Implications of symmetry energy on neutron star cooling

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Introduction

Neutron stars (NSs), renowned for their extraordinary density, present a unique and compelling realm for investigating novel states of matter [1]. The nuclear symmetry energy, $E_{\rm sym}$, and its sensitivity to changes in matter density assume significant importance in shaping the characteristics of highly asymmetric nuclear matter, particularly with respect to its isospin dependence. Nevertheless, our understanding of the behavior of $E_{\rm sym}$ remains limited due to the absence of substantial empirical data from terrestrial sources.

An exceptional method for exploring the realm of the nuclear symmetry energy is electron−nucleus scattering, which offers the capability to achieve precise measurements of neutron and proton charge distributions within the nucleus. Several measurements on neutron−skin thickness have been reported viz. PREX Collaboration [2], PREX-2 [3], CREX [4]. The data obtained from the CREX experiment provides support for a softer equation of state (EoS) in the context of neutron-rich matter, whereas PREX-2 results tend to favor a stiffer EoS. Although a tension exists between the findings of PREX-2 and CREX, it is noteworthy that the results of PREX-2 hold intriguing implications from an astrophysical perspective, particularly within the realm of NS cooling studies. This work suggests that with the newly obtained nuclear symmetry energy and its density dependence (i.e. $E_{\rm sym}(n_0) \sim 38.1 \pm 4.7$ MeV, $L_{\rm sym}(n_0) \sim 106 \pm 37$ MeV), rapid cooling of NSs in the mass range of $(1.2 - 1.6\ M_\odot)$ is possible via direct Urca (DU) process. When superfluid suppression is taken into account, the theoretical cooling models match observed surface temperatures of isolated NSs.

Formalism

In order to construct the dense matter EoS, we implement the density-dependent DD-MEX [5] coupling parametrization within the framework of Covariant Density Functional (CDF) model. The DD-MEX coupling model satisfies the recent NS astrophysical constraints in addition to describing the finite nuclei properties to a good extent. In the framework of the CDF formalism, the interaction between nucleons and iso-vector ρ mesons governs the nuclear symmetry energy, while its density dependence dictates the slope of the symmetry energy. The energy per baryon in asymmetric nuclear matter can be represented through Taylor's expansion around $\delta = 0$, as follows:

$$E(n,\delta) = E(n,0) + \frac{1}{2}\left[\frac{\partial^2 E(n,\delta)}{\partial \delta^2}\right]_{\delta=0} \delta^2 + \mathcal{O}(\delta^4) \quad (1)$$

with n and δ being the baryon number and degree of asymmetry respectively. To maintain consistency with the properties of finite nuclei, $E_{\rm sym}$ at 0.1 fm^{-3} is fixed to ~ 28 MeV [6]. Next to determine the thermal evolution of NS, we consider the following equation [7],

$$C(\tilde{T})\frac{d\tilde{T}}{dt} = -L_\nu^\infty(\tilde{T}) - L_s^\infty(T_s) \quad (2)$$

with $\tilde{T}$, T_s representing the red-shifted internal temperature and effective surface temperature respectively. L_ν^∞, L_s^∞ denote the red-shifted neutrino and photon luminosities.

Results & Discussions

In this section, we describe the outcomes of the cooling scenario for isolated NSs, taking into account the modified EoSs that align with

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TABLE I: Radial distance (r_{DU}) and number density (n_{DU}) at which the DU process occurs within model stars featuring various masses (M), radii (R), and central densities (n_c).

$M/M_\odot$	R/km	n_c/n_0	$r_{\rm DU}$/km	n_{DU}/n_0
1.2	13.8	1.91	3.0	1.86
1.4	13.7	2.10	5.7	1.87

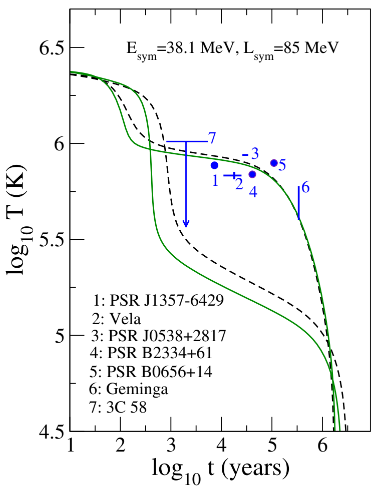

FIG. 1: Cooling curves evaluated with modified EoSs for 1.2 $M_\odot$ (dashed) and 1.4 $M_\odot$ (solid) NS configurations. The numbers represent the different astrophysical cooling constraints. The steeper curves are for normal matter while the less steeper ones are for superfluid matter.

the findings of PREX-2. We then proceed to contrast these results with observed data pertaining to various isolated NSs. In this work, we calibrate the EoSs considering the symmetry energy parameter values $E_{\rm sym}$ and $L_{\rm sym}$ at n_0 to be 38.1, 85 MeV respectively which provide the threshold NS mass for DU process, $M_{DU} \sim 1.125\ M_\odot$. We depict the theoretical cooling curves for isolated NSs with masses of 1.2 $M_\odot$ and 1.4 $M_\odot$. The result is presented in Fig.-1 which was generated utilising *NSCool* [8]. The DU thresholds for various NS mass configurations with considered modified EoS are presented in Table-I. The findings as presented in Table-I exhibit similarities in both superfluid and non-superfluid nuclear matter cases. The cooling rates of the stars are illustrated in Fig.-1 for both normal and superfluid matter. It's noteworthy that in the outer layers of the star, neutrons form $^1S_0$ pairing states, while towards the core, pairing takes place through the $^3P_2$ channel, as the $^1S_0$ pairing becomes repulsive under high-density conditions [9]. We consider the energy gaps for neutron superfluidity as $\Delta \sim 0.3$ MeV ($^3P_2$ channel) and $\Delta \sim 0.43$ MeV ($^1S_0$ channel). In case of proton superfluidity, we consider $\Delta \sim 0.52$ MeV ($^1S_0$ channel). Furthermore, it is noteworthy that as the mass of the star increases, the cooling curves exhibit a notably steeper decline, indicative of a comparatively faster cooling rate. This phenomenon arises from the fact that, in the case of more massive stars, the DU process is permissible over a relatively larger extent, in contrast to lower-mass stars. This investigation reveals that our model of isolated NSs, which incorporate iron heat-blanketing envelopes, is capable of elucidating the thermal characteristics of a substantial number of stars from 1.2 $M_\odot$ onwards. This explanation takes into consideration the influence of superfluidity suppression.

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