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Model-dependence of neutrino emissivities and neutrino luminosities of neutron stars from the direct Urca processes and the modified Urca processes

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Abstract

The neutrino emissivities in β-stable neutron star matter from the direct Urca (DU) processes and the modified Urca (MU) processes have been investigated by adopting 26 Skyrme interactions. Several physical quantities related to the MU processes and the DU processes have been calculated and discussed. The model-dependence of the neutrino emissivities from the DU processes is found to stem mainly from the model-dependence of the effective mass, while the neutrino emissivities from the MU processes are determined by the competition between the effects of the symmetry energy and the effective mass. Besides, we have investigated the total neutrino luminosities of neutron stars, with the masses of 1.2, 1.4, 1.6 and $1.8M_{\odot}$, from the DU processes and the MU processes. The neutrino luminosity of a neutron star is found to be primarily determined by whether the electron DU process is allowed or not. As long as the electron DU process can occur, the total luminosity turns out to be 5 to 8 orders of magnitude larger as compared with the case that the DU process is forbidden, which indicates that the strongest model-dependence of the neutrino luminosity comes from that of the symmetry energy and the equation of state (EOS) of neutron star matter. In the case that the DU processes are allowed, the discrepancy of the calculated neutrino luminosity using various Skyrme interactions remains noticeable, which is essentially attributed to the model-dependence of the symmetry energy, the EOS of NS matter and the effective masses.

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1. Introduction

Neutron stars (NSs) are the densest manifestation of massive objects in the universe and provide natural astrophysical laboratories for testing theories of dense matter [1]. Modelling the cooling of NSs is one of the most potential methods to investigate the structures of NSs [2–5]. Great progress has been made in the investigation on neutron star (NS) cooling recently. For example, X-ray observations of the NS in the Cas A supernova remnant over the past decade suggest the star is undergoing a rapid drop in surface temperature [6–8] and several mechanisms have been proposed to explain this phenomenon [9–12]. Neutrino emissivity of a NS is of a great physical interest since it is one of the most important physical inputs for solving the thermal balance equation along with the thermal transport equation [13], which are used to get the cooling curves of NSs [3,4,14]. Therefore, investigating the model-dependence of the neutrino emissivity inside a NS may enable us to obtain a better understanding of the NS cooling.

The so-called standard scenario of NS cooling is based upon neutrino emission from the modified Urca (MU) process in the interior of NSs. It is believed that the MU process can go through two channels:

$$n + n \longrightarrow p + n + l + \bar{\nu}_l, \quad p + n + l \longrightarrow n + n + \nu_l; \tag{1}$$

$$n + p \longrightarrow p + p + l + \bar{\nu}_l, \quad p + p + l \longrightarrow n + p + \nu_l, \tag{2}$$

which are referred as the neutron and proton branches of the MU process, respectively. The label l denotes the leptons considered here, i.e., electrons and muons. The MU process was first introduced in Ref. [15] in the context of NS cooling. The neutrino cooling rate in the neutron branches was calculated in Refs. [16–18]. The proton branch of the MU process was first pointed out in Ref. [19]. The energy loss rate of the proton branch was calculated first in Ref. [18], which showed that the proton branch is negligible compared with the neutron one. However, the authors of Ref. [20] pointed out that the proton branch is as efficient as the neutron one after taking into account the electron momentum in the momentum conservation. The so-called direct Urca (DU) processes are expected to be the most efficient neutrino reactions in the non-standard scenario of NS cooling [2,21,22] and the corresponding reactions can be expressed as follows:

$$n \longrightarrow p + l + \bar{\nu}_l, \quad p + l \longrightarrow n + \nu_l. \tag{3}$$

It has been pointed out in Ref. [23] that the β-stable neutron star matter with a proton-to-neutron ratio in excess of some critical value lying in the range of 11%–15% can cool by the DU process. Furthermore, the authors of Ref. [21] have shown that neutron star matter with any proton-to-neutron ratio can rapidly cool by the DU process if the Λ hyperons are present.

As an effective interaction, the Skyrme force has simple analytical expression in calculating the nuclear matter. It has been well developed, and widely used to describe the properties of nuclear matter as well as the structure of finite nuclei [24,25]. Furthermore, the Skyrme interaction has also been applied to investigate properties of NSs [26,27]. As has been pointed out in Ref. [28], there are more than 240 Skyrme parameter sets currently available in the literature. In the present paper, we shall investigate the neutrino emissivities and the neutrino luminosities from the MU and DU processes in NSs by adopting 26 Skyrme parameter sets. Particularly, we