when the neutrinos propagate through stellar matter via the Mikheyev-Smirnov-Wolfenstein (MSW) effect. The neutrino conversion efficiency via the MSW effect depends on the density gradients. Recently, such shock effects have been focused (e.g., [5]). The time dependence of the neutrino events monitors the evolution of the density profile thus could provide a powerful test of the mixing angle and the mass hierarchy (e.g., [6, 7, 8]). Most of those phenomenology of supernova neutrinos have been based on the spherically symmetric models of core-collapse supernovae (e.g., [9, 10]). On the other hand, there are observations indicating that core-collapse supernovae are globally aspherical (e.g., [11]). Pushed by them, various mechanisms have been explored thus far by supernova modelers to understand the central engine (e.g., [3]).

We study the neutrino oscillations in the case of the magnetohydrodynamic (MHD) explosions of core-collapse supernovae [12]. Based on such models, we calculate numerically the detection of supernova neutrinos in the highly non-spherical envelope through the MSW effect.
2. Numerical method

We take time-dependent density profiles from our MHD simulations of core-collapse supernovae [12], in which a 25 M_⊙ presupernova model [13] was adopted and the magnetic fields is $\sim 10^{12}$G. This progenitor lacks the hydrogen and helium layer during stellar evolution, which is reconciled with observations that the progenitors associated with long-duration gamma-ray bursts (LGRB) are type Ib/c supernovae [14]. In this case, the highly collimated shock pushed by the strong magnetic pressure can blow up the massive stars along the rotational axis [12]. It is noted that to maximize the shock effect a sharpness of the shock [15]. The flavor conversion through the MSW effect occur in two resonances, one is at higher density called H-resonance, and the other is at lower density called L-resonance.

Along the time-dependent density profiles, we solve numerically the time evolution equation for the neutrino wave functions [15]. The neutrino oscillation parameters are taken as $\sin^2 2\theta_{12}=0.84$, $\sin^2 2\theta_{23}=1.00$, $\Delta m^2_{23}=8.1 \times 10^{-5}$eV$^2$ and $|\Delta m^2_{13}|=2.2 \times 10^{-3}$eV$^2$. We assume the inverted mass hierarchy and $\sin^2 2\theta_{13}=1.0 \times 10^{-3}$ in our computations. The neutrino energy spectra at the surface of the star are calculated [4] using the results of a numerical simulation by the Lawrence Livermore group (e.g., [9, 8]). The luminosity is taken to decay exponentially with a timescale of 3 s [15]. We calculate expected event numbers of the supernova neutrinos at the SK [15], and assume that the supernova occurs in our Galactic center (10 kpc). We neglect the effects of neutrino self-interactions, the resonant spin-flavor conversion and do not consider the Earth matter effect in this study.

3. Result and Discussion

We define a ratio of the high-energy to the low-energy event numbers as in [8]: $R({\text{High/Low}}) = (\text{event number of } 20 - 60 \text{ MeV})/(\text{event number of } 5 - 20 \text{ MeV})$. The influence of the shock wave in the H-resonance appears in $\bar{\nu}_e$, and that in the L-resonance appears in $\nu_e$ in the inverted mass hierarchy. Left panels of Figure 1 show the time evolution of the event number, and right panels show $R({\text{High/Low}})$. Solid (red) line and dotted (blue) line are for the polar and the equatorial direction, respectively. Top panels are $\bar{\nu}_e$, and bottom panels are $\nu_e$. In the left panels, we can see the event number of the polar direction increases slightly, and decreases compared with that of the equatorial direction. This is because the shock reaches to the resonances, and the low-energy neutrinos increase and the high-energy neutrinos decrease. On the other hand, the event number of the equatorial direction does not change sharply, because the shock does not reach to the resonances for the equatorial direction. It is noted that the decrease in the events comes mainly from the decrease of the high-energy neutrinos rather than the increase of the low-energy neutrinos. This is because the cross section of main reaction for detection of $\bar{\nu}_e$ is proportional to the square of the neutrino energy. The decrease of the event number by the shock passage is about 36% of the event number without the shock. Since the expected events are $\sim 2500$ at the sudden decrease, it seems to be possible to identify such a feature by the SK class detectors. Such a large number imprinting the shock effect is thanks to the mentioned early shock-arrival to the resonances, peculiar for the MHD explosions. The event number of $\nu_e$ become much fewer than that of $\bar{\nu}_e$. This is because the cross section of the main reaction for detecting $\nu_e$ is about $10^{-2}$ times smaller than that of $\bar{\nu}_e$.

In right panels, $R({\text{High/Low}})$ begins to decrease, which might be an observable signature of the shock entering to the resonances. Along the polar axis, the shock reaches to the H-resonance at $\sim 0.5$ s, and the L-resonance at $\sim 1.2$ s. It should be noted that those timescales are very early in comparison with the ones predicted in the neutrino-driven explosion models, typically $\sim 5$ s and $\sim 15$ s for the H- and L- resonances, respectively (e.g., [6, 7]). This arises from the fact that the MHD explosion is triggered promptly after core bounce without the shock-stall, which is in sharp contrast to the neutrino-driven explosion models ([6, 7]). The progenitor of the MHD models, possibly linked to LGRB, is more compact due to the mass loss of hydrogen and
helium envelopes during stellar evolution, which is also the reason for the early shock-arrival to the resonances.

4. **Summary**

We studied neutrino oscillations from core-collapse supernovae that produce MHD explosions, which are attracting attention recently as a possible relevance to magnetars and/or LGRB. Based on our simulation, we calculated numerically the event number of the supernova neutrinos in the highly non-spherical envelope through the MSW effect, and investigated how the explosion anisotropy could have impacts on the observed neutrinos at the SK for a Galactic supernova. In the case of the inverted mass hierarchy with a relatively large $\theta_{13}$, the event numbers observed from the polar direction show steepest decrease, reflecting the passage of the shock to the resonances. This reflects a unique nature of the MHD explosion featuring a very early shock-arrival to the resonances. Our results suggested that the two features in the $\nu_e$ and $\bar{\nu}_e$ signals, if visible to the SK for a Galactic supernova, could be an observational signature of magneto-driven supernovae.

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**Figure 1.** Left panels are the time evolution of the event number, and right panels are the ratio of the high-energy to low-energy event number. Solid (red) lines and dotted (blue) lines are for the polar and the equatorial direction, respectively. Top panels are $\bar{\nu}_e$, and bottom panels are $\nu_e$. 