Supernova neutrinos in the proto-neutron star cooling phase and nuclear matter

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Abstract. A proto-neutron star (PNS) is a newly formed compact object in a core collapse supernova. Using a series of phenomenological equations of state (EOS), we have systematically investigated the neutrino emission from the cooling phase of a PNS. The numerical code utilized in this study follows a quasi-static evolution of a PNS solving the general-relativistic stellar structure with neutrino diffusion. As a result, the cooling timescale evaluated from the neutrino light curve is found to be long for the EOS models with small neutron star radius and large effective mass of nucleons. It implies that extracting properties of a PNS (such as mass and radius) and the nuclear EOS is possible by a future supernova neutrino observation.

1. Introduction

Core collapse supernovae, which are the spectacular death of massive stars, emit an enormous amount of neutrinos. In the case of SN1987A, a few tens of events were actually detected [1, 2, 3] and contributed to confirm the standard scenario for supernova neutrino emission. Although the neutron star formed in SN1987A has not yet been observed, its mass estimations had been attempted by using the neutrino event number [4, 5]. For this purpose, the equation of state (EOS) which characterizes the properties of high-density nuclear matter is necessary because the supernova neutrino light curve depends on not only the mass but also radius of the neutron star [6]. Otherwise, we should determine the mass and radius simultaneously from the neutrino signal. In this study, using a series of phenomenological EOSs, we evaluate the time scale of supernova neutrino emission for the cooling phase of a proto-neutron star (PNS), which is a newly formed compact object in a core collapse supernova. Then, we show that the radius of neutron star is a good indicator for the cooling time scale to characterize the dependence on the neutron star EOS.

2. Setup

In this study, we use a series of phenomenological EOS proposed in [6]. The construction of the EOS consists of two steps: describing the zero-temperature matter and introducing the finite-temperature effects. Furthermore, our EOS model is smoothly connected to the Shen EOS [7] at subsaturation densities where the phase transition from uniform nuclear matter to inhomogeneous matter occurs.

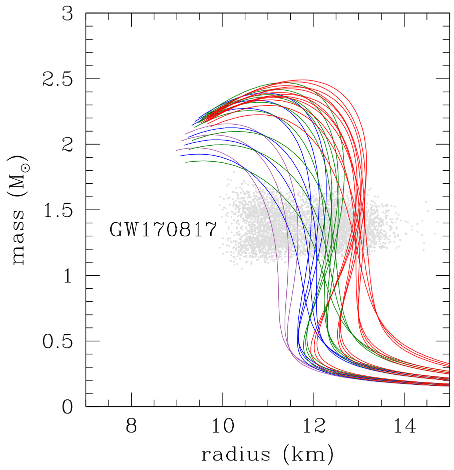

Figure 1. Mass–radius relations of cold neutron stars for our EOS models. Purple, blue, green and red lines correspond to the models with $S_{00} = 35$, 40, 45 and 55 MeV, respectively. The dots show the constraints from GW170817 taken from [9].

For the zero-temperature matter, we employ the energy per baryon written in the expansion form:

$$w(n_b, Y_p) = w_0 + \frac{K_0}{18n_0^2}(n_b - n_0)^2 + S(n_b)\,(1 - 2Y_p)^2, \tag{1}$$

where n_b is the baryon number density and Y_p is the proton fraction. Throughout this paper, we set $n_0 = 0.16$ fm^{-3} and $w_0 = -16$ MeV for the saturation density and saturation energy. As for the incompressibility of symmetric nuclear matter, we adopt the values of $K_0 = 220$, 245 and 270 MeV. In Eq. (1), $S(n_b)$ is the symmetry energy and we consider the quadratic form:

$$S(n_b) = S_0 + \frac{L}{3n_0}(n_b - n_0) + \frac{1}{n_0^2}\left(S_{00} - S_0 - \frac{L}{3}\right)(n_b - n_0)^2, \tag{2}$$

where S_0 and L are the coefficients of the symmetry energy and its derivative at the saturation density, respectively. The symmetry energy at the density of $2n_0$, which is denoted as S_{00} in Eq. (2), is recently constrained to 46.9 ± 10.1 MeV using the data of GW170817 [8]. Here, we examine the cases with $(S_0, L, S_{00}) = (30, 35, 35)$, $(30, 35, 40)$, $(30, 35, 45)$, $(30, 35, 55)$, $(31, 50, 40)$, $(31, 50, 45)$, $(31, 50, 55)$, $(32, 65, 45)$, $(32, 65, 55)$ and $(33, 80, 55)$, in units of MeV. In Fig. 1, the mass–radius relations of neutron stars for these EOS models are shown and we can see that the radius is 11–13 km for neutron stars with the canonical masses, which is consistent with the constraints from GW170817 [9].

For taking into account the effect of finite temperatures, we employ the thermodynamic contributions from an ideal Fermi gas. For instance, so as to calculate the Helmholtz free energy in our EOS model, the energy difference between the finite-temperature matter and zero-temperature matter of an ideal Fermi gas is added to the zero-temperature matter energy in Eq. (1). In this process, the effective mass of nucleons in units of thier rest mass, u, is assumed to be $u = 0.5$, 0.75 and 1.

In this study, we perform the cooling simulations of a PNS with the baryonic mass of $1.47M_\odot$, which corresponds to the gravitational mass of $\sim 1.33M_\odot$ in our EOS models. We adopt the same initial condition with [6, 10], which is taken from the result of core collapse simulation of a massive star. For computing the quasi-static evolutions, we use the numerical code for simulations of spherically symmetric PNS cooling [11]. For simplicity, neither additional mass accretion nor convection are taken into account. The cooling simulations of the PNS are followed until the luminosity of $\bar{\nu}_e$ drops to 5×10^{48} erg s^{-1}.

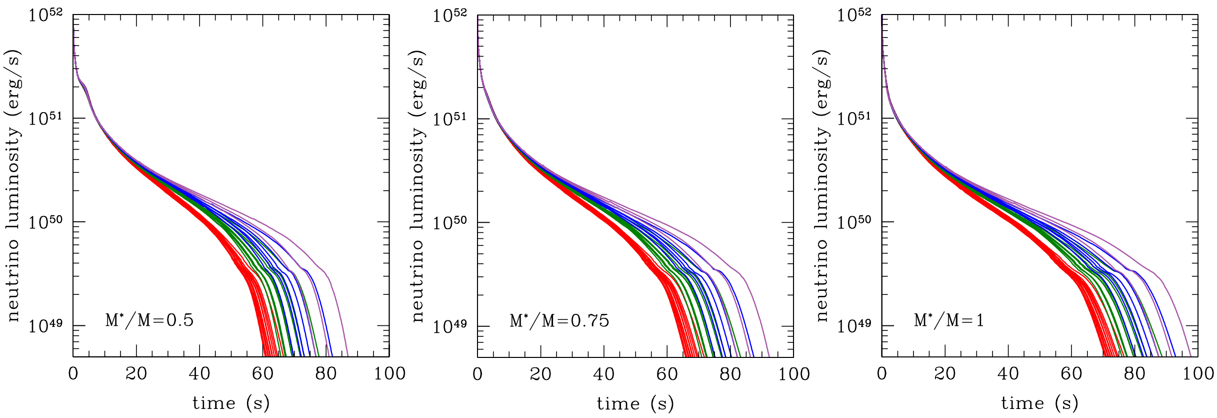

Figure 2. Light curve of $\bar{\nu}_e$ for the PNS models with effective masses of $u = 0.5$ (left), $u = 0.75$ (center) and $u = 1$ (right). Purple, blue, green and red lines correspond to the models with $S_{00} = 35$, 40, 45 and 55 MeV, respectively.

3. Results

In Fig. 2, we show the light curve of $\bar{\nu}_e$ for all the EOS models. In our numerical results, all the models share the property that the time evolution of the neutrino luminosity is divided into three phases. Since the PNS shrinks and its surface area gets smaller, the neutrino luminosity reduces steeply in the early phase until about 20 s. After the contraction of the PNS halts, the neutrino light curve has a shallow decay phase. In this phase, the trapped neutrinos leak out from the surface gradually. Finally in the late phase, the neutrino luminosity decreases again steeply because the neutrinoless β-equilibrium is achieved in the PNS.

For quantifying the decay timescale of the neutrino light curve, we consider the e-folding time of the luminosity of $\bar{\nu}_e$, $\tau_{\bar{\nu}_e}$, as

$$L_{\bar{\nu}_e}(t + \tau_{\bar{\nu}_e}) = \frac{L_{\bar{\nu}_e}(t)}{e}, \tag{3}$$

where $L_{\bar{\nu}_e}$ is the luminosity of $\bar{\nu}_e$ and e is the base of the natural logarithm. Then, $\tau_{\bar{\nu}_e}$ has the maximum value in the shallow decay phase and we regard it as the cooling timescale of the PNS:

$$\tau_{\rm cool} \equiv \max_t \tau_{\bar{\nu}_e}(t). \tag{4}$$

In Fig. 3, we show the relation between the neutron star radius and the cooling timescale. We can see that the models with larger effective masses have a longer decay timescale of the neutrino luminosity. It is consistent with the fact that the thermal energy stored in the PNS is larger for the models with larger effective masses. Furthermore, we can recognize that the cooling timescale is significantly correlated with the radius of the cold neutron star. In other words, the dependence on the zero-temperature EOS is encapsulated in a single parameter, while we have examined various EOS models with different incompressibilities and symmetry energies. Here, the models with smaller neutron star radii have a longer cooling timescale. It is consistent with the fact that the central density is higher and the neutrino mean free path is shorter for a neutron star with a smaller radius. Incidentally, while we have focused on the dependence on S_{00} in our previous study [6], the results shown in this study imply that the neutron star radius is actually more essential.

4. Concluding remarks

In this paper, we have presented the results of a systematic investigation of the neutrino emission from the cooling of a PNS with the gravitational mass of $\sim 1.33 M_{\odot}$. For this purpose, a series

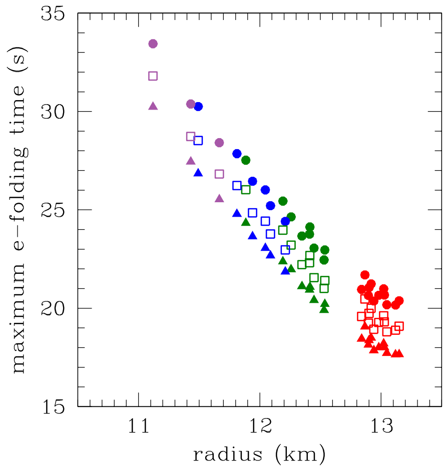

Figure 3. Relation between the radius of a cold neutron star and the maximum *e*-folding time of luminosity of $\bar{\nu}_e$. The filled triangles, open squares and filled circles are for the PNS models with effective masses of $u = 0.5$, $u = 0.75$ and $u = 1$, respectively. Purple, blue, green and red plots correspond to the models with $S_{00} = 35$, 40, 45 and 55 MeV, respectively.

of phenomenological EOS models has been employed. As a result, we have found that the EOS models with smaller neutron star radius and larger effective mass of nucleons have a longer cooling timescale, which is evaluated from the neutrino light curve. If the next supernova explosion occurs in our Galaxy, the neutrinos will be detected for at least longer than 30 s [12] and the cooling timescale would be measured. Then, properties of the newly formed neutron star and, thereby, the nuclear EOS may be extracted. Further investigation including the dependence on the neutron star mass will be reported in elsewhere [13].

Acknowledgments
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