# Stable hybrid stars with colour superconducting quark matter core

B.K. Agrawal[1*]
[1] *Saha Institute of Nuclear Physics, Kolkata - 700064, India*

## Introduction

The present knowledge of quantum chromodynamics at high density indicates that quark matter might be in color superconducting phases. Thus, hybrid stars might contain color superconducting quark matter (CSQM) core surrounded by nuclear mantle. The possible CSQM phases are the two-flavor color superconductor (2SC), colour flavour locked (CFL) phase, and crystalline color superconductor. The speculation that the CSQM exists in the core of the hybrid stars has triggered many theoretical investigations.

The nuclear matter phase of the hybrid star is described by the various models which can be grouped into (i) non-relativistic potential models, (ii) non-relativistic mean-field models, (iii) field theoretical based relativistic mean-field models (FTRMF) and (iv) Dirac-Brueckner-Hartree-Fock model. The CSQM appearing at the core of hybrid stars are usually described within the MIT bag model and NJL model. The studies based on the MIT bag model indicate the existence of stable configurations of hybrid stars with the CFL quark matter core. The scenario is some what different when NJL model is employed to study the hybrid stars with CSQM core. Until recently [1], NJL like model ruled out the CSQM phase at the core because it rendered the hybrid star unstable. Only very recently, it has been demonstrated that large enough values of the scalar diquark coupling strength in NJL model can yield stable configurations of the hybrid star containing 2SC and CFL quark matter core [2]. It is also shown in Ref. [2] that inclusion of a isoscalar vector coupling term in the NJL model would increase the maximum mass of the hybrid stars to lie within the current observational limit. The values of the strengths for the scalar diquark and isoscaler vector couplings are not yet known.

We compute the equations of state (EOSs) which correspond to the nuclear matter at low densities and CSQM in the 2SC or CFL phase at high densities. The EOSs for CSQM are calculated within the NJL model for different values of coupling strengths for the scalar diquark and isoscaler vector terms. The EOS at intermediate densities are obtained using Maxwell construction. These EOSs are used to construct stable configurations of static and rotating hybrid stars.

## Equations of state

We employ a set of diverse EOSs for the nuclear matter obtained using various approaches, like, variational, non-relativistic mean field (NRMF) and relativistic mean field (RMF). In Table I, we list some key properties of the static neutron stars obtained using these nuclear matter EOSs. The significant differences in the neutron star properties for these EOSs are mainly due to differences in their high density behaviour.

The EOSs for the CSQM in the 2SC or CFL phase are obtained within the NJL model. In this model, the pressure for a given quark chemical potential $\mu$ is given as,

$$P = 4K\sigma_u\sigma_d\sigma_s - \frac{1}{4G_D}\sum_{c=1}^{3}|\Delta_c|^2 - 2G_S\sum_{\alpha=1}^{3}\sigma_\alpha^2 + \frac{\omega_0^2}{4G_V} + \sum_{i=1}^{18}\int_0^\Lambda \frac{dk}{2\pi^2}k^2\,|\epsilon_i| + P_e - B \quad (1)$$

where, $\sigma_{u,d,s}$ are the quark-antiquark condensates, $\Delta_c$ are the three diquark condensates, $\omega_0$ is the expectation value for isoscalar vector like meson $\omega$, $\epsilon_i$ are the dispersion

*Electronic address: bijay.agrawal@saha.ac.in

TABLE I: Properties of static Neutron star.

| EOS | Approach | $\epsilon_{\max}$ $[10^{15} g/cm^3]$ | $M_{\max}$ $[M_\odot]$ | $R_{\max}$ [km] | $R_{1.4}$ [km] |
|---|---|---|---|---|---|
| APR | Variational | 2.80 | 2.19 | 9.9 | 11.3 |
| SLY4 | NRMF | 2.84 | 2.05 | 10.0 | 11.7 |
| BSR10 | RMF | 2.14 | 1.97 | 11.6 | 13.3 |
| TM1 | RMF | 1.87 | 2.19 | 12.4 | 14.4 |
| NL3 | RMF | 1.55 | 2.79 | 13.3 | 14.7 |

relation[3], and $P_e$ is electron pressure. The values of $\sigma_i$ and $\Delta_c$ are determined using, $\frac{\partial P}{\partial \sigma_i} = \frac{\partial P}{\partial \Delta_c} = 0$. The constant $B$ in (Eq. 1) is so determined that $P$ vanishes at zero density and temperature. Once, the pressure as a function of quark chemical potential is known, quark matter EOS can be easily computed. We construct quark matter EOS for different values of $G_D$ and $G_V$, while, $G_S\lambda^2 = 1.835$, $K\lambda^5 = 12.36$, $\lambda = 602.3$ MeV and current quark masses $m_u = m_d = 5.5$ MeV, $m_s = 104.7$ MeV taken from Ref. [3].

## Hybrid stars with CSQM core

We find that the stable configurations of hybrid stars are possible only when the EOSs for the CSQM are constructed with $G_D \gtrsim 1.2G_S$ and $G_V \lesssim 0.2G_S$ within the NJL model. The third family compact stars appearing in Fig. 1 corresponds to hybrid stars with CFL quark matter core. The maximum masses of the hybrid stars seems to be almost independent of the choice of the nuclear matter EOS. However, the composition of the hybrid stars depend on the nuclear matter EOS. The TM1 and NL3 EOSs yield hybrid stars containing a thin layer of 2SC quark matter in between the CFL quark matter core and the nuclear mantle. In Fig. 2, we plot the values of the maximum rotation frequency $f_{\max}$ for the stable configuration of hybrid stars. We see that the values of $f_{\max}$ are quite sensitive to the choice of the nuclear matter EOS as well as to the value of the coupling constant $G_V$. It is interesting to note from Figs. 1 and 2, the values of $G_D$ and $G_V$ for a given nuclear matter EOS can be so adjusted that the resulting hybrid star has (a) the maximum mass $\sim 1.5M_\odot$ in the static limit which is higher than the most accurately measured maximum mass of $1.44M_\odot$ and (b) the maximum allowed rotation frequency is larger than the current observational limit of 716 Hz.

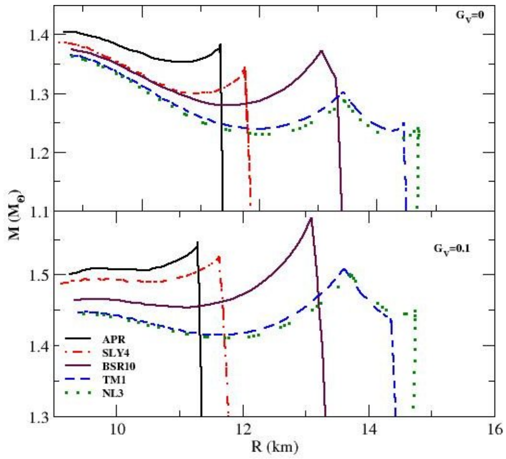


FIG. 1:Mass-radius relationship.

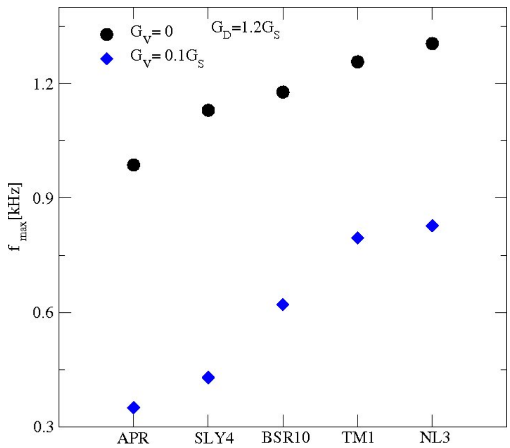


FIG. 2: Maximum rotation frequency.

## References


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