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Collective flavor conversion including the neutrino halo in core-collapse supernovae

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Abstract. We investigate collective neutrino oscillation (CNO) including neutrino halo effects in an iron core-collapse supernova model. We find that CNO suddenly occurs beyond the propagating shock front evolved from a $9.6M_{\odot}$ star. Also, we find that neutrinos inwardly scattered by background matter can be ignored outside the shock front where CNO can occur, compared with outward-going neutrinos. Neutrinos get free from matter suppression and scattering with background matter beyond the shock front. Neutrino halo with wider intersection angles produces additional flavor transformation and sharpens the spectral splits.

1. Introduction

Core-collapse supernova (CCSN) emits intense neutrino fluxes from a proto-neutron star (PNS). Since these neutrinos are created in the center, their spectra possess information on the equation of state in nuclear-matter density. However, propagating neutrinos undergo a flavor mixing by neutrino oscillations and lose the original flavor information. The flavor conversion has three types of neutrino oscillations, i.e., vacuum, matter, and collective neutrino oscillation (CNO). The first two oscillations are linear effects and well-known by many neutrino experiments [1]. Recently, the last one, CNO, induced by the neutrino-neutrino interactions has attracted significant attention [2]. This flavor conversion occurs near the PNS and shows peculiar features, called spectral splits, which are not seen in linear effects. Many previous studies usually adopt the "bulb model" under many assumptions and symmetries and have investigated this phenomenon. However, recent studies have revealed that symmetry breaking can produce new instabilities.

Cherry *et al.* pointed that some fraction of emitted neutrinos can experience a direction-changing neutrino-nucleus outside the neutrino sphere [3]. These scattered neutrinos produce a neutrino 'halo' with large intersection angle and can affect the neutrino-neutrino interaction.

Recently, the COHERENT experiment has reported the direct detection of coherent elastic neutrino-nucleus scattering [4]. This result has proven the neutrino scattering with background matter and the formation of neutrino halo population within CCSNe. The previous paper studied this impact, employing an electron-capture CCSN model with steep density gradient in envelope. The scattering rate deceases outside the density gradient and neutrinos inwardly scattered from outer layer can be ignored. These inward-going neutrinos can destroy the bulb framework under post process. CNO with the bulb+halo model was able to be performed safely only outside the density gradient in the envelope.

In this study, we investigate the impact of neutrino halo effects on CNO in an iron-CCSN simulation. Here, we compare CNO including the halo neutrino scattering (the with-halo case) with the traditional bulb model (the no-halo case).

2. Calculation method

2.1. Supernova model

We calculate an explosion simulation of a two-dimensional CCSN with a $9.6M_\odot$ metal-free progenitor model (Z9.6) provided by A. Heger (2017, private communication, this model is a extension of Heger et al. 2010 [5] toward the lower mass). This hydrodynamical simulation is performed by 3DnSNe code [6]. The spacial resolution is $(N_r, N_\Theta) = (512, 128)$ on a spherical polar coordinate and the radial grid covers from the center to the outer boundary of 5000 km.

2.2. Neutrino halo

Emitted neutrinos from the PNS can experience a direction-changing scattering with background nucleon/nucleus. This scattering is a flavor-blind phenomenon via neutral-current reaction. We can estimate the neutrino scattering out of flavor mixing. Cross section for a coherent elastic scattering was obtained in Ref. [7]:

$$\sigma\left[E_\nu,(Z,N)\right] \approx \frac{G_{\rm F}^2}{\pi}E_\nu^2\left[\frac{1}{2}\left(C_A-C_V\right)A+\frac{1}{2}\left(2-C_V-C_A\right)(Z-N)\right]^2, \quad (1)$$

where mass number is A, proton number is Z, and neutron number is N. The neutrino scattering rate depends on the density profile and the composition in background. Gathering the scattering information at each radial and each angular bin in the two-dimensional CCSN model, we can re-construct the halo population and non-scattered neutrino components. Here, we need to consider the contribution from inward-scattered neutrinos. We check the contribution ratio of inward-scattered neutrinos to outward-propagating neutrinos at each grid. If this ratio is less than 10% at a certain point, we can ignore the inward contribution at the point. On the other hand, if not, inward contribution is dominant and we can not safely calculate CNO in the region.

2.3. Collective neutrino oscillation

Using the halo neutrino population calculated in the previous section, we can obtain the flavor conversions including the neutrino halo effects. The flavor evolution for a density matrix ρ_ν is given by a von-Neumann equation,

$$i\partial_r\rho_\nu = \left[H_{E,u},\ \rho_\nu\right] \quad (2)$$

$$H_{E,u} = \frac{1}{v_{r,u}}\left(U\frac{M^2}{2E}U^\dagger + \sqrt{2}G_{\rm F}n_eL\right) + \sqrt{2}G_{\rm F}\int {\rm d}E'{\rm d}u'\left(\frac{1}{v_{r,u}v_{r,u'}}-1\right)\left(\rho_\nu-\overline{\rho}_\nu\right), \quad (3)$$

where the first term and the second term in the total Hamiltonian $H_{E,u}$ express vacuum and matter oscillation, respectively. The last term is CNO Hamiltonian and includes the halo effects.

The halo flux is included in the density matrices and it gives anisotropic angular distribution. The broader intersection angle term is transformed into the radial velocity,

$$v_{r,u} = \sqrt{1 - u\frac{R^2}{r^2}} \tag{4}$$

$$u = \sin^2 \theta_R, \tag{5}$$

where θ_R is an emission angle relative to radial direction. If we adopt the bulb model, emission source corresponds to the neutrino sphere $R = R_\nu$. And if we consider the coherent neutrino scattering as the bulb+halo model, this is the neutrino-halo sphere $R = R_H$.

In this work, we choose the following neutrino parameters as in Ref. [1]: $\Delta m^2_{21} = 7.37 \times 10^{-5}$ eV^2, $|\Delta m^2_{31}| = 2.54 \times 10^{-3}$ eV^2, $\sin^2\theta_{12} = 0.297, \sin^2\theta_{13} = 0.0216$, and CP-violation phase $\delta = 0$. We consider only the inverted mass ordering case $\Delta m^2_{31} < 0$.

3. Results

We show the density profile along the polar direction and the radial evolution of the energy- and angle-averaged survival probability at postbounce time 136 ms as a representative snapshot in Figure 1. The flavor transformation does not occur until $r \sim 430$ km due to matter suppression

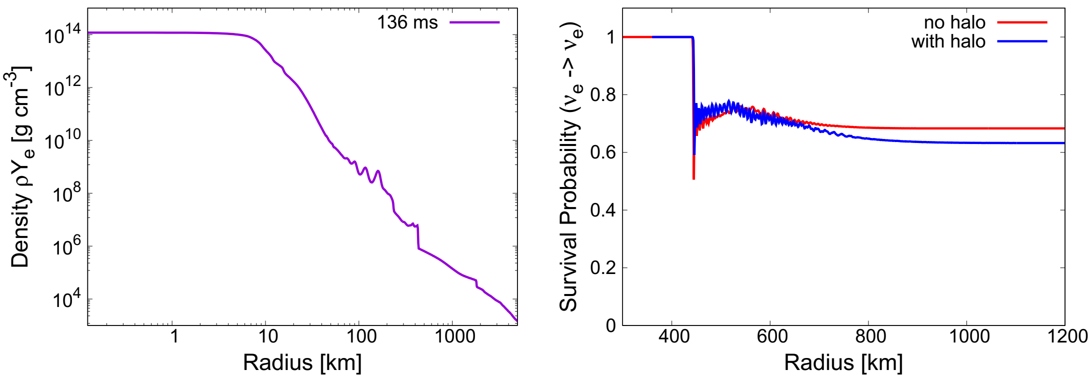

Figure 1. Left figure shows the density profile and right one is the radial evolution of survival probability at 136 ms. These survival probabilities are averaged over energy and angular distribution in both no-halo and with-halo case.

in the no-halo case. At this snapshot, the shock wave reaches at $r \sim 430$ km and the oscillation starts just after the neutrinos pass through the shock front. Neutrinos suddenly get free from matter suppression beyond the shock front. Also, we find that the contribution ratio of the inward neutrinos is less than 10% outside the shock front while the inward contribution can not be ignored inside the shock wave. CNO calculation including halo populations behind the shock front does not work well, but it does not affect neutrino spectra because matter effects suppress CNO completely. We can safely calculate CNO with halo effects outside the shock front. Comparing the survival probability between the no-halo case and with-halo case, the onset radius of CNO is identical. The impact of the shock gradient on the onset radius does not change even in the with-halo case.

Figure 2 show the final neutrino spectra averaged over angular distribution after collective flavor conversions at $r = 1200$ km. Left figure is the no-halo case and right one is the with-halo case. Comparing the with-halo case with the no-halo case, neutrino halo effects produce additional flavor conversion. It sharpens the spectral splits around a critical energy. In the no-halo case, the Hamiltonian contribution is proportional to the inverse fourth of radius for

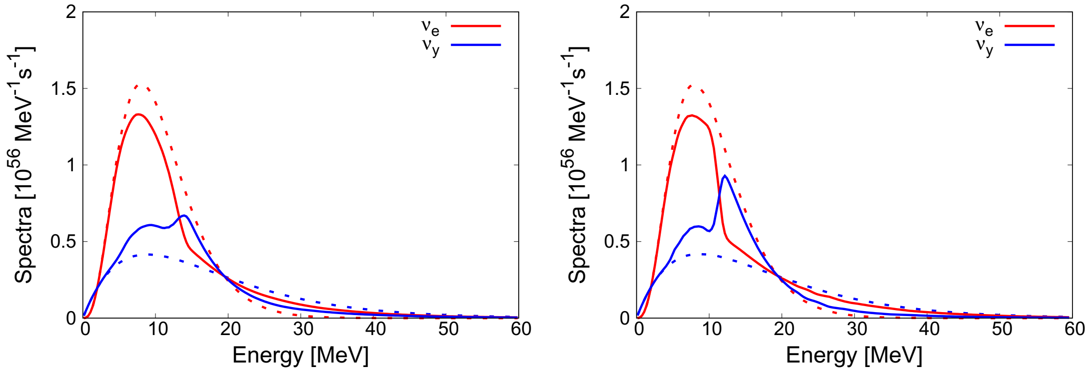

Figure 2. Neutrino spectra after CNO ceases at 1200 km. Left panel is in the no-halo case and right one is in the with-halo case. The solid lines are for final spectra after CNO and the dashed lines for original ones.

the large radius limit, $r \gg R_\nu$ due to the intersection angles. However, in the with-halo case, the intersection angle term $\langle 1 - \cos\theta \rangle$ becomes softer due to the halo neutrinos with broader angular distribution, and the Hamiltonian contribution remains stronger at large radius than in the no-halo case. The halo populations prevent multiangle matter effects from smearing the spectral splits and sharpens the neutrino spectra.

4. Conclusions

We have calculated collective flavor transformation including neutrino halo effects in the iron core-collapse supernova of a $9.6M_\odot$ star. We have shown that the shock gradient reduces the influence of background matter on both CNO and coherent neutrino scattering. Neutrino halo effect softens dependence of CNO Hamiltonian on radius due to the wider intersection angles, and sharpens the spectral splits. This feature makes detected neutrino spectra more non-thermal.

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