Neutron Star Equation of state in single and two fluid formalism

Bhavnesh Bhat,* Piyush Marmat, Himanshu Grover,
Jaikhomba Singha, Ankit Kumar, and P. Arumugam†
Department of Physics, Indian Institute of Technology Roorkee, Uttarakhand - 247667, INDIA

Introduction

Neutron stars(NSs) are compact astrophysical objects formed as a result of supernovae explosions, as massive stars end their main-sequence evolution. The interiors of such stars have temperatures that can sustain the superfluidity of neutrons. The superfluid dynamics inside such a star can be studied using the single, and two-fluid formalism [1]. In this work, we have developed a realistic equation of states for superfluid neutron stars in the single and two-fluid formalism, taking different parametrization schemes for the meson coupling constants.

Formalism

The Lagrangian Density for the $\sigma-\omega-\rho-\delta$ model is given as [1]

$$\mathcal{L} = \bar{\psi}[\gamma_\mu(i\partial^\mu - g_\omega V^\mu - g_\rho R^\mu \frac{\tau}{2}) - (m_n - g_\sigma\sigma)]\psi + \frac{1}{2}(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2) - \frac{1}{4}V_{\mu\nu}V^{\mu\nu} + \frac{1}{2}m_\omega^2 V_\mu V^\mu - \frac{1}{4}R_{\mu\nu}.R^{\mu\nu} + \frac{1}{2}m_\rho^2 R_\mu.R^\mu + \frac{1}{2}(\partial_\mu\delta\partial^\mu\delta - m_\delta^2\delta^2) \tag{1}$$

where

$$V_{\mu\nu} = \partial_\mu V_\nu - \partial_\nu V_\mu$$

, and

$$R_{\mu\nu} = \partial_\mu\rho_\nu - \partial_\nu\rho_\mu - g_\rho(\rho_\mu \times \rho_\nu).$$

We substitute self-interaction with density-dependent couplings to understand nuclear and neutron matter at higher densities.

*Electronic address: bhavnesh_b@ph.iitr.ac.in
†Electronic address: arumugam@ph.iitr.ac.in

Due to the presence of superfluid neutrons, the two fluid formalism segregates the first fluid to the superfluid neutrons, and all other charged species like protons and leptons are considered the other fluid. Strong interaction between protons and neutrons causes entrainment in the NSs interior. This is quantified in the two-fluid formalism through the elements of entrainment matrix $\mathcal{K}^{XY}$ and of its inverse $\mathcal{Y}_{XY}$. These are functions of three quantities, i.e., neutron density (n_n), proton density (n_p), and square of relative velocity between the two fluid (Δ^2). In this work, the two fluids are assumed to co-rotate implying [1],

$$\Delta^2 = 0$$

The entrainment coefficients:

$$Y_{XY} \equiv \mathcal{Y}_{XY}|_{\Delta^2=0,\mu^n=\mu^p} \tag{2}$$

which depend on the total baryon density n_B.

Results and Discussion

We have developed various EOSs for density-dependent coupling parameterizations, viz., TW99[4], DDME2[6], DD2[7], DD-LZ1[5] in the framework of two fluid formalism. The two fluid EOSs reduce to single fluid EOS when entrainment is removed. The mass-radius relationship obtained by solving the Tolman-Oppenheimer-Volkov equations using this single fluid EOSs are shown in Fig. 1. The mass constraints (taken from [2]) suggest that TW99 does not satisfy all the constraints.

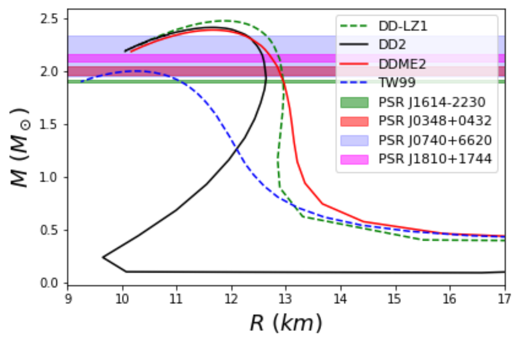

FIG. 1: Mass Radius Diagram for DDLZ1, DD2, DDME2, TW99 models with observational constraints. TW99 not satisfying.

For the case of two fluids, we show the variation of the energy density with pressure in Fig. 2. It is important to note that these plots have been generated for the case of co-rotating fluids. As we can see from Fig. 2, we observe the softness of TW99 compared to other Models. This is further confirmed by Fig. 1, where the TW99 cannot satisfy the constraints.

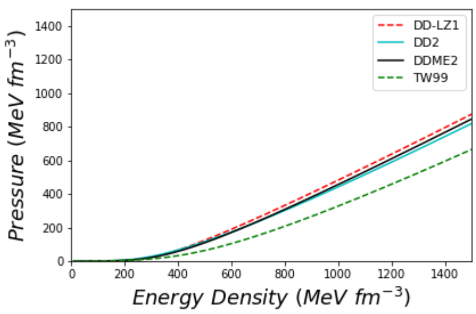

FIG. 2: Energy Density vs Pressure plot in two fluid formalism for DDLZ1, DD2, DDME2, TW99 models. The TW99 is softer than other models.

We plotted the inverse entrainment coefficients (given in Eq.2) versus the baryon density for the various EOSs generated above. From Fig. 3 we can infer that there is not much variation of entrainment in proton-proton (pp) and neutron-proton (np) interactions. The entrainment for neutron-neutron (nn) interaction vary significantly for the TW99 model in comparison to other models. This could be due to the softer nature of this EOS.

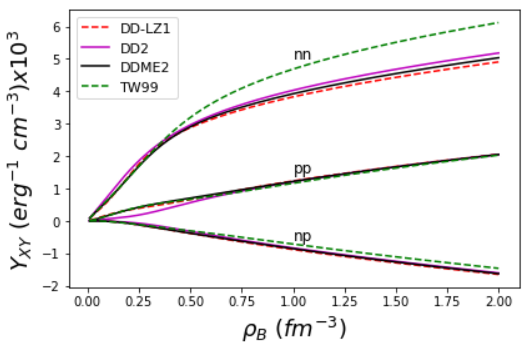

FIG. 3: Inverse entrainment coefficients versus baryon density for DDLZ1, DD2, DDME2, TW99 models. Low variation of pp and np

Conclusion

In this work, we successfully developed new EOSs in two fluid formalism. We presented the results obtaind for co-rotating fluids inside a neutron star for such EOSs. These EOSs will be further used to obtain the configurations of superfluid NS using `LORENE` [3] libraries. Subsequently, these properties can be studied at various rotational frequencies.

JS, HG and AK acknowledges the financial support from MOE (Govt. of India) for his Ph.D. thesis work.

References

[1] Sourie *et al.*, Phys. Rev. D, **93**, 083004 (2016).
[2] J. Singha *et al.*, Res. Astron. Astrophys., **22**, 055001 (2022).
[3] LORENE, `https://lorene.obspm.fr/`.
[4] Typel *et al.*,Nucl. Phys. A, **656**, 331–364 (1999)
[5] Wei *et al.* ,Chinese Physics C, **44**, 074107 (2020)
[6] Lalazissis *et al.* ,Phys. Rev. C, **71**, 024312 (2005)
[7] Typel *et al.* ,Phys. Rev. C, **81**, 015803 (2010)