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Impacts of Collective Neutrino Oscillations on Neutrino Signatures from Collapsars

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In this contribution, we explore the impacts of collective neutrino oscillations on the neutrino signals in the light of collapsar models of long-duration gamma-ray bursts (GRBs). Based on our collapsar simulations with three different precollapse angular momentum, we estimate the emergent neutrino spectra with or without the collective neutrino oscillations. To mimic the collective effects, we manually swap the neutrino spectra as a first step. In the case of an inverted mass hierarchy with a small mixing angle ($\sin^2 2\theta_{13} = 10^{-4}$), we show that the event numbers of neutrinos could increase by a factor of $\lesssim 5$ due to the spectral swap. By a currently planned Mton-class detector, we point out that the neutrino signals, sharply depending on the angular momentum of the collapsing stars, could be directly visible for a 10 Mpc distance scale. For a progenitor with smaller initial angular momentum, the neutrino signals could show a sudden disappearance, which coins the epoch when the accretion disk whose thermal pressure is carried away by neutrinos, is absorbed into the black hole. These signatures, if observed, could provide us a new astrophysical information to unveil the collapsar dynamics.

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1. Introduction

Long-duration gamma-ray bursts (GRBs) are one of the energetic phenomena in the universe, while their central engines have not been clarified yet [1, 2]. The duration of the long GRBs may correspond to the accretion to the central black holes (BHs), which suggests the observational consequence of the BH formation. Pushed by those observations, the collapsar model has received quite some interest as their central engines [1, 3]. In the collapsar model, the outflow is formed with the BH and the accretion disc, which is consequent of gravitational collapse of a massive star. This accretion disc is thought to emit neutrinos. In the collapsars, the neutrino luminosity from the accretion disc is high, and the duration time of the neutrino radiation is long. On the other hand, the neutrino luminosity from the supernova (SN) decreases in exponential, and the duration time is about 10 s. The neutrinos of collapsar are different from that of the supernova, and might have a special feature. Therefore, it is necessary to calculate the neutrinos to clarify the GRB dynamics.

On the other hand, the neutrinos from the GRBs are not much calculated. Moreover, it is difficult to observe the neutrinos from the GRBs directly because the distance of the GRBs is about $\gtrsim O$(Mpc). However, the Mton-class detectors which are pursued [4, 5, 6, 7] might be able to detect the neutrinos from the GRBs. Moreover, the GRB rate is ~ 230 Gpc^{-3} yr^{-1} (e.g. [8] and references therein), and we can estimate a few event 100 Mpc^{-3} in several years though the SN rate is ~ 1 yr^{-1} per our galaxy. Therefore, there is possibility that the neutrino astronomy can be done by using GRB because the event rate is high.

By foreseeing the large volume detector, it is important for clarifying the dynamics of the engine of GRB to expect the neutrino signal from GRB. We calculate how the neutrino radiation from three collapsar models at several Mpc scale is observed on the earth taking into account the MSW matter effects and the neutrino self-interactions whether it affects the neutrinos in the collapsar (e.g., [9] , and references therein).

2. Collapsar Model and Numerical Method

We use three collapsar models calculated by Harikae, model A: MHD-driven collapsar model in weak magnetic field (10^9 G), model B: neutrino-driven collapsar model in no magnetic field, and model C: no-outflow collapsar model which a disk disappears at 3.3 s [10]. The neutrinos are radiated from the accretion disk of the collapsar. In model A and B, the neutrinos keep being radiated more than ten seconds, and the neutrino luminosities of models A and B are higher than that of usual SNe. Time evolution of the luminosity is different from each model. Using the luminosities and average energies of each model, the original neutrino spectra at the neutrino sphere are calculated by a simple formula [11].

The neutrinos are influenced by two effects in the star, the neutrino self-interactions and the MSW matter effects. We consider two cases, one case is only the MSW effects, and the other case is the MSW effects and the neutrino self-interactions whether it affects the neutrinos in the collapsar. We calculate the neutrino spectra considering the neutrino self-interaction approximately. The neutrino self-interaction is the phenomena changing the neutrino flavor in the SN core [9, 12]. A stepwise flavor conversion develops across a critical energy E_c; $P(E) \simeq 1$ (for $E < E_c$) and $P(E) \simeq 0$ (for $E > E_c$), where $P(E)$ is the survival probability of $\nu_e \rightarrow \nu_e$ (or $\overline{\nu}_e \rightarrow \overline{\nu}_e$) at the end of the self-

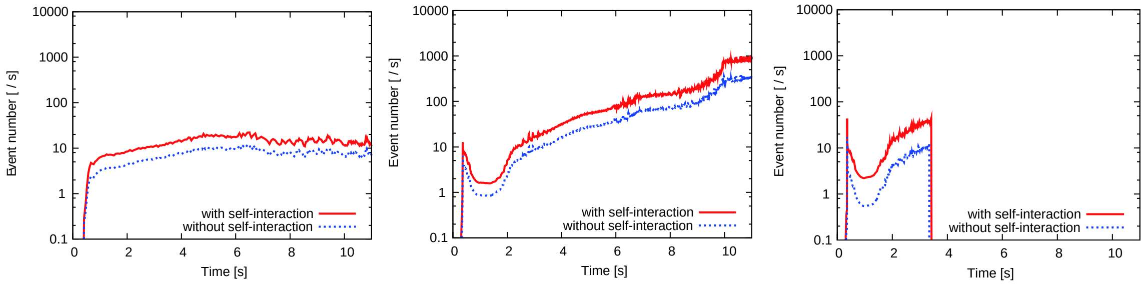

Figure 1: The event number at 1 Mpc with 5 Mton detector. Left, middle and right panel are in model A, B and C, respectively. Red (solid) line and blue (dotted) line show the event number with and without the neutrino self-interaction, respectively.

interaction. We set that E_c of ν_e is 7 MeV [12]. We assume that $P(E)$ of $\overline{\nu}_e$ is 0 in all energy range, because E_c of $\overline{\nu}_e$ is smaller than 4 MeV [12], and we calculate by the neutrino energy range in 5 - 60 MeV. In the case of inverted hierarchy, the self-interaction is found for both large and small values of θ_{13} [13].

We consider the MSW matter effect of the neutrino oscillations and, calculate the neutrino spectra on the surface of the star [14]. We solve numerically the time evolution for the neutrino wave functions along the density profiles of each model of the collapsar simulation result, and obtain survival probabilities of the neutrinos at the surface of the star [14]. The neutrino oscillation parameters are taken as $\sin^2 2\theta_{12}$=0.84, $\sin^2 2\theta_{23}$=1.00, Δm_{12}^2=8.1$\times$10^{-5}eV^2 and $|\Delta m_{13}^2|$=2.2$\times$10^{-3}eV^2 (e.g., the summary in [15] and references therein). We set the CP violating phase equal to zero in the CKM matrix for simplicity. For the unknown properties, we assume the inverted mass hierarchy and $\sin^2 2\theta_{13}$=1.0$\times$10^{-4}. Using the survival probabilities at the surface, we calculate the neutrino energy spectra at the surface of the star are calculated [14].

We calculate the expected neutrino event number with 5 Mton water Cherenkov detector [14]. The finite energy resolution of the detector is neglected here. The event number is obtained by integrating over the angular distribution of the events. For simplification, we take the efficiency of the detector $\eta(E_e)$: $\eta(E_e) = 0$ (for $E_e < 7$ [MeV]) and $\eta(E_e) = 1$ (for $E_e \geq 7$ [MeV]) [14]. Here, we consider the detection of $\overline{\nu}_e$ because the cross section of $\overline{\nu}_e$-induced reaction to detect the neutrinos is the largest of all reactions. Albeit important, we do not consider the Earth matter effect to highlight first the signature of neutrinos from the collapsar.

3. Results

Fig. 1 shows the event number with 5 Mton water Cherenkov detector, which is assumed at 1 Mpc. Red (solid) line and blue (dotted) line are the event number with and without the neutrino self-interaction, respectively. Left, middle and right panel of Fig. 1 are in model A, B and C, respectively. The behavior of the event number depends on the neutrino luminosity. In model A and B, the neutrino keeps being observed over ten seconds, because the duration time of the neutrino radiation from collapsar is continued. Note that the radiation of the SN neutrinos ends in about 10 s. In middle panel of Fig. 1, there are many event compared with left panel. This is because the neutrino luminosity of model B is larger than that of model A. In right panel of Fig. 1 (model C), the event rate sharply decreases at 3.3 s, because the disk which radiate the neutrinos disappears at that time.

We can see the event number with self-interaction in each model is larger than that without self-interaction. We observe mainly $\bar{\nu}_e$ because the cross section of $\bar{\nu}_e$ detection is largest of all detection. In the case with self-interaction, the spectra of $\bar{\nu}_e$ are larger than that without self-interaction. In addition, the main reaction for $\bar{\nu}_e$ detection is proportional to the square of the neutrino energy, and the spectra of high-energy side in case with self-interaction are larger than that in case without self-interaction. Therefore, the event number with the self-interaction is larger than that without the self-interaction.

We estimate the event rate of the neutrinos in each collapsar model. We average the event number for 2 - 10 s because the collapsar disk has been stable. We calculate the event rate of the neutrinos from the collapsar at 1, 5, and 10 Mpc. The detector is assumed 5 Mton. The number of the neutrinos decreases by the square of the distance, and the detection of the neutrinos is difficult. Therefore, the event rate decrease according to the distance. In each model, the event rate with the self-interaction is two times larger than that without self-interaction. In model B, the event rate with self-interaction is 1.11 s^{-1} at 10 Mpc. Here, we roughly assume that the duration time of GRB is the lifetime of the collapsar disk, and the neutrinos are radiated from the collapsar disk. If the duration time of the collapsar disk is 30 s [16], the total event number from GRB at 10 Mpc with the self-interaction is about 33.3 in model B. There is a possibility that the neutrinos from the collapsar at 10 Mpc are observed. Therefore, there is a possibility to be able to use the neutrinos from GRB, which might be an alternative to conventional neutrino astronomy by the SN neutrinos.

4. Summary and Discussion

Using three collapsar models, we calculated the expected event number of the neutrinos from GRB at several Mpc scale taking into account the MSW matter effects and the neutrino self-interaction. The collapsar model is received some interest for the central engines of the long GRB. We found that there was a possibility that the neutrinos from GRB at Mpc scale could be detected directly if there are the Mton-class detectors. The behavior of the event number depended on the neutrino luminosity, and the neutrino kept being observed over ten seconds, because the duration time of the neutrino radiation from collapsar was continued. In the neutrino burst model (model B), there are many event compared with the MHD jet model (model A). Therefore, the observation of the neutrinos of MHD model might be more difficult than that of the neutrino burst model. In no-outflow model (model C), the event rate sharply decreases because the disk which radiates the neutrinos disappears at 3.3 s. Moreover, the event number of the neutrinos from the collapsar became large considering the neutrino self-interactions if it affects the neutrinos in the collapsar.

If the neutrinos radiated from the collapsar disk, the duration of the collapsar disc would control the detection number of neutrinos. For the direct detection of the neutrinos from GRB, the duration of the collapsar disk might be important. The neutrino from GRB leads to the verification of the neutrino physics. In this study, the influence of the shock wave is not considered. If the shock wave reaches high-resonance region ($\sim O(10^3)$ g/cm^3) [14], the number of neutrinos with self-interaction might decrease.

If the central engine is powered by the neutrinos such as our model B, neutrino-induced gravitational waves (GWs) are detectable for 1 Mpc events by LISA and 100 Mpc by DECIGO/BBO [17]. The GWs and the neutrino detections are helpful for probing the explosion mechanism. Therefore, the Mton-class detector is necessary, and it might be clarified the dynamics of long GRBs by the direct detection of the neutrinos from GRBs.

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