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Dependence of neutron star cooling on the equation of state with a possible exotic particle

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Cooling of neutron stars born after supernova explosion is highly related to neutrino emissivity. So as to account for the observed low-temperature isolated neutron stars (INS), a fast cooling process, such as the Direct Urca (DU) process, is needed. Whether DU process occurs or not is determined by the interior proton fraction Y_p. Therefore, to study the time variation of neutron star temperature we have to consider interior equation of state (EoS). In this study, we adopt the Togashi EoS, which has been recently constructed with use of nuclear potentials under finite temperature. As comparison EOSs, we also use the Shen and LS220 EOSs. The Togashi EoS is consistent with experimental and observational constraints. We show however that the Togashi EoS is inconsistent with observations of INS because the symmetry energy remains low enough to prevent DU process from occurring even if the baryon density reaches at sufficiently high density region over nuclear saturation density. In order to solve this problem encountered by the Togashi EOS, other fast cooling processes are needed. As an example, we examine the pion condensation process.

KEYWORDS: neutron stars

1. Introduction

The structure of neutron stars is determined by the equation of state (EoS), which strongly gives an effect on their cooling curves. An EoS in the core has been still unknown due to uncertain nuclear potentials, and many theoretical models of cooling curves have been proposed (e.g. [1]). Compared with the observed age and surface temperature of isolated neutron stars (INS), we can examine the validity of the constructed models. Furthermore, from some observations of neutron stars, uncertain EoS has been constrained to some extend. For example, the discovery of the massive neutron stars with $M \approx 2\ M_\odot$ rules out many EoSs with the maximum mass of less than $2\ M_\odot$ [2]. For another example, the analysis of gravitational wave GW170817 emitted from neutron star merger indicates small radius with $R \lesssim 13$ km and requires the EoS which is soft around the nuclear density (e.g. [3]). From these constraints we can have deep discussions about cooling models.

In this study, we adopt the Togashi EOS which has been recently constructed with using realistic two-body potential and phenomenological three-body potential [6], and we focus on this new model and its cooling curves in this work. For comparison, we also use the Shen [4], LS220 [5]. The maximum mass of neutron stars with the Togashi EoS is $2.21\ M_\odot$ and is larger than the mass of heaviest neutron star observed so far [7]. Furthermore, the Togashi EoS has a radius of $R \approx 11.6$ km with a canonical mass $M = 1.4\ M_\odot$ and this radius is consistent with the observations of GW170817 [8] and the low mass X-ray binaries [9]. Thus, the Togashi EoS is consistent with these observational

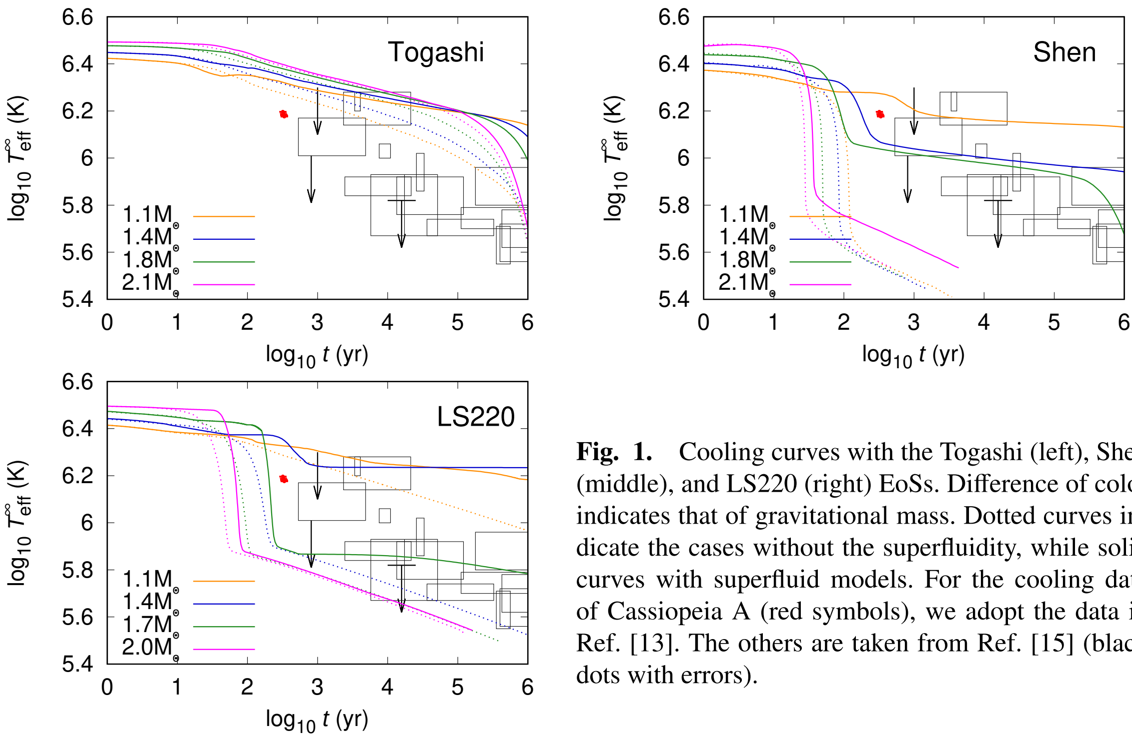

Fig. 1. Cooling curves with the Togashi (left), Shen (middle), and LS220 (right) EoSs. Difference of color indicates that of gravitational mass. Dotted curves indicate the cases without the superfluidity, while solid curves with superfluid models. For the cooling data of Cassiopeia A (red symbols), we adopt the data in Ref. [13]. The others are taken from Ref. [15] (black dots with errors).

constraints as well as the LS220 EOS.

For the thermal evolution of neutron stars, mainly following two problems are important. One is whether the fast cooling process occurs or not. Especially, the nucleon Direct Urca (DU) process, which is the strongest cooling process, makes neutron stars cool rapidly. In case of *npe* matter, the threshold of the DU process is given by $Y_p \gtrsim 1/9$, where Y_p is proton fraction. Therefore, the EoS determines the presence or absence of the DU process. The other is the selection of adequate superfluid model, which is the relation between the density and superfluid transition temperature. Nucleon superfluidity gives a suppression on the neutrino emissions, including the DU process. That is, depending on the strength of superfluid effect, the cooling effect of neutron stars becomes weaker compared without superfludity. The superfluid model is gained by solving the gap equation with an uncertain nuclear potential and hence how the neutrino emission is suppressed has been still unclear. Thus, the chosen EoS and superfluid model mostly determine the outline of the cooling curve. To examine these influence on cooling curves, several work has been done so far [10, 11].

In this work, we calculate cooling curves with the three EoS of Shen, LS220, and Togashi EoSs. We discuss the relation between the threshold of the DU process and the symmetry energy, and calculate cooling curves with pion condensation process using the Togashi EoS. Details on this study is seen in Ref. [12]

2. Results

In this study, the surface compositions of neutron stars are fixed to be 73% of ^{1}H, 25% of ^{4}He, and 2% of ^{56}Ni. Moreover, to see the EoS dependence of cooling curves, we use superfluid models, which are CLS model for $^1S_0$ neutrons, CCDK model for $^1S_0$ protons and EEHO model for $^3P_2$ neutrons described in Ref. [13]. We adopt the simple suppression factor of the neutrino emissivities as $\exp(-aT_{\rm cr}/T)$ with $a = 1.76$ in $^1S_0$ state and $a = 8.40$ in $^3P_2$ state where $T_{\rm cr}$ is superfluid transition temperature, and we do not consider the change of the heat capacity by superfluidity. Furthermore, we do not consider the magnetic field of INS though the magnetic field tends to increase the surface temperature of INS [14]. Under these conditions, we calculate cooling curves with the Togashi, Shen,

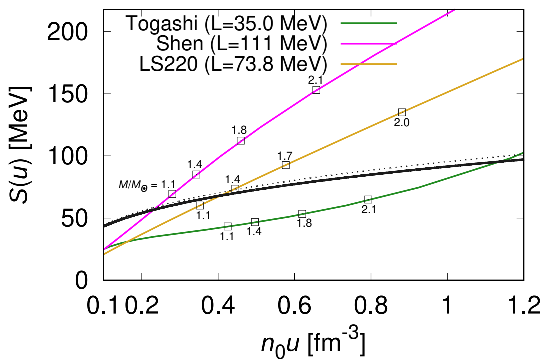

Fig. 2. Symmetry energies of three EoSs: Togashi (green), Shen (pink), and LS220 (orange). We describe the L value of above EoSs in this figure. We adopt the saturation density $n_0 = 0.155$ fm^{-3} for LS220 EoS. The DU process thresholds of npe and $npe\mu$ matter correspond to the dotted and solid black curves, respectively. The symmetry energies at the central baryon number density are plotted for 1.1, 1.4, 1.8, and 2.1 $M_\odot$ models with Togashi and Shen EoSs, and 1.1, 1.4, 1.7 and 2.0 $M_\odot$ models with LS220 EoS.

and LS220 EoSs. The results are described in Fig. 1. The cooling curves with the Shen EoS cannot account for the observations of INS with or without superfluidity because any cooling curves are below observed thermal data with $t \lesssim 10^4$ yr and $T_{\rm eff}^{\infty} \gtrsim 10^{6.2}$ K. Oppositely, the cooling curves with the LS220 EoS are suitable since the effective temperature of all INS observations are between the cooling curves with $M = 1.1\ M_\odot$ or $1.4\ M_\odot$ and $M = 2.0\ M_\odot$. In comparison with some standard works [10,11,14], our cooling curves locate in higher-temperature regions at the photon cooling stage ($t \gtrsim 10^5$ yr) because the treatments of the heat capacity and superfluidity are inconsistent. Moreover, in case of the LS220 EoS, the heat capacity we use is around twice as large as that other works adopt in high-density regions. These influences are however negligible when we focus on the observations in neutrino cooling era. While the neutron stars with the LS220 and Shen EoSs cause the DU process with $M < 1.1\ M_\odot$ and $M < 1.4\ M_\odot$, respectively, the DU process does not occur with the Togashi EoS. This is because the view of rapid cooling cannot be seen around $t \approx 10^{1-2}$ yr. This means that the Togashi EoS is inconsistent with the INS having low temperature regardless of superfluidity.

3. Discussion

Whether the DU process occurs or not is due to the value of symmetry energy of the EoS. The dependence of the symmetry energy $S(u)$ on the baryon number density is plotted in Fig. 2. We also show the symmetry energy at the threshold of the DU process. The L value described in Fig. 2 has a positive correlation with the symmetry energy $S(u)$. We can recognize that the DU process's threshold mass predicted in Fig. 2 matches with our results for each model of EoS. For example, the neutron stars with the Togashi EoS cool moderately because the threshold mass of the DU process is $M > 2.1\ M_\odot$ due to small symmetry energy or small L value. However, the Togashi EoS is consistent with the observations related to neutron star mass and radius. If the Togashi EoS is hypothesized, then as the method to dissolve the disagreement, we need to consider other fast cooling processes caused by some exotic particles such as pions, kaons, and hyperons. Note that however this suggestion is not always right with other EOSs. For example, the extra cooling processes are indifferent to the LS220 EOS, which can explain the INS observations without exotic particles.

Generally, calculated results of cooling curves change drastically if exotic particles are included in neutron stars. Although there are many EoSs having exotic particles inside the neutron stars, we consider only neutrino process coming from the pion condensation for the models with Togashi EoS omitting the feedback to the EoS from pions. Among many studies concerning the pion condensation process, we adopt the process with Landau-Migdal parameter $\tilde{g}' = 0.5$ in Ref. [16]. As the superfluid models for $^3P_2$ neutrons, we take account of the EEHO1 model shown in Fig. 3 while other superfluid models are same as our original settings. The results are shown in Fig. 4. If nucleon superfluidity is unconsidered, neutron stars cool very fast due to the pion condensation process. However, adopting the EEHO1 model for $^3P_2$ neutrons, 1.8 $M_\odot$ star cools rapidly compared to the case for 1.4 $M_\odot$ star. As a consequence, the results with the EEHO1 model can reproduce most of the INS observations.

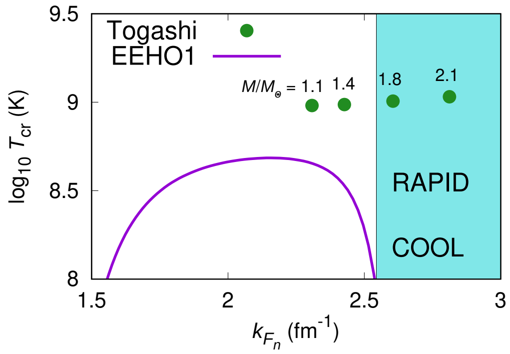

Fig. 3. EEHO1 model between the superfluid transition temperature T_{cr} vs. Fermi wave number of neutrons k_{F_n} for $^3P_2$ neutron state. Four green points are added against k_{F_n} with the Togashi EoS at the initial temperature.

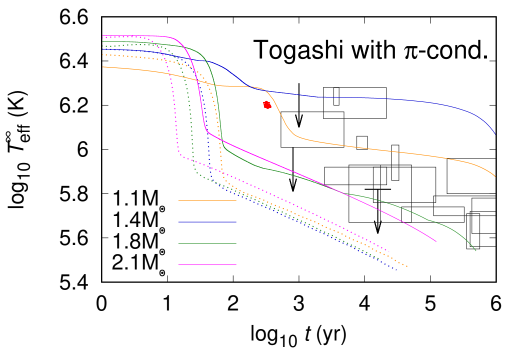

Fig. 4. Cooling curves with pion condensation process using the Togashi EoS. Superfluid models for $^3P_2$ neutrons are applied with use of EEHO1, which is shown in Fig. 3.

4. Concluding Remarks

We investigated the consistency between some constraints on EoS and the LS220, Shen, and Togashi EoSs. The Togashi EoS is consistent with the observations about mass and radius and the symmetry energy predicted in nuclear experiments. Next, we calculated cooling curves with their EoSs and discussed the EoS dependence on the cooling curves. The neutron stars with the Togashi EoS cool moderately while ones with other EoSs cool rapidly with some masses. This is because the symmetry energy or the Togashi EoS with any masses is smaller than one at the threshold of the DU process though the small value of the symmetry energy is preferred by some observations of neutron star radius. To dissolve the disagreement using the Togashi EoS, we need to consider other fast cooling processes caused by some exotic particles. We calculated the cooling curves with pion condensation process. As a results, we found the consistent cooling models with the observations of INS. However, we did not consider the effect of pion about EoS in this study and hence cooling calculations with an EoS including the effect of exotic particles are valuable.

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