Properties of rotating equilibrium sequences of compact stars

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Generally the behavior of matter in the interior of a neutron star is governed by the internal pressure, where all the neutrons obey the β-equilibrium condition with leptons and protons. An extended review of theoretical and observational aspects of neutron star, from the surface to the core, with the emphasis on their structure and equations of state can be found in Ref. [1]. Further it is well known that the integral parameter for a foolproof structure of neutron star depends on their equation of state from an ideal theory, which can explain the β-equilibrium condition at high density. At present, a wide spectrum of different EoS for neutron star matters has been designed from different interactions such as Skyrme [2], the Akmal-Pandharipande-Ravenhall [3] and the relativistic mean field theory (RMF) [4] (see, e.g., [1] for reviews and the references therein for details).

Within the present scenario of the neutron star (NS) formation, the first millisecond pulsar B1937 + 21 rotating at frequency 641 Hz [5], remained the most rapidly one for more than two decades. Later the discovery of pulsar J1748-2446ad and XTE J1739-285 with a faster rotating NS of frequency 716 Hz and 1122 Hz, respectively. In fact, the angular velocity distribution of a neutron star evolves to a uniform rotation within a very short time period in any supernova event. Moreover, the sub-kHz frequencies are still too low to significantly affects the structure of massive neutron stars [1]. However, for rapid rotation i.e. the sub-millisecond pulsar with super-kHz frequencies, the rotation

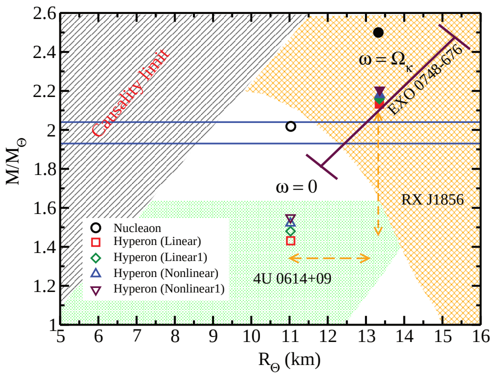

FIG. 1: (Color online) The obtained mass and radius trajectories of static and rotational compact stars are compared with the recent mass observational datas [12, 13] (the region between two solid horizontal blue line). See text for more details.

affects the massive neutron stars. For more extensive global collection of literature, see Friedman $ Stergioulas (2013) [6]. This present work will provide a relativistic mean field descriptions of the static and rotating (sub-millisecond to super-millisecond) compact star properties for various hyperon-meson couplings.

In the present study, we applied an effective field theory motivated relativistic mean field approach to the nuclear matter, where we investigated the influence of hyperon matter and the rotational profile on the properties of the compact star. It is to be noted that the model used for the study of the EoS of the hyper-nuclear is a chiral effective Lagrangian (E-RMF) [7], the extension of the standard relativistic mean field theory [8]. We have generated four EoSs for the hyper-nuclear matter under β-equilibrium conditions at high density

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using various hyperon-meson coupling ratios. The calculated maximum mass $M_\odot$ and the radius $R_\odot$ for the static nuclear and hyperon stars are obtained from the well-known TOV equations using the EoSs of E-RMF. The estimated results for the maximum mass and radius trajectory for the static and rotating compact star in Fig. 1. The dashed orange vertical and horizontal lines in the figure stands for the shift of mass and radius respectively due to the inclusion of rotational profile to the EoSs of compact star. Moreover, a gravitational redshift of 0.35 [9] observed from EXO 0748-676 is also shown in this figure. The mass-radius constraints from thermal radiation of isolated neutron star RX J1856 [10] (orange hatched area) and from QPOs in the LMXBs 4U 0614+09 [11] (blue hatched area) are given for constraining the EOSs of compact stars. Ensuing these recent observations [9–13], it is clearly illustrated that the maximum mass predicted by any theoretical models should reach or near the limit $\sim 2.0M_\odot$, which is consistent with our present prediction from the EoS of nucleonic matter compact star. But, the mass reduced somewhat by inclusion of hyperon matter to the EoSs under β-equilibrium conditions. In other words, the maximum mass obtained from nuclear matter EoS is reduced by ~ 0.4 unit due to presence of hyperon matter at high density. For example, the mass predicted from the nuclear and hyper-nuclear matter are $\sim 2.1M_\odot$ and $\sim 1.5M_\odot$, respectively from the TOV equation (see Figs. 1). Hence, one can easily contend that the predicted maximum mass from the hyperon matter EoSs is underestimated to the the recent mass observations [12, 13], which is the well known *Hyperon Puzzle*.

In continuation to the hyperon problem, we have included the rotational profile under axis-symmetric constant rotation with Keplerian frequency into account using rotational star equation, which increase the mass of the compact star by ~ 0.5 solar mass in magnitude as compared to the static case. In the figure, we have given the mass-shedding points (i.e. the maximum gravitational mass) for Keplerian frequency of compact stars with respect to axis-symmetric stationary rotation. From the figure, it is clear that the mass and the radius increases monotonically with the rotational frequency. Instability with respect to the mass-shedding from the equator implies that the gravitational mass and radius should be smaller than the maximum mass at Keplerian limit for a specific EoSs. Nevertheless, both features i.e. hypeon matter in the compact star and the rotation profile are of great practical importance and interest. In summary, the present study is very useful in the admiration of the expectation of static and stationary rotating hyper-nuclear compact stars at high density.

References

[1] S. L. Shapiro *et al.*, *Black holes, white dwarfs and neutron stars*. John Wilery and Sons, New York, (1983).

[2] J. R. Stone *et al.*, Phys. Rev. C **68**, 034324 (2003).

[3] A. Akmal *et al.*, Phys. Rev. C **58**, 1804 (1998).

[4] J. D. Walecka, *Theoretical Nuclear and Subnuclear Physics*, Imperial College and World Scientific, London and Singapore, (2004), ISBN 981-238-898-2.

[5] D. C. Backer *et al.*, Nature **300**, 615 (1982).

[6] J. L. Friedman and N. Stergioulas, *Rotating relativistic stars*, Cambridge University Press, United Kingdom (2013).

[7] R. J. Furnstahl, B. D. Serot and H. B. Tang, Nucl. Phys. A **598**, 539 (1996).

[8] B. D. Serot and J. D. Walecka, in *Advances in Nuclear Physics*, edited by J. W. Negele and Erich Vogt *Plenum Press, New York*, Vol. **16**, p. 1

[9] J. Cottam *et al.*, Nature (London) **420**, 51 (2002).

[10] T. Klahn et *al.*, Phys. Rev. C **74**, 035802 (2006).

[11] S. van Straaten *et al.*, Astrophys. J. **540**, 1049 (2000).

[12] P. B. Demorest *et al.*, Nature **467**, 1081 (2010).

[13] J. Antoniadis *et al.*, Science **340**, 6131 (2013).