Universality of different properties of rotating neutron stars with realistic equation of state

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Introduction

Pulsars are rotating neutron stars (NS) with time period ranging from seconds to sub milliseconds. Nearly 2500 pulsars are known till date. Pauli Exclusion Principle dictates the appearance of strange degrees of freedom such as hyperons, Bose-Einstein condensate of anti kaons, quarks & pions in the exceptionally high density baryonic matter relevant to NS core. Presence of strange hadrons results in softer Equation of State (EoS) which lowers the maximum mass of the NS.

The Model

We adopt a density dependent relativistic mean field model where, baryon-baryon interactions are mediated by σ, ω & ρ mesons. The model Lagrangian density is,

$$L= \sum_B \overline{\psi_B} \left(i\gamma_\mu \partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu - g_{\rho B}\gamma_\mu \tau_B . \rho^\mu\right) \psi_B + \frac{1}{2}(\partial_\mu \sigma \partial^\mu \sigma - m_\sigma^2 \sigma^2) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2} m_\omega^2 \omega_\mu \omega^\mu - \frac{1}{4}\rho_{\mu\nu} . \rho^{\mu\nu} + \frac{1}{2} m_\rho^2 \rho_\mu . \rho^\mu + \sum_l \overline{\psi_l} (i\gamma_\mu \sigma^\mu - m_l)\psi_l$$

The ϕ mesons take care of the hyperon-hyperon interactions, while the leptons are considered non-interacting. The baryon meson couplings are density dependent & are determined following the DD2 model [1, 2].

EoS & maximum mass of the NS

The equations of motion for the meson & baryon fields are solved to compute the EoS for the NS core. The dense interior of NS may contain neutron, proton & exotic particles like λ, Ξ & antikaon condensates. We consider different EoS for different constituents: np (nucleons only), npλ (np+λ), npλΞ (npλ+Ξ), npK (np+antikaon condensates) and npλΞK (npλΞ+antikaons).

We have performed our calculations for a range of optical potential of antikaons in nuclear medium (U_K =-60 to -140 MeV). Due to the presence of hyperons, the effect of antikaon condensates is pronounced for U_K>140 MeV. So we report our result of npλΞK case for U_K=-140 MeV only. All our EoS with various exotic components are consistent with the observational limit of $2M_\odot$ [3, 4], unlike most of the existing exotic EoS [1].

Results

The pulsars are not perfect spheres. A small degree of asymmetry arises as a consequence of their rapid rotation. This asymmetry in spherical mass distribution creates a distortion in the gravitational field outside the star. We calculate the moment of inertia (MI) & quadrupole moment (Q), the parameters that lead to explore the deformation properties of NS.

There are several model EoS available and we need reliable observational data to pinpoint the correct one. Realistic observations of NS mass ($2M_\odot$) [3, 4] has abandoned most of the soft EoS. However we need data for radius also, which is expected from MI measurement of Square kilometer array (SKA) telescope in near future. Breu & Rezzolla [5] recently showed that a universality relation exist for normalized moment of inertia (I/M^3), that is essentially independent of EoS for nuclear matter. Their

study of universality is particularly important to determine radius with high accuracy.

We studied the relation between normalized MI and normalized Q for different exotic constituents mentioned in the previous section, using RNS code [6]. In Figs. 1 and 2, we considered np, npλ, npλΞ, npλΞK (U_K= −140MeV) and npK (U_K= -60 to −140MeV) respectively. In both the cases, we find similar trends that universality deviates at higher QM/J^2 as the rotation frequency of the star changes. These results are consistent with the findings of [5, 7]. The universality is maintained irrespective of the constituents of the strange NS matter.

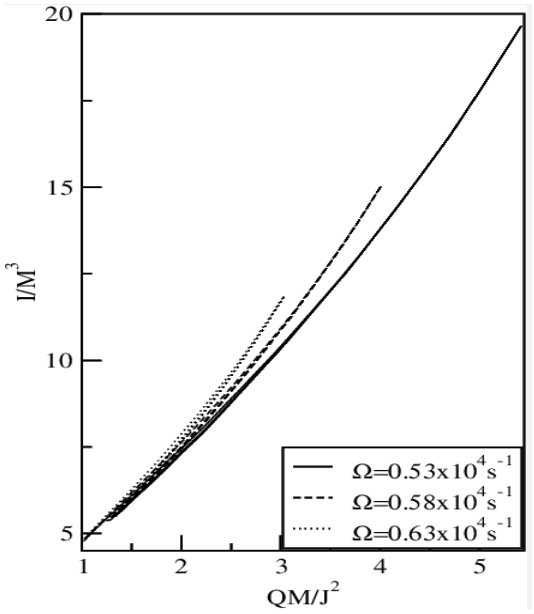

Fig. 1 Normalized MI ($\boldsymbol{I}/M^3$) with normalized Q (QM/J^2) for np, npλ, npλΞ, npλΞK (U_K= −140MeV)

Summary

We have shown the variation of normalized MI with respect to normalized Q for all the constituents np, npλ, npλΞ, npλΞK (U_K = −140 MeV) and npK (U_K = −60 to −140 MeV). MI is normalized with respect to M^3 & Q is normalized with respect to J^2/M. We found universality among them for all the EoS considered here. In future we plan to incorporate these results to study stability and oscillation properties of hyper massive neutron stars formed after a binary merger.

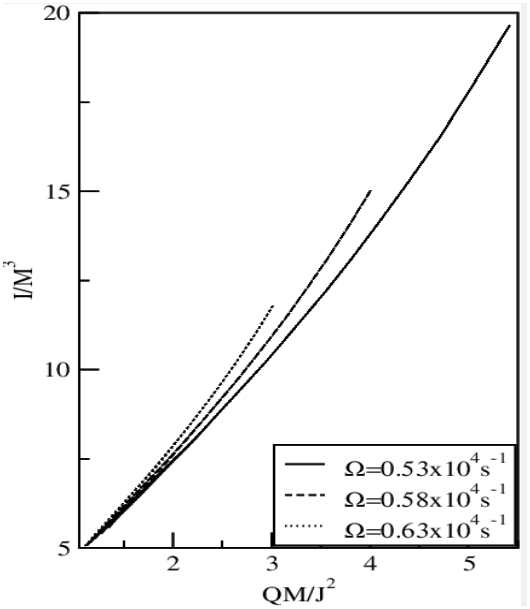

Fig. 2 Normalized MI ($\boldsymbol{I}/M^3$) with normalized Q (QM/J^2) for npK (U_K= -60 to −140MeV)

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