# Impact of nuclear symmetry energy on neutron star properties

Queena[1],[*] Raj Kumar[1],[†] and Shashi K. Dhiman[1][‡]
[1] *Department of Physics Himachal Pradesh University Shimla-05, INDIA*

## INTRODUCTION

Neutron stars are stellar objects made up of asymmetric dense nuclear matter and have extreme properties. The dense core of the neutron star enables us to study nuclear matter beyond saturation density. The composition of the matter at such high density is not known exactly to the date, but the thermodynamic state of the matter is theorized by the equation of state (EoS). The knowledge of neutron star properties is necessary to probe the high density behaviour of EoSs for the baryonic matter in the $\beta$ equilibrium. It is a well known fact that various properties of neutron star, such as the radius and tidal deformability, are sensitive to the symmetry energy J and its density dependence L. We study the effects of nuclear symmetry energy on the mass-radius relation and tidal deformability of neutron stars. To aim this, we generate different models which have same isoscalar nuclear matter properties like binding energy per nucleon (E/A), incompressibilty coefficient K and ratio of effective mass to nucleonic mass (M*/M ) at saturation density ($\rho_0$) as that of BSRV-CPREX interactions [1] based on relativistic mean-field (RMF) model but having different values of $J$ and L. We construct a set of EoSs of $\beta$- equalibrated nucleonic matter for RMF models that have the same isoscalar properties but different density dependence of the symmetry energy, and then employ these EoSs to study the impact of the symmetry energy on neutron-star properties like maximum mass ($M_{max}$), radius ($R_{1.4}$) and dimensionless tidal deformability ($\Lambda_{1.4}$) corresponding to canonical mass neutron star ($1.4M_{\odot}$).

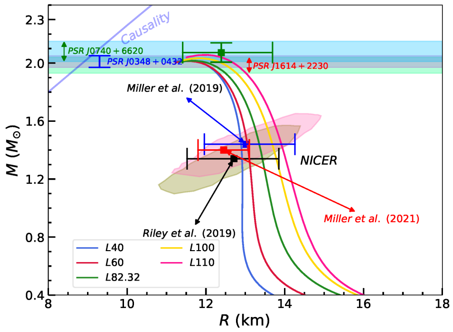

FIG. 1. Mass-radius relations of neutron stars obtained using the unified EOSs.

## THEORETICAL MODEL

The effective Lagrangian density for the RMF model describes the interaction of baryons via the exchange of $\sigma$, $\omega$, $\rho$ and $\delta$ mesons up to the quartic order.The Lagrangian density for a system consisting of neutrons, protons, electrons, and muons is given by [1]

$$\begin{aligned}
\mathcal{L} \;=\; & \sum_{N\,=\,n,p} \overline{\Psi}_N[i\gamma^{\mu}\partial_{\mu} - (M_N - g_{\sigma}\sigma - g_{\delta}\delta.\tau_N) - g_{\omega}\gamma^{\mu}\omega_{\mu} \\
& - \frac{1}{2}g_{\rho}\gamma^{\mu}\tau_{3N}.\rho_{\mu} - e\gamma_{\mu}\frac{1+\tau_{3N}}{2}A_{\mu})]\Psi_N \\
& + \frac{1}{2}(\partial_{\mu}\sigma\partial^{\mu}\sigma - m_{\sigma}^2\sigma^2) - \frac{\overline{\kappa}}{3!}g_{\sigma N}^3\sigma^3 - \frac{\overline{\lambda}}{4!}g_{\sigma N}^4\sigma^4 \\
& - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_{\omega}^2\omega_{\mu}\omega^{\mu} + \frac{1}{4!}\zeta g_{\omega}^4(\omega_{\mu}\omega^{\mu})^2 \\
& - \frac{1}{4}\rho_{\mu\nu}\rho^{\mu\nu} + \frac{1}{2}m_{\rho}^2\rho_{\mu}\rho^{\mu} + \frac{1}{2}\Lambda_v g_{\omega}^2 g_{\rho N}^2\omega_{\mu}\omega^{\mu}\rho_{\mu}\rho^{\mu} \\
& + \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}(\partial_{\mu}\delta\partial^{\mu}\delta - m_{\delta}^2\delta^2) \\
& + \sum_{\ell=e,\mu}\overline{\Psi}_{\ell}\left(i\gamma^{\mu}\partial_{\mu} - M_{\ell}\right)\Psi_{\ell} \qquad (1)
\end{aligned}$$

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## RESULTS AND DISCUSSION

We generate diferent relativistic interactions BSRV-CPREX(L=40), BSRV-CPREX(L=60), BSRV-CPREX(L=100) and BSRV-CPREX(L=110) which possess the same isoscalar nuclear matter properties at saturation density $\rho_0$ as that of original parameter (BSRV-CPREX) model (L = 82.32) but have different values of L. The models are generated from the original BSRV-CPREX model by tuning $g_{\rho}$ and $\omega$ -$\rho$ mesons mixed interaction couplings to achieve a given value of L. Table 1, depicts our results

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[*] queenadhiman26@gmail.com
[†] raj.phy@gmail.com
[‡] shashi.dhiman@gmail.com

TABLE I. Symmetric nuclear matter at ($\rho_0$) and neutron star properties for different parameters generated from original parameter BSRV-CPREX(L = 82.32 MeV).

| | $\rho_0$ | $M^*/M$ | $E/A$ | $K$ | J | $L$ | $M_{max}$ | $R_{1.4}$ | $\Lambda_{1.4}$ |
|---|---|---|---|---|---|---|---|---|---|
| | $(fm^{-3})$ | - | (MeV) | (MeV) | (MeV) | (MeV) | $M_\odot$ | (km) | |
| L=40 | 0.15 | 0.60 | -16.09 | 226.99 | 29.91 | 40 | 2.04 | 12.91 | 530.67 |
| L=60 | 0.15 | 0.60 | -16.09 | 226.99 | 32.99 | 60 | 2.04 | 13.09 | 619.27 |
| L=82.32 | 0.15 | 0.60 | -16.09 | 226.99 | 34.99 | 82.32 | 2.04 | 13.41 | 682.77 |
| L=100 | 0.15 | 0.60 | -16.09 | 226.99 | 36.27 | 100 | 2.06 | 13.75 | 781.78 |
| L=110 | 0.15 | 0.60 | -16.09 | 226.99 | 37.02 | 110 | 2.07 | 13.97 | 865.57 |

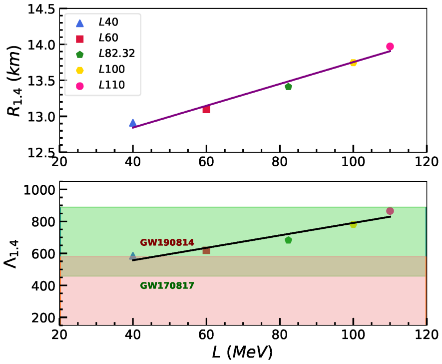

FIG. 2. Variation of $R_{1.4}$ and $\Lambda_{1.4}$ with density dependence of symmetry energy (L).

for the various nuclear matter parameters E/A, K, M*/M, $J$ and $L$ at $\rho_0$ and neutron star matter properties like maximum mass ($M_{max}$), radius ($R_{1.4}$) and dimensionless tidal deformability $\Lambda_{1.4}$). It is shown that the maximum mass is not very sensitive to $L$, but $R_{1.4}$ increases with $L$. Also we observe that $\Lambda_{1.4}$ also increases with $L$. In Fig. 1 we display the mass-radius relation obtained for a set of EoSs computed with the above mentioned generated interactions. It is found that the maximum mass of neutron stars lies in the range of 2.04-2.07 $M_\odot$, which is compatible with the observational constraints of PSR J0740+6620 ($M = 2.14^{+0.10}_{-0.09} M_\odot$) [2], PSR J0348+0432($M = 2.01 \pm 0.04 M_\odot$) [3]. The recent analysis of GW170817 data provides a consistent upper limit for the radius of a 1.4$M_\odot$ neutron star as $R_{1.4} < 13.8 km$ [4]. Our resulting $R_{1.4}$ with different $L$ is compatible with this constraint except for $L$=110. In Fig. 2 the behaviour of $\Lambda_{1.4}$ and $R_{1.4}$ with $L$ has been displayed. The analysis of GW170817 data has placed a constraint on the tidal deformability of a 1.4$M_\odot$ neutron star, i.e. $\Lambda_{1.4} \leq (580)$ [5]. It is evident from the figure that relatively softer values of L are favoured to satisfy the revised limit of $\Lambda_{1.4}$ as observed by GW170817 event and neutron star radius from astrophysical obsrvations.

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