Determination of the nuclear incompressibility and symmetry energy from neutron star tides

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Introduction

The equation of state(EoS) of nuclear matter determines the properties of microscopic nuclei and also macroscopic celestial objects, as neutron stars, supernova or neutron star merger. Its accurate knowledge is, however, still unknown due to the incomplete understanding of the nuclear force. Learning about how nuclear matter reacts to compression forces and how strong is the neutron-proton asymmetry at high densities is essential to understand the nuclear force. Observables associated with these properties are key factors in unravelling the mystery of the nuclear force. The tidal deformability of a binary neutron star as inferred very recently from GW170817 event [1] is one such observable.

The present communication is an attempt, in view of the recent observation GW170817, to explore the dependence of the tidal deformability on the various nuclear matter parameters describing the EoS. We study the correlations of the tidal deformability parameter with the different several nuclear matter parameters associated with a EoS by employing a representative set of relativistic mean field (RMF) models and of Skyrme Hartree-Fock (SHF) models. The considered EoS parameters are the incompressibility K_0, skewness coefficient Q_0, slope of the incompressibility M_0, symmetry energy coefficient J_0, symmetry energy slope L_0, and its curvature $K_{\mathrm{sym},0}$ evaluated at saturation density.

The Equations of states

The correlations of the properties of neutron stars with the various nuclear matter parameters of the EoS are studied using a set of eighteen relativistic and twenty-four non-relativistic nuclear models (Ref. [2] and there in). These models have been employed for the study of finite nuclei and NS properties. Our set of models are based on RMF and SHF frameworks. The employed RMF models are BSR2, BSR3, BSR6, FSU2, GM1, NL3, NL3$\sigma\rho$4, NL3$\sigma\rho$6, NL3$\omega\rho$02, NL3$\omega\rho$03, TM1, and TM1-2 and DD2, DDHδ, DDHδMod, DDME1, DDME2, and TW. The considered SHF models are the SKa, SKb, SkI2, SkI3, SkI4, SkI5, SkI6, Sly2, Sly9, Sly230a, Sly4, SkMP, SKOp, KDE0V1, SK255, SK272, Rs, BSk20, BSk21, BSk22, BSk23, BSk24, BSk25, and BSk26. The values of the nuclear matter properties vary over a wide range for our representative set of EoSs and for all the models are consistent with the observational constraint provided by the existence of 2 $M_\odot$ NS as can be seen from the supplementary material of Ref. [3].

Results and Discussions

We study the correlations of the tidal deformability Λ, the Love number k_2 and the radius of NSs R with various nuclear matter parameters. We consider the constraints from the properties of the binary neutron star that satisfy the low spin prior [1]. The tidal deformability is found to be weakly or only moderately correlated with the individual nuclear matter parameters of the EoS. The stronger correlation of Λ is found only for specific choices of the linear combinations of the isoscalar and isovector EoS parameters. The parameter Λ is strongly correlated with the linear combination of the slopes of incompressibility and symmetry energy coefficients, i.e., $M_0 + \beta L_0$. Further, the parameter Λ and the Love number k_2 both are strongly correlated with the linear combination of $M_0 + \eta K_{\mathrm{sym},0}$. The solid lines in Fig. 1 are obtained using linear regression. These linear

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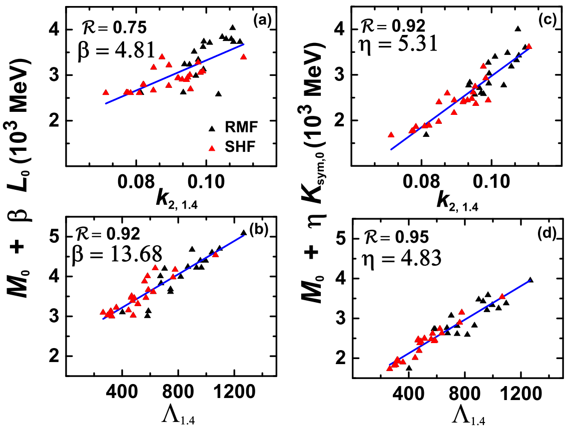

FIG. 1: (Color Online)(a-b) The $M_0 + \beta L_0$ and (c-d) $M_0 + \eta K_{\mathrm{sym},0}$ versus the tidal Love number $k_{2,1.4}$ (top panels) and dimensionless tidal deformability $\Lambda_{1.4}$ (bottom panels) for a 1.4 $M_\odot$ NS, using a set of RMF and SHF models.

regressions yield,

$$\frac{M_0}{\mathrm{MeV}} + 13.68\frac{L_0}{\mathrm{MeV}} = (2.09 \pm 0.14)\ \Lambda_{1.4} + (2383.12 \pm 96.42), \quad (1)$$

$$\frac{M_0}{\mathrm{MeV}} + 4.83\frac{K_{\mathrm{sym},0}}{\mathrm{MeV}} = (2.11 \pm 0.11)\ \Lambda_{1.4} + (1278.13 \pm 77.76). \quad (2)$$

The gravitational-wave observations set an bound $344 < \Lambda_{1.4} < 859$ [2]. With the aid of the correlations of $\Lambda_{1.4}$ with linear combinations of nuclear matter parameters as considered together with the bounds on $\Lambda_{1.4}$ and the empirical ranges of L_0 obtained in Ref. [4, 5], we have constrained the values of M_0 and $K_{\mathrm{sym},0}$ to lie in the intervals $2254 < M_0 < 3631$ MeV and $-112 < K_{\mathrm{sym},0} < -52$ MeV or $1926 < M_0 < 3768$ MeV and $-140 < K_{\mathrm{sym},0} < 16$ MeV, depending on the constraints set on L_0 in the range 40-62 MeV and 30-86 MeV,respectively.

The strong correlation of tidal deformability with the NS radius for a 1.4 $M_\odot$ NS yields $R_{1.4}$ in the range $11.82 - 13.72$ km as seen in Fig. 2.

Conclusions

The tidal deformability shows a strong correlation with specific linear combinations of the isoscalar and isovector nuclear matter parameters associated with the EoS. Such correlations suggest that a precise value of the tidal deformability can put tight bounds on several EoS parameters, in particular, on the slope of the incompressibility and the curvature of the symmetry energy. The tidal deformability obtained from

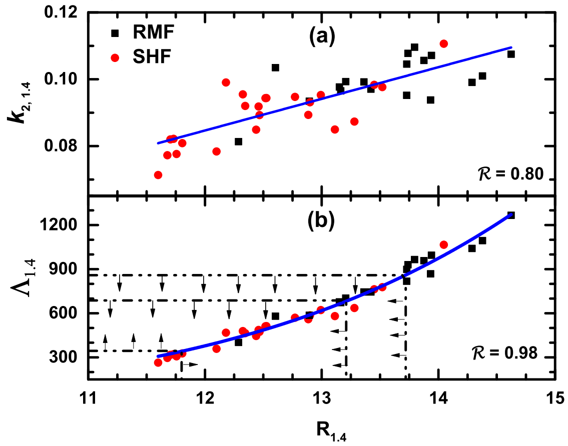

FIG. 2: (Color Online)(a) The variation of tidal Love number $k_{2,1.4}$ and (b) the dimensionless tidal deformability $\Lambda_{1.4}$ with the radius $R_{1.4}$ obtained for the RMF (black squares) and SHF (red circles) models. The solid lines in the top and bottom panels are the best fitted linear and curve lines, respectively. The horizontal dot-dot-dashed lines represent the bounds obtained in Ref. [2]

the GW170817 and its UV/optical/infrared counterpart sets the radius of a canonical 1.4 $M_\odot$ neutron star to be $11.82 \leqslant R_{1.4} \leqslant 13.72$ km. The precise measurement of tidal deformability will provide an alternative and accurate estimate for M_0, $K_{\mathrm{sym},0}$ and $R_{1.4}$.

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