Constraints on EOS from recently observed massive neutron stars

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The discovery of the massive neutron star PSR J1614-2230 [1]and PSR J0348+0432 [2] has raised new challenges for the theories of dense matter beyond nuclear saturation density. Shapiro delay measurements from radio timing observations of the binary millisecond pulsar indicate a large mass of $1.97 \pm 0.04 M_{\odot}$ of the neutron star [1]. The core of a neutron star may contain hyperons but according to existing models of dense matter, the presence of hyperons considerably soften the equation of state (EOS), resulting in reduction of masses of star [3, 4]. Most relativistic models which assumes hyperons in the core of a star obtain maximum neutron star masses in the range $1.4 - 1.8 M_{\odot}$ which are in conflict with the large pulsar masses. There are few models in literature which produces stars with maximum masses larger than $2M_{\odot}$ but those calculations are done assuming strong hyperon vector repulsion [5]. It is also calculated that both hadronic and hybrid stars can bear very high mass under the influence of strong magnetic field [6] In the present work we consider a representative set of 21 different EOSs with maximum gravitational mass $M^{\rm stat}_{\rm max}$ of non-rotating star varying from $1.63 M_{\odot}$ - $2.50 \mathrm{M}_{\odot}$ [7]. These EOSs are constructed using various theoretical models of nuclear dense matter which can broadly be divided into four subsets. The chemical composition of these EOSs are varying from the nucleons to hyperons, kaons, and quarks in β-equilibrium. The first subset of EOSs have been calculated by using variational potential approach involving neutrons, protons, electrons and muons in beta equilibrium, and there are only four EOSs in this group, BJ-C, WS, APR, and FPS. The BJ-C EOS is calculated from the variational potential which is same as that Reid potential, this from of potential is a sum of Yukawa functions, whose coefficients are adjusted in each partial wave to fit experimental nucleon-nucleon data. The dense nuclear matter of BJ-C EOS is composed of nucleons, electrons and various hyperons of mass, $\mathrm{M}_H \leq 1236$ MeV. The WS EOS has been obtained by using Urbana v_{14} (UV14) two-nucleon interaction with three-nucleon interactions model. The inclusion of three nucleon potential significantly stiffer the EOS than those with unmodified two-nucleon potential only. The APR EOS is calculated by employing the Hamiltonian consists of Argonne v_{18} two-nucleon interaction (AV18) and Urbana model IX (UIX) for three-nucleon interaction by including the relativistic boost corrections δv to the nucleon-nucleon scattering data. The AV18 potential provides excellent fit to all the nucleon-nucleon scattering data in the Nijmegen database. In the second subset we have considered EOSs composing with neutrons, protons, electrons, muons, hyperons and kaon condensed state based on relativistic or non-relativistic mean-field models. The EOSs GM1, SSK, GSK1, DH, TM1, G2, BSR7, and BSR15 are constructed in beta equilibrium within the framework of relativistic mean field approximation. Further EOSs GM1-H, TM1-H, and BSR7-H are soften by including the hyperons by using hyperon-meson and hyperon-hyperon in-

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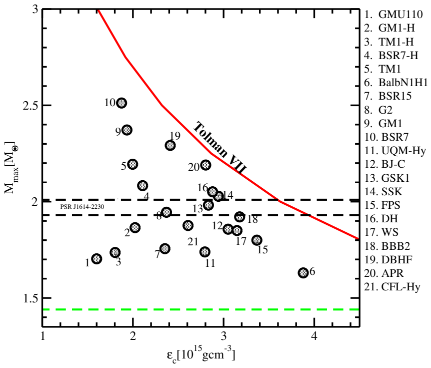

FIG. 1: The maximum gravitational mass of static Compact Star and central mass density for all 21 EOSs employed in the present calculations. The horizontal dashed line (green) for mass 1.44M$\odot$ of PSR 1913+16 and horizontal dashed black line for upper and lower limit of mass 1.97±0.04M$\odot$ of PSR J1614-2230 are showing the accurately measured mass constraints. For comparison the relationship of central energy density with maximum gravitational mass of Tolman VII solution, Eq. (6) in Ref.[9] for w = $\epsilon_s/\epsilon_c = 0.0$ is shown as solid curve (red).

teraction parameters as discussed in Ref.[8]. The GMU110 EOS has been soften at high density due to the phase transition of hadron matter to kaon condensed matter. The EOSs DH, GSK and SSk are constructed in beta equilibrium by using Skyrme Hartree Fock theory. The third subset of our EOSs are calculated by employing Brueckner-Hartree-Fock model EOS BBB2 and Dirac Brueckner-Hartree-Fock model EOS DBHF, both involving neutrons, protons, electrons and muons in its chemical composition in beta equilibrium.

In fourth subset of EOSs, we consider the hybrid EOSs consist of hadrons phase, mixed phase of hadrons and quarks matter and pure quarks matter. The hadrons phase of these EOSs have considered within Relativistic Mean Field approximation using BSR7 [8] parameterizations.

The maximum gravitational mass of static CS and central energy density ϵ_c is presented in Fig.1 for all 21 EOSs employed in the present calculations. The horizontal dashed line (green) for mass 1.44M$\odot$ of PSR 1913+16 and horizontal dashed black line for upper and lower limit of mass 1.97±0.04M$\odot$ of PSR J1614-2230 are showing the accurately measured mass constraints. For comparison the relationship of central energy density with maximum gravitational mass of Tolman VII solution, given in Eq. (6) in Ref.[9] for w = $\epsilon_s/\epsilon_c = 0.0$ is shown as solid curve (red). It can be seen from the figure that the maximum mass lies below Tolman VII envelope [9] which marks the upper limit to the energy density inside a star of indicated mass.
We find that the maximum gravitational mass of static limit CS ranges from 1.6M$_\odot$ - 2.5M$_\odot$ and their canonical radius $R_{1.4}$ varies from the 10 - 15 km, which is reasonably well within the available observational bounds for CS mass and radius $R_{1.4}$. The maximum mass for all the EOSs lies below Tolman VII envelope [9] which mark the upper limit to the maximum gravitational mass of CS in central energy density-CS mass plane. It is also found that only few EOS satisfied the constrain of PSR J1614-2230. Further none of the equation constituted with relativistic mean field model satisfied this condition. This result may vary on induction of strong magnetic field.

References

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

[2] J. Antoniadis and et al., Science **340**, 1233232 (2013).

[3] N. K. Glendenning, Phys. Rev. D **46**, 1274 (1992).

[4] M. Baldo, G. F. Burgio, and H. J. Schulze, Phys. Rev. C **61**, 055801 (2000).

[5] G. Mahajan and S. K. Dhiman, Phys.Rev.C **84**, 045804 (2011).

[6] R. H. Casali, L. B. Castro, and D. P. Menezes, Phys.Rev.C **89**, 015805 (2014).

[7] S. K. Dhiman, G. Mahajan, and B. K. Agrawal, Nucl. Phys. A **836**, 183 (2010).

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

[9] J. M. Lattimer and M. Prakash, Phys. Rev. L **94**, 111101 (2005).