Moment of inertia of massive rotating protoneutron stars with hyperons: Evolution and Universality

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I. INTRODUCTION

Protoneutron stars (PNS) are the end products of supernovae explosion of massive stars. The evolutionary scenario proposed by Ref. [1] suggests four stages of PNS evolution. Initially, just after birth, the PNS has trapped neutrinos (ν) and lepton fraction $Y_L = 0.4$ with entropy per baryon $s_B = 1$. When the outer layer is being deleptonized, the central object is still ν trapped ($Y_L = 0.4$), but ν diffusion heats the core up to $s_B = 2$. After complete deleptonization, the core becomes ν-free and again attains high entropy ($Y_\nu = 0, s_B = 2$). Finally, the star settles as a cold stable neutron star (NS) in beta equilibrium. We denote these four stages as I to IV.

The high density core is generally made up of neutrons, protons and electrons. The Fermi energy of nucleons are sufficiently large to populate the Λ hyperons which softens the equation of state (EOS). The compact stars with hyperons have lower maximum mass compared to nucleons only stars.

Data for pulsar masses (M) are well known, but radius (R) measurement is a challenging problem. Precise measurement of moment of inertia using the Square Kilometer Array (SKA) telescope may overcome the uncertainties to determine radius since $I \propto MR^2$ [2]. Again, having a universal relation may allow us to determine the radius with high accuracy once we measure I and M [3, 4]. In this work, we study the universal relations among normalized moment of inertia ($\bar{I} := I/M^3$) and stellar compactness ($\mathcal{C} := M/R$) [5, 6].

II. EQUATION OF STATE OF PNS MATTER

We describe the high dense matter in the framework of relativistic mean field (RMF) model using GM1 parameter sets where the interaction among baryons is mediated by σ, ω and ρ mesons. The Lagrangian density ($\mathcal{L}_B$) of the RMF model is given by Ref. [7],

$$\begin{aligned}\mathcal{L}_B = &\sum_B \bar{\Psi}_B(i\gamma_\mu\partial^\mu - m_B + g_{\sigma B}\sigma \\ &- g_{\omega B}\gamma_\mu\omega^\mu - \frac{1}{2}g_{\rho B}\gamma_\mu\boldsymbol{\tau}_B\cdot\boldsymbol{\rho}^\mu)\Psi_B \\ &+ \frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} \\ &+ \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\boldsymbol{\rho}^{\mu\nu} \\ &+ \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\boldsymbol{\rho}^\mu \\ &- \frac{1}{3}g_2 m_N(g_{\sigma N}\sigma)^3 - \frac{1}{4}g_3(g_{\sigma N}\sigma)^4\end{aligned}$$

where m_B is the bare mass of the baryon B and $\boldsymbol{\tau_B}$ is the isospin operator.

III. RESULTS AND DISCUSSIONS

We consider two types of EOS: np (nucleons only) and npΛ (including hyperons) to study how the emergence of Λ hyperons and their interaction affect the PNS evolution. We use numerical library LORENE [8] to report our results.

In Fig.1, we consider a star with fixed baryonic mass ($1.8M_\odot$) and show the variation of moment of inertia (I) with frequency up to Kepler limit. I increases with frequency. We have seen the gravitational mass remains almost independent of EOS in all the evolutionary stages. But there's an EOS-dependent

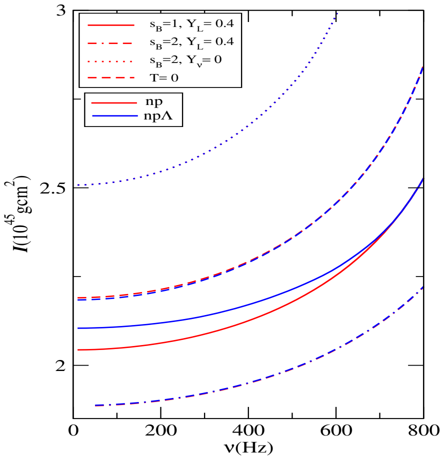

FIG. 1: Moment of inertia (I) with frequency.

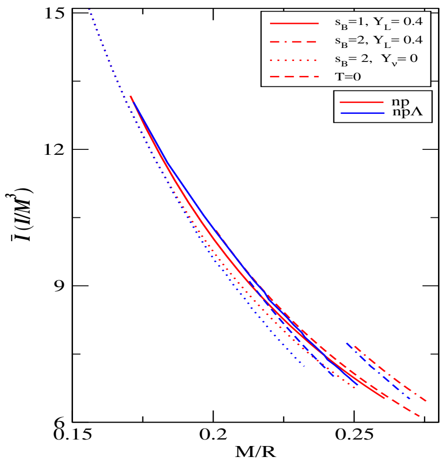

FIG. 2: Normalized moment of inertia (I/M^3) variation with compactness (M/R).

spread in radii in stage I which is reflected in the moment of inertia plot.

We explore the universality relation in Fig.2. We plot normalized moment of inertia ($\bar{I}$) with compactness ($\mathcal{C}$) for frequency 300 Hz. We find that normalized I lines are almost independent of the composition of the star corresponding to each PNS stage in case of less compact stars. However, the lines corresponding to different temperature, lepton fraction and compositions are distinctly separated at higher compactness.

IV. SUMMARY

In this work, we study moment of inertia of a massive rotating PNS at different evolutionary stages. The important finding of our study is the deviation from $\bar{I} - \mathcal{C}$ universal relations at higher compactness.

Acknowledgement

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