Structural Properties of Rotating Hybrid Stars with Color - Superconducting Quarks Matter

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Introduction

The recently extracted limits of gravitational maximum mass of compact star and their radii and detection of gravitation waves GW170817 [1] from rotating stars are the motivating astrophysical observables to investigate a set of plausible equation of states (EOSs) of dense nuclear matter. These investigations can guide us to unfold the particle composition of nuclear dense matter and constrain the EOS from crust to the inner core of compact star. The nuclear equation of state is computed within the framework of energy density functionals based on the relativistic mean field theory by employing BSR1 [6] and IOPB-I [5] models. The color superconducting quarks matter phase of equation of state is based upon a Quarks Quasiparticle model(QQPM) derived from a non-relativistic energy density-functional approach. The medium effects are included in the cold quarks matter in terms of variation in effective mass of quarks and effective bag parameters as function of chemical potential with the bag constant as, $(B_0)^{1/4} = 135$MeV, 155MeV. A plausible set of hybrid equations of state for superdense hadron-quarks matter is used to the construct hybrid stars, which reasonably satisfy constraints provided the data of compact stars of astrophysical interest. We construct the mixed phase of EOS made up of the hadron matter and quark matter by employing the Glendenning construction [2] for hybrid compact star. In order to study the properties of a rapidly rotating Hybrid Neutron Star, we should first construct the Equation of State of the star.

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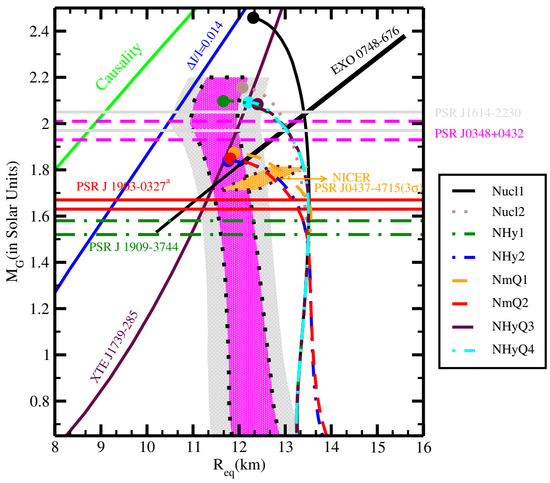

FIG. 1: Relationship between gravitational mass and radius of non - rotating compact star for various EOSs. The region excluded by causality light green solid line and rotation constraints of neutron star XTE J1739-285 solid maroon line are given. The mass and radius limit estimated from Vela pulsar glitches $\Delta I/I$=0.014 is shown as blue solid line. The mass limits of pulsars PSR J1614-2230 and PSR J0348+0432 are plotted for comparison. The limits on compact star mass and radius from Ozel's analysis of EXO 0748-676 with 1σ (dark solid black line) and 2σ (extended black line) error bars are also shown. The mass radius relationship obtained in Ref.[7] from extracted data of EOS by using QMC+Model A. The orange region bounded by the dotted maroon lines is representing the mass - radius relationship extracted for the proposed pulsar PSRJ0437-4715 for 3σ confidence level in the NICER program [8].

Relativistic Rotation of Stars

The matter inside the star is approximated by a perfect fluid and the energy-momentum tensor is given by

$$T^{\mu\nu} = (\mathcal{E} + P)u^{\mu}u^{\nu} - Pg^{\mu\nu} \qquad (1)$$

TABLE I: The structural properties of rotating compact stars, the maximum gravitational mass $M_{max}(M_{\odot})$ and its corresponding equatorial radius R_{max}(km), central energy density $\mathcal{E}_c(\times 10^{15} g/cm^{-3})$, baryon density $\rho(fm^{-3})$, the maximum Keplerian frequency f_K(Hz).

		Nuc1	Nuc2	NHy1	NHy2	NmQ1	NmQ2	NHyQ3	NHyQ4
Keplerian	$M_{max}/M_{\odot}$	2.97	2.60	2.53	2.20	2.26	2.21	2.52	2.54
	R_{max}(km)	16.28	16.26	16.40	16.57	16.88	16.24	16.73	16.63
	$\mathcal{E}_c(\times 10^{15} g/cm^{-3})$	1.56	1.70	1.63	1.67	1.62	1.78	1.53	1.59
	$\rho(fm^{-3})$	0.72	0.79	0.78	0.81	0.79	0.86	0.74	0.76
	f_K(Hz)	1483	1396	1364	1261	1268	1299	1309	1341

where $\mathcal{E}$, P and u^{μ} are the energy density, pressure, and four-velocity, respectively. In order to solve Einstein's field equation for the potentials γ, ρ, β and ω, we adopt the KEH method [3] and use the public RNS code [4] for calculating the properties of a roating star.

Results and Discussions

In Fig.(1), we present the results for relationship between gravitational mass and radius of non - rotating compact star for various EOSs constructed in the present work. The TOVs for the EOSs presented in Figure(1) - Nucl1 and Nucl2 are the EOSs computed with parameters BSR1 and IOPB-I, respectively. The EOSs NHy1 and NHy2 are represented by the compositions of nucleons and hyperons, where hyperons appeared at a threshhold baryon number density $\rho_b \approx 0.35\text{fm}^{-3}$. The EOSs presented in Figure(1) as NmQ1 and NmQ2 are composed of nucleons and quarks in beta equilibrium with mixed phase of EOS varies from $\rho_b \approx$ 0.35-0.55fm^{-3}. Where the quark phase of EOS has been computed by employing Quark Quasiparticle model by considering the color superconduction phase in quark-gluon plasma. In the present work, we have used CFL color superconducting gap parameter, Δ =50MeV and, effective Bag function consisting of μ - dependence and conventional MIT Bag constant (B_0) to include the effects of Quantum Chromo Dynamics, where $B_0^{1/4}$ is taken as 155MeV. Finally, the EOSs NHyQ3 and NHyQ4 have particle compositions of nucleons, hyperons and quarks in beta equilibrium where the threshold density of hyperons $\rho_b \approx 0.35\text{fm}^{-3}$ and the quarks phase transition occur at $\rho_b = 0.56\text{fm}^{-3}$. We considered unconfined quarks matter for EOS NHyQ3 with Δ = 0MeV and, in case of EOS NHyQ4, Δ =50MeV, whereas $B_0^{1/4}$ = 135MeV for both the EOSs. The maximum masses of keplerian sequences with various EOSs, also the corresponding equatorial radii and baryon number densities are displayed in TableI. Likewise, for the same value of the gravitational mass, the rotating configurations exhibit reduced baryon number densities compared to the corresponding non-rotating stars, which is due to the effect of the centrifugal force, which effectively stiffens the equation of state. Moreover, the mass increase is accompanied by a relatively large increase of the equatorial radius, due to the rotational deformation of the star.

References

[1] E. R. Most, L. R. Weih, L. Rezzolla, and J. Schaffner-Bielich, Phys. Rev. Lett. 120 , 261103 (2018).

[2] N. K. Glendenning, Springer-Verlag, New York (2000).

[3] H. Komatsu, Y. Eriguchi, and I. Hachisu, Mon. Not. R. Astron. Soc. 239 , 153 (1989).

[4] http://www.gravity.phys.uwm.edu/rns/.

[5] B. Kumar, S. K. Patra, and B. K. Agrawal, Phys. Rev. C 97 , 045806 (2018).

[6] S. K. Dhiman, R. Kumar, and B. K. Agrawal, Phys. Rev. C 76 , 045801 (2007).

[7] J. Nattila, A. Steiner, J. Kajava, V. Suleimanov, and J. Poutanen, Astron. Astrophys. 591, A25 (2016).

[8] K. C. Gendreau, Z. Arzoumanian, and T. Okajima, Proc. of SPIE 8443 , 844313 (2012).