F-mode oscillations in neutron stars: impact of hyperons and nuclear parameters

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Introduction

The density gradient of neutron star (NS) ranges from below nuclear saturation density ($n_0 \sim 2 \times 10^{17}$g cm^{-3}) to several times n_0. With large uncertainties in the behaviour of high-density NS matter, it was argued that strange baryons (or hyperons) or even a deconfined quark phase could be a stable component inside the neutron star core. The microscopic description of NS matter relates to the macroscopic observables of neutron stars through the pressure density relationship: known as equation of state (EoS). Though the information about the NS mass or radius from isolated NSs is not very precise, improved measurements of NS global properties come from binary neutron stars (BNS) either via electromagnetic or gravitational waves (GW) observations. In binary, the tidal deformation of NS depends on the NS EoS, and hence the detection of GW from BNS can be used to constrain the NS EoS. In the case of isolated NSs, non-axisymmetric perturbations result in GW generation through the stellar oscillation modes. Since the f-mode is more likely to be excited in isolated as well as in late inspiral of a BNS merger, and the frequency is within the range of current and upcoming GW detectors, we focus on the f-mode oscillations of NSs in this work. Further, using NS asteroseismology involving NS f-mode characteristics, one can infer NS properties, or the inverse asteroseismology relation can be used to constrain the NS EoS.

In this work, we investigate how the appearance of hyperons inside the NS core affects f-mode oscillations in neutron stars. We further investigate the impact of nuclear and hyper-nuclear parameters on the NS observable properties and the f-mode characteristics (frequency and damping time).

Method

a. EoS model: We describe the NS matter using a phenomenological relativistic mean field (RMF) model, where meson exchanges carry out the baryon-baryon interaction. The complete description of the Lagrangian density and hence the EoSs used in this work can be found in [1]. In the RMF model, the model parameters are obtained by reproducing the nuclear and hyper-nuclear data at n_0. The nuclear saturation parameters are nuclear saturation density (n_0), the binding energy per nucleon (E/A or $E_{\rm sat}$), incompressibility (K), the effective nucleon mass (m^*), symmetry energy (J) and slope of symmetry energy (L) at saturation. Hyperon coupling constants are fixed using hyperon nucleon potential depths (U_Y) or using quark symmetry properties. We fix the potentials for hyperon Λ and Σ to their adapted values at $U_\Lambda = -30$MeV and $U_\Sigma = +30$MeV respectively and consider the uncertainty associated with U_Ξ, i.e, -40MeV $\leq U_\Xi \leq 40$ MeV. The uncertainty of the nuclear and hyper-nuclear parameters considered in this work can be found in [2].

b. NS observables and f-mode characteristics: For a given EoS, NS observables like mass (M) and radius (R) can be obtained by solving the Tolman-Oppenheimer-Volkoff (TOV) equations. For the tidal deformability parameter $\bar{\Lambda}$, additional differential equations must be solved along with TOV equations [3]. To obtain the complex frequency of the f-mode $\omega = 2\pi f + \frac{i}{\tau_f}$ (f is the mode frequency and τ_f is the damping time), we use the methodology developed in our previous work [2].

Results

For the EoSs considered in this work, we additionally ensure that the EoS must produce a $2M_\odot$ stable NS mass to satisfy the maximum observed NS mass. We display the variation of

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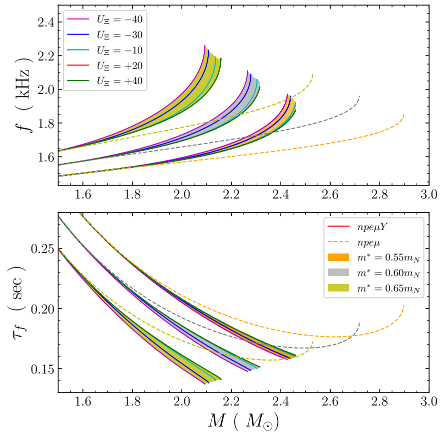
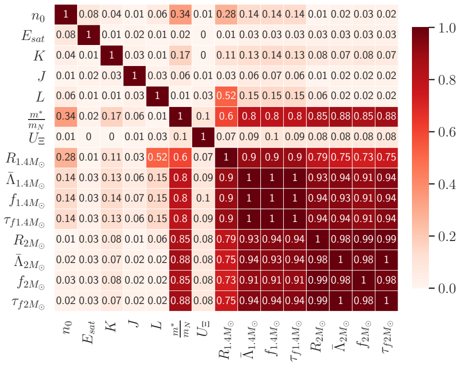


FIG. 1: (upper panel) Variation of f-mode frequency (f) as a function of neutron star mass (M) for different EoSs with varying m^* and U_Ξ. Hyperons are represented by solid lines and the corresponding pure nucleonic lines are represented by dashed lines. The other nuclear and hyper-nuclear parameters are fixed to, $J = 32$ MeV, $L = 60$ MeV, $K = 240$ MeV, $E_{\rm sat} = -16$ MeV, $U_\Lambda = -30$ MeV and $U_\Sigma = 30$ MeV. (Lower panel) Variation of damping time with stellar mass.

f-mode frequency f (and damping time τ_f) as a function of NS mass M in fig. 1. It is clear from fig. 1 that the f-mode frequency increases after the appearance of hyperons compared to the corresponding pure nucleonic EoSs, which generally occurs for $M \geq 1.5 M_\odot$. In contrast, the damping time decreases after the appearance of hyperons. For a fixed value of m^*, f-mode frequency (damping time) decreases (increases) with increasing the U_Ξ.

Further, we investigate the impact of nuclear and hyper-nuclear parameters by studying the correlations among the saturation parameters, NS parameters, and f-mode characteristics. We present the correlation matrix among the saturation parameter themselves as well as with the NS properties of a canonical $1.4 M_\odot$ and a massive $2 M_\odot$ in fig. 2. The NS observables show strong correlations among themselves and with the f-mode parameters. We notice that m^* shows strong correlations with the NS observables and f-mode characteristics. The symmetry energy **slope** L shows a moderate correlation with the radius of a $1.4 M_\odot$ NS. We do not notice any significant correlation of U_Ξ with NS observables or f-mode characteristics.



	n_0	E_{sat}	K	J	L	$\frac{m^*}{m_N}$	U_Ξ	$R_{1.4M_\odot}$	$\bar\Lambda_{1.4M_\odot}$	$f_{1.4M_\odot}$	$\tau_{f1.4M_\odot}$	$R_{2M_\odot}$	$\bar\Lambda_{2M_\odot}$	$f_{2M_\odot}$	$\tau_{f2M_\odot}$
n_0	1	0.08	0.04	0.01	0.06	0.34	0.01	0.28	0.14	0.14	0.14	0.01	0.02	0.03	0.02
E_{sat}	0.08	1	0.01	0.02	0.01	0.02	0	0.01	0.03	0.03	0.03	0.03	0.03	0.03	0.03
K	0.04	0.01	1	0.03	0.01	0.17	0	0.11	0.13	0.14	0.13	0.08	0.07	0.08	0.07
J	0.01	0.02	0.03	1	0.03	0.06	0.01	0.03	0.06	0.07	0.06	0.01	0.02	0.02	0.02
L	0.06	0.01	0.01	0.03	1	0.01	0.03	0.52	0.15	0.15	0.15	0.06	0.02	0.02	0.02
$\frac{m^*}{m_N}$	0.34	0.02	0.17	0.06	0.01	1	0.1	0.6	0.8	0.8	0.8	0.85	0.88	0.85	0.88
U_Ξ	0.01	0	0	0.01	0.03	0.1	1	0.07	0.09	0.1	0.09	0.08	0.08	0.08	0.08
$R_{1.4M_\odot}$	0.28	0.01	0.11	0.03	0.52	0.6	0.07	1	0.9	0.9	0.9	0.79	0.75	0.73	0.75
$\bar\Lambda_{1.4M_\odot}$	0.14	0.03	0.13	0.06	0.15	0.8	0.09	0.9	1	1	1	0.93	0.94	0.91	0.94
$f_{1.4M_\odot}$	0.14	0.03	0.14	0.07	0.15	0.8	0.1	0.9	1	1	1	0.94	0.93	0.91	0.94
$\tau_{f1.4M_\odot}$	0.14	0.03	0.13	0.06	0.15	0.8	0.09	0.9	1	1	1	0.94	0.94	0.91	0.94
$R_{2M_\odot}$	0.01	0.03	0.08	0.01	0.06	0.85	0.08	0.79	0.93	0.94	0.94	1	0.98	0.99	0.99
$\bar\Lambda_{2M_\odot}$	0.02	0.03	0.07	0.02	0.02	0.88	0.08	0.75	0.94	0.93	0.94	0.98	1	0.98	1
$f_{2M_\odot}$	0.03	0.03	0.08	0.02	0.02	0.85	0.08	0.73	0.91	0.91	0.91	0.99	0.98	1	0.98
$\tau_{f2M_\odot}$	0.02	0.03	0.07	0.02	0.02	0.88	0.08	0.75	0.94	0.94	0.94	0.99	1	0.98	1

FIG. 2: Correlation matrix among the nuclear, hyper-nuclear parameters, NS observables and f-mode characteristics.

Conclusions

The appearance of hyperons increases (decreases) the f-mode frequency (damping time) compared to the pure nucleonic matter EoS. The hyperon potential U_Ξ has a minor impact on the f-mode characteristics. From the correlation study, it is clear that in the framework of RMF models, the NS observables and f-mode characteristics are controlled mainly by m^*. Among other saturation parameters, **the slope of** symmetry energy shows a moderate correlation with the radius of $1.4 M_\odot$. Detecting f-mode oscillations from isolated NSs will provide an ideal scenario for studying NS physics. In Pradhan et al. [2], we have shown that from the detection of f-mode frequency along with the $\bar\Lambda$ once can comment on the presence of hyperons using the $f - \bar\Lambda$ relation.

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References

[1] B. K. Pradhan and D. Chatterjee, Phys. Rev. C 103 (2021), 035810

[2] B. K. Pradhan, D. Chatterjee, M. Lanoye, and P. Jaikumar, Phys. Rev. C 106 (2022), 015805

[3] Tanja Hinderer, 2008 ApJ 677 1216.