On Stability of Hybrid Stars with Density Dependent Bag Model

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1. Introduction

The highly dense and compact neutron star (NS) cores theoretically provide favorable conditions for hadronic matter (HM) to undergo phase transition (PT) to quark matter (QM) and form hybrid stars (HSs). The stability of such HSs depend on a lot conditions like the composition and equation of state (EoS) of both HM and QM, the type of construction considered to achieve PT and density at which PT occurs.

In the present work, we consider the MIT Bag model to describe the QM. Since PT implies vanishing of the difference between the perturbative and the true vacuum at high density [1, 2], we consider density dependence of $B(\rho)$ that involves the value of $B(\rho)$ where the quarks achieve asymptotic freedom (B_{as}). The HM phase, on the other hand, is composed of nucleons and may (NH) or may not (N) contain the hyperons ($H = \Lambda, \Sigma^{-,0,+}, \Xi^{-,0}$). It is already seen that the value of B_{as}, for a particular hadronic composition, has significant effect on achieving reasonable HS configurations [1, 2] in the light of various observational constraints. In the present work, we investigate how B_{as} and the composition of HM individually play important roles in the stability of HSs.

2. Formalism

The hadronic phase is described by the effective chiral model [3]. We compute the hadronic EoS both with (NH) [4] and without (N) [3] hyperons. The HM involves the scalar σ, vector ω and isovector ρ mesons. The same model parameter set is chosen as in [4]. For NH the scalar hyperon couplings are chosen as x_{σ_H}=0.68 while the vector hyperon couplings x_{ω_H} are obtained using the potential depths of the individual hyperon species [2].

For the pure quark phase the MIT Bag model is considered without repulsive effects of the quarks. We consider density dependent bag pressure $B(\rho)$ given by a Gaussian distribution form [1]

$$B(\rho) = B_{as} + (B_0 - B_{as}) \exp\left[-\beta(\rho/\rho_0)^2\right]$$

Here β controls the decrease of $B(\rho)$ with the increase of density. We choose $B_0 = 400$ MeV fm^{-3} and $\beta = 0.17$ following [1]. Since PT occurs at high density, B_{as} has great significance on HSs properties [2].

With Maxwell construction, we invoke PT and seek stable HS configurations. For the purpose we consider hadronic EoS with (NH) and without (N) hyperons. For each case B_{as} is varied to understand the dependence of stability of HSs on the hadronic composition and also the value of B_{as}.

3. Results

In figure 1 we plot the pressure vs chemical potential (μ) for HM for N and NH cases. In this plot we show the same for QM with different values of B_{as} and also for density independent bag pressure case (B=constant). It is clear that in case 'N', the hadron-quark crossover takes place at higher chemical potential as compared to the NH case. This fact remains same for each value of B_{as}. Therefore comparatively delayed PT is expected for the case without hyperons. This is manifested in the structural properties and stability of the

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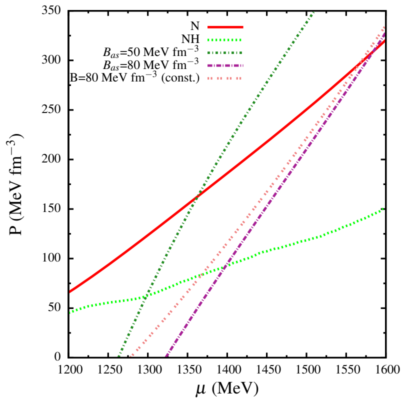

FIG. 1: Pressure vs chemical potential showing intersection of pure quark and pure hadronic EoS with (NH) and without (N) hyperons.

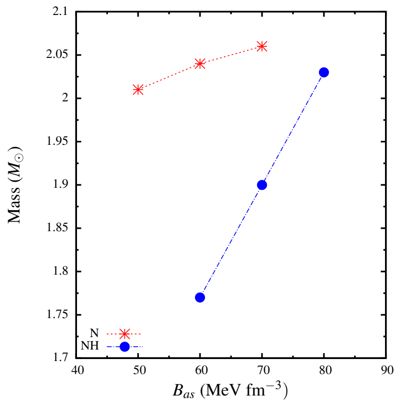

FIG. 2: Variation of maximum gravitational mass wrt B_{as} of the HSs with (NH) and without (N) hyperons.

HSs. The delayed onset of quarks in the case N as a result of which the hybrid EoS stiffens more and the corresponding $M-R$ solution becomes unstable faster than that of the NH case. PT in case N results in higher values of the HS mass compared to that in NH case (seen from figure 2). For case N we have shown the results with values of B_{as} that yield HS configurations satisfying the maximum mass constraint from the most massive pulsar PSR J0740+6620. For N case, choosing B_{as} beyond 70 MeV fm^{-3} no longer give stable stable HS solutions. However, it is seen that when hyperons are included (NH), stable HS solution is obtained upto B_{as}=80 MeV fm^{-3}. This is also true when bag parameter is independent of density i.e, B=80 (const.) MeV fm^{-3} (M=1.98 $M_\odot$). For any particular HM composition (N or NH), too high value of B_{as} results in very delayed PT and therefore unstable HS configuration. In table I we report the crossover chemical potential (μ_t), hadron (ρ_{h_t}) and the quark (ρ_{q_t}) densities at transition, for different values of B_{as} for each N and NH case.

TABLE I: Hadron-quark crossover chemical potential (μ_t), hadron (ρ_{h_t}) and the quark (ρ_{q_t}) densities at transition, for different values of B_{as} with (NH) and without (N) hyperons.

	B_{as} (MeV fm^{-3})	μ_t (MeV)	ρ_{h_t}/ρ_0	ρ_{q_t}/ρ_0
N	50	1362.50	4.84	6.44
	60	1456.82	5.62	7.71
	70	1528.03	6.34	8.85
NH	60	1345.90	4.64	6.22
	70	1364.84	4.88	6.48
	80	1413.48	5.38	7.13
	80 (const.)	1371.00	4.97	6.58

4. Summary and Conclusion

Hadron-quark PT in HS cores is studied. Both the presence and absence of hyperons are considered in HM while QM is described by the MIT Bag model with density dependence of the bag pressure. We find that the structure and stability of HSs depend significantly on the composition of HM (with respect to presence or absence of hyperons) as well as on B_{as}, which decides the density at which quarks attain asymptotic freedom.

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References

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