Effect of fast rotation on neutron stars

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Introduction

Neutron stars are the manifestation of the densest form of cold matter in the observable universe and they represent the end point of the life cycle of the star. Theoretically, the properties of neutron stars such as its mass, radius and related properties are the imprints of a particular equation of state (EoS). At $\approx (2-3)\rho_0$, where ρ_0 is the normal nuclear matter density, the presence of exotic forms of matter like hyperons, quark or mixed phase starts to appear and has substantial impact on the EoS, which in turn gets reflected in the global properties of the star. Since we are still devoid of having any smoking gun signals from observations pertaining to the presence of these novel phase, apparently it becomes important to investigate and address these issues in a proper theoretical framework. Till date, more than 1800 pulsars have been discovered with varying degrees of predictions, which invoke both challenge as well as interest in search for the realistic EoS for neutron stars. There are observations which support a soft EoS at high density and there are also observations which contradict that. These apparent contradictions leaves ample opportunity to probe the various aspects of an EoS in detail and emphasize the need of constraints. With this motivation, we now employ models of relativistic effective field theory [1] to address these inevitable issues relating to the neutron star properties and discuss implications of fast rotations on the stellar structure. The model embodies various interactions and cross couplings, that satisfies the nuclear matter saturation properties and is generalized to include the lowest lying octet of baryons to study the static as well as rotational attributes of the star, corresponding to five different parameter sets from the relativistic mean-field theory.

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Results and Discussion

The details of the hadronic model and the derivation of the equation of motion of the meson fields along with the energy density and pressure for nuclear matter can be found in Ref. [2]. For calculating the gross properties of rotating neutron star, we use the code written by Stergioulas [3] based on the Komatsu-Eriguchi-Hachisu method to construct uniformly rotating star models.

The effect of rotation is to increase the equatorial radius of the star and also to increase the mass that can be sustained at a given central energy density. For star rotating at kepler velocity we show the obtained mass of the neutron star sequence plotted as a function of the central density of the star in Fig. 1(A). We find that the mass of the neutron star increases for all the models, however the resulting central density of the star drops. Quantitatively, we find an increase of $\approx (15-20)$ % in the stellar mass and the decrease in the central density is $\approx (5-17)$ % which corresponds to $\approx (0.2-1.6)\rho_0$. At the mass-shedding limit, the maximum mass of the star is found in the range $(1.49-2.18)\ M_\odot$. Fig. 1(B) shows the corresponding models of neutron stars at $\Omega = \Omega_k$ (mass-shedding limit) in the M-R plane. The filled circles shows the point of maximum mass for the models. In comparison to the static star, we find an increase of $\approx (38-43)$% in the equatorial radius at maximum mass.

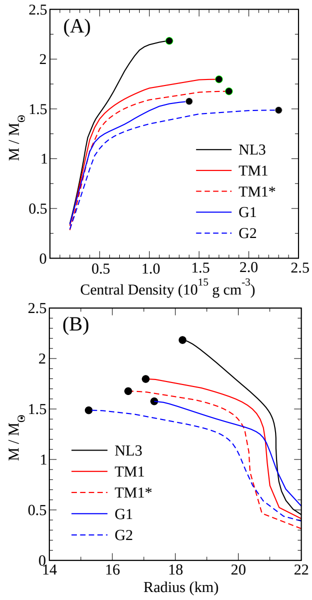

FIG. 1: For star rotating at kepler velocity (A): Mass of the neutron star sequence plotted as a function of the central density of the star. (B): Mass as a function of radius for the corresponding sequence. The filled circles denotes the values at maximum mass.

TABLE I: Comparison of the global properties of the neutron star in the static limit i.e., $\Omega = 0$ (upper row) and the stars rotating with kepler velocity ($\Omega = \Omega_k$) at maximum mass (lower row) for the corresponding EoS as tabulated. The maximum mass ($M/M_\odot$), the equitorial radius (R_{eq}), normalized central density ($\varepsilon/\varepsilon_0$), rotational frequency (f) and flattening parameter (R_p/R_e) are given respectively.

EoS	M ($M_\odot$)	R_{eq} (Km)	$\varepsilon_c/\varepsilon_0$	f (Hz)	R_p/R_e
NL3	1.79	13.20	4.64	–	–
	2.18	18.23	4.40	1095	0.56
TM1	1.51	12.36	6.17	–	–
	1.80	17.06	6.00	1100	0.58
TM1*	1.42	11.30	8.99	–	–
	1.68	16.50	6.59	1117	0.58
G1	1.33	12.45	5.06	–	–
	1.58	17.33	5.00	1009	0.59
G2	1.29	10.64	10.15	–	–
	1.48	15.25	8.42	1183	0.59

Rotating neutron stars not only can constrain the EoS of dense matter, but is also interesting because they can be the source of gravitational wave radiation, the mechanism which is believed to take away the star angular momentum thereby resulting in the slow down of the stars. We studied five different models from effective mean-field theory with different interactions and the nuclear saturation properties to analyze their effect on the equation of state of dense matter. We find that a soft EoS (one with lower value of incompressibility) results in star with small maximum mass, small radius, and large rotation rate and vice versa. We note an increase of $\approx$ (15-20)% in the maximum mass, with a corresponding $\approx$ (5-17)% decrease in the central density of the star rotating with kepler velocity. The models explain fast rotors with frequency $f > 1kHz$, which is in agreement with the fastest observed frequency of $f = 1122Hz$. However, it is rather interesting that the star seems to sustain faster rotations (an increase in rotational frequency up to $\approx$ 50%) without any further deformation. However all the models presently under consideration attains similar deformation in magnitude. The observation of millisecond pulsar would constrain the equation of state of matter at high densities, however, for various dynamical processes, such as the R-mode instability may prevent neutron stars from reaching such high spin rates. It would be interesting to study the aspects and effect of r-modes in regulating the spin of neutron stars within similar framework. Work is in progress in this direction.

References

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