Exploring the role of hyperons in neutron star physics using a relativistic mean field approach

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Introduction

Neutron stars, among the most compact objects in the universe, offer a unique environment to study the behaviour of strongly interacting matter under extreme conditions. These stars contain matter at densities far beyond the nuclear saturation density, reaching up to five to ten times that of normal nuclear matter density. At such extreme densities, new and exotic particles, such as hyperons (baryons containing strange quarks) are expected to form. This is because the Fermi energy of nucleons increases to the point where it becomes energetically favourable for hyperons to appear, as their rest mass energy is comparable to the Fermi energy of the nucleons, which can happen at densities around (2-3) times saturation density of ordinary nuclear matter. The introduction of hyperons into neutron star matter has profound effects on the star's properties, particularly through the equation of state (EoS), which describes the relationship between energy density and pressure. When hyperons appear, they tend to soften the EoS, reducing the internal pressure for a given density. This softening directly impacts the maximum mass that a neutron star can support, leading to a reduction in the predicted maximum mass. This phenomenon is referred to as the " hyperon puzzle " first introduced in 1960 [1]. The puzzle arises because, while the inclusion of hyperons in theoretical models seem natural at high densities, many observations of neutron stars suggest maximum masses that exceed the predictions of such softened equations of state.

In this work, we have employed the HPU's (named after Himachal Pradesh University) [2] parametrizations within the framework of RMF model, which includes β-equilibrated matter composed of nucleons only, and extended it to a model that also includes hyperons. This allows us to investigate the effect of hyperons on the EoS and their role in neutron star structure, especially in terms of their influence on the maximum mass.

Theoretical model

The effective Lagrangian density for the RMF model $\mathcal{L}_{RMF}$, describes the interaction of nucleons through the exchange of σ, ω, and ρ mesons, with interactions considered up to quartic order. The detailed form of this Lagrangian can be found in [2]. In order to extend this formalism to include hyperons, the sum in the Lagrangian must be taken over the complete baryon octet, which consists of nucleons (protons and neutrons) as well as hyperons (Λ, Σ, and Ξ) [3]. To account for hyperon-hyperon interactions, two additional meson fields σ^* (a scalar meson) and ϕ (a vector meson) are introduced. These mesons mediate the interactions between hyperons, providing a more complete description of the forces at play in high-density environments where hyperons are present. The corresponding Lagrangian for the hyperon sector, L_Y ($Y = \Lambda, \Sigma, \Xi$), can be written as:

$$\begin{aligned}\mathcal{L}_Y &= \sum_Y \overline{\Psi}_Y (g_{\sigma^* Y}\sigma^* - g_{\phi Y}\gamma^\mu \phi_\mu)\Psi_Y + \frac{1}{2}(\partial_\nu \sigma^* \partial^\nu \sigma^* \\ &- m_{\sigma^*}^2 \sigma^*) - \frac{1}{4} S_{\mu\nu} S^{\mu\nu} + \frac{1}{2} m_\phi^2 \phi_\mu \phi^\mu \end{aligned} \quad (1)$$

Thus the total Lagrangian density for the model consisting of complete baryon octet can be written as

$$\mathcal{L} = \mathcal{L}_{RMF} + \mathcal{L}_Y \quad (2)$$

The hyperons-meson couplings g_{iY} ($i = \sigma, \omega, \rho$) in the respected Lagrangian can be expressed in terms of nucleons-mesons couplings using the SU(6) model [3]. The values used for couplings ($g_{\rho Y}$, $g_{\phi Y}$, $g_{\sigma^* N}$, $g_{\phi N}$) can be found in [3] and for $g_{\sigma^* Y}$ in [4] respectively. For determining the remaining values of coupling constants ($g_{\sigma Y}, g_{\omega Y}$) the expression for potential depth for a given hyperon species in the nuclear matter at saturation density (ρ_0) can be used

$$U_Y^{(N)} = -g_{\sigma Y}\sigma(\rho_0) + g_{\omega Y}\omega(\rho_0) \quad (3)$$

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Here the values of $U_Y^{(N)} = (-28, 30, -24)$ MeV [4] for ($Y = \Lambda, \Sigma, \Xi$) respectively and $\sigma(\rho_0)$ and $\omega(\rho_0)$ are the fields value at saturation density without including hyperons. To find the values of couplings we have taken fixed values of $g_{\omega Y}$ from the SU(6) model and find the respected values of $g_{\sigma Y}$. The rest masses of hyperons are taken from [7].

Results and Discussion

In the present work, we revisited our parameter sets (HPU's) [2] to investigate the effect of hyperons on neutron star properties using a hybrid star formalism, which includes both nucleons and hyperons. The goal is to explore these effects without significantly compromising the nuclear matter properties at saturation density. The models that incorporate the complete baryon octet (nucleons + hyperons) are referred to as (HPUY's) model. In HPUY1 we have used the original HPU1 parameter set but in case of HPUY2 and HPUY3 we have changed the value of ω meson self coupling term ζ from (0.00682 to 0.00452) and (0.00330 to 0.00050) respectively to satisfy the mass constraints from PSR J0740+6620 (M = 2.08 ± 0.07 $M_\odot$) [6] and the changed values of ζ has been used for (HPU2, HPU3) models respectively in table I for comparison regarding neutron star properties.

TABLE I: Neutron star properties and threshold density (ρ_{th}) of hyperons for various parameter sets.

	M_{max} ($M_\odot$)	R_{max} (km)	$R_{1.4}$ (km)	$\Lambda_{1.4}$	ρ_{th} (fm^{-3}) Λ	Σ^-	Ξ^-	Ξ^0
HPU1	2.50	11.93	12.96	610.7	-	-	-	-
HPUY1	2.05	11.28	12.93	611.2	0.352	-	0.363	0.978
HPU2	2.42	12.23	13.27	719.8	-	-	-	-
HPUY2	2.01	11.74	13.26	718.9	0.336	0.813	0.353	-
HPU3	2.45	12.07	13.41	740.0	-	-	-	-
HPUY3	2.01	11.45	13.41	743.4	0.334	-	0.349	-

In Fig. 1, we display the results for the gravitational mass of static neutron stars and its radius for (HPU's) and (HPUY's) models. The horizontal band corresponds to the mass M = 2.35 ± 0.17 $M_\odot$ of PSR J0952-0607 [5] and M = 2.08 ± 0.07 $M_\odot$ of PSR J0740+6620 [6]. The mass radius constraints from NICER observation [8, 9] are also shown by shaded regions. It is observed that with the hybrid star approach the maximum gravitational mass of the static (non-rotating) neutron star decreases as we move from HPU's to HPUY's model. For HPUY's model the maximum mass lies in the range 2.01 - 2.05 $M_\odot$ and satisfies the mass constraints reported from pulsar PSR J0740+6620. Also from table I one can observe that there is no significant change in the neutron star properties of canonical mass neutron star (1.4 $M_\odot$) because of the appearance of hyperons at higher density. The threshold density for the appearance of hyperons for the HPUY's model is also given in table I.

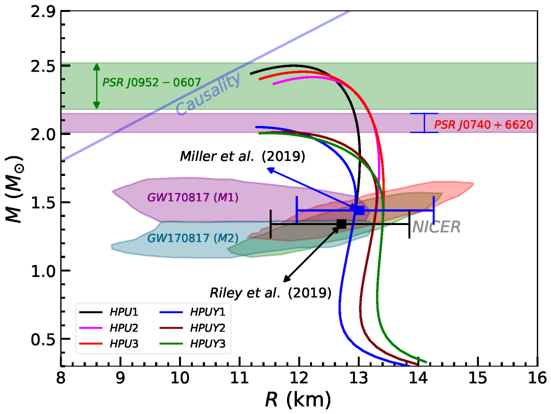

FIG. 1: (Color online) Relationship between neutron star mass and its radius for various models.

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