Temperature and density dependence of asymmetric nuclear matter and protoneutron star properties within an extended relativistic mean field model

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Abstract

The effect of temperature and density dependence of the asymmetric nuclear matter properties is studied within the extended relativistic mean field (ERMF) model, which includes the contribution from the self and mixed interaction terms by using different parametrizations obtained by varying the neutron skin thickness $\Delta r$ and $\omega$-meson self-coupling ($\zeta$). We observed that the symmetry energy and its slope and incompressibility coefficients decrease with increasing temperatures up to saturation densities. The ERMF parametrizations were employed to obtain a new set of equations of state (EOS) of the protoneutron star (PNS) with and without inclusion of hyperons. In our calculations, in comparison with cold compact stars, we obtained that the gravitational mass of the protoneutron star with and without hyperons increased by $\sim 0.4M_\odot$ and its radius increased by $\sim 3$km. Whereas in case of the rotating PNS, the mass shedding limit decreased with increasing temperature, and this suggested that the keplerian frequency of the PNS, at $T = 10$ MeV should be smaller by $14 – 20\%$ for the EOS with hyperon, as compared to the keplerian frequency of a cold compact star.

PACS numbers: 26.60.+c, 91.60Fe, 97.10.Kc, 97.10.Nf

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I. INTRODUCTION

The behavior of nuclear matter at high density and finite temperature is one of the challenging problems in contemporary modern nuclear physics. Among the successful and widely used approaches to study nuclear matter are nonrelativistic mean field theory, with effective nucleon-nucleon interactions such as skyrme forces [1–3], and relativistic mean field (RMF) theory [4]. The RMF theory is more fundamental as it starts from hadronic field theory with strongly interacting baryons and mesons as degrees of freedom [5], and it describes very well the basic properties of nuclei near the valley of stability [6] and the properties of exotic nuclei with large numbers of neutrons or protons [7]. The properties of cold nuclear matter can be studied by imposing the constraints of bulk nuclear matter properties at the saturation density \( \rho_0 = 0.16 \text{fm}^{-3} \), recent experimental limits establish the following values: symmetry energy \( E_{\text{sym}} = 30 \pm 5 \text{MeV} \) [8, 9], slope of symmetry energy \( L = 88 \pm 25 \text{MeV} \) [10], and incompressibility coefficient \( K = 240 \pm 20 \text{MeV} \) [11–13]. It is considered theoretically that the density dependence of symmetry energy can be represented by \( E_{\text{sym}}(\rho_0) = 31.6(\rho/\rho_0)^\gamma \), with \( \gamma = 0.69-1.05 \) at subnormal density [10], which led to the extraction of a value for the slope of the nuclear symmetry of energy \( L = 88 \pm 25 \text{MeV} \). This symmetry energy value is also in harmony with the symmetry energy obtained from the isoscaling analysis of the isotope ratio in intermediate energy heavy ion collisions [14].

Recently, heavy-ion reactions induced in laboratories have provided the atmosphere necessary to produce hot neutron rich matter similar to that existing in astrophysical situations. The reactions especially, which are induced by radioactive beams, provide a unique means to investigate the isospin-dependent properties of asymmetric nuclear matter at Cooling Storage Ring (CSR) at the HIRFL in China, the Radioactive Ion Beam (RIB) at RIKEN in Japan, FAIR/GSI in Germany, SPIRAL2/GANIL in France, the Facility for Rare Isotope Beam (FRIB) in the United States. The heavy ion collision data from analyzing isospin diffusion and size of the neutron skin in \(^{208}\text{Pb}\) [4, 10] have helped us significantly in understanding symmetry energy. The symmetry energy of hot neutron rich matter in a low density regime [15] is important for understanding the liquid gas phase transition of asymmetric nuclear matter, the dynamical evolution of massive stars and the supernova explosion mechanism.

The density dependence of symmetry energy influences the nature and stability of the phases of compact star (CS), the feasibility of direct URCA cooling process within interior of CS, the composition and thickness of inner crust of CS, the frequency of its crustal vibrations and radius of CS.
Many correlations have been studied to understand the density behavior of symmetry energy \[16\]. However, the fundamental origin of this apparent evolution of symmetry energy is still not clear, and it is particularly important to understand to what degree its evolution depends on the density and/or temperature of nuclear matter. Apart from symmetry energy, the nuclear matter equation of state (EOS) also depend upon the values of incompressibility \[17\]. In recent times the giant monopole resonance has made it possible to find the value of incompressibility \[18\]. Accurate knowledge of the density and temperature dependence of symmetry energy and incompressibility can lead to plausible EOS of the asymmetric matter.

The properties of the compact stars are mainly determined by the EOS of nuclear dense matter, which is charge neutral matter in \(\beta\) equilibrium \[19\]. Any given EOS of baryonic matter determines uniquely the mass-radius relationship of a compact star and, in particular, the maximum mass a compact star can achieve before collapsing into a black hole \[20\]. Theoretical investigations of high-density \(\beta\) stable have lead to the conclusion that hyperons will appear at densities of about 2-4 times the saturation density \((\rho_0)\) and soften the EOS in high density regimes, as the conversion of nucleons to hyperons can relieve the fermi surface and leads to a reduction of compact star mass \[21, 22\]. For compact star matter with uniform distribution, the composition is determined by the requirement of charge neutrality and \(\beta\)-equilibrium conditions. The threshold density for a hyperon species is determined not only by its charge and mass but also by the meson fields. The stiffer the EOS without hyperons is, the greater is the softening effect when hyperons are included \[20, 23\]. Further the presence of hyperons should allow direct URCA like cooling involving the beta decay of the hyperons.

In this work we have extended our previous ERMF model \[24\] to study the effect of temperature on asymmetric nuclear matter and the properties of protoneutron stars (PNS). This paper is organized as follows. In Sec. II, we briefly describe the extended relativistic mean field theory. In Sec. III we present the results and discussion for nuclear matter properties and structure properties of non rotating PNS and rotating PNS with keplerian frequency. In Sec. IV we present our conclusions for the present work.

II. FORMALISM

The Lagrangian density for the ERMF model describes the interactions from self and mixed terms for the scalar-isoscalar \((\sigma)\), vector-isoscalar \((\omega)\), and vector-isovector \((\rho)\) mesons \[24, 25\].

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For completeness the Lagrangian density for the extended ERMF model can be written as,

\[ \mathcal{L} = \mathcal{L}_{BM} + \mathcal{L}_\sigma + \mathcal{L}_\omega + \mathcal{L}_\rho + \mathcal{L}_{\sigma\omega\rho}. \]  

(1)

The description of the various terms of the Lagrangian and the Euler-Lagrangian equations for ground state expectation values of the meson fields are provided in Ref. [24]. At finite temperatures the baryon vector density \( \rho_B \), scalar density \( \rho_{sB} \) and charge density \( \rho_p \) are, respectively,

\[ \rho_B = \langle \Psi_B \gamma^0 \Psi_B \rangle (n_i - \bar{n}_i) = \frac{\gamma}{(2\pi)^3} \int_0^{k_B} d^3k (n_i - \bar{n}_i), \]

(2)

\[ \rho_{sB} = \langle \Psi_B \Psi_B \rangle (n_i + \bar{n}_i) = \frac{\gamma}{(2\pi)^3} \int_0^{k_B} d^3k \frac{M_B^*}{\sqrt{k^2 + M_B^*}} (n_i + \bar{n}_i), \]

(3)

\[ \rho_p = \langle \Psi_B \gamma^0 \frac{1 + \tau_{3B}}{2} \Psi_B \rangle (n_i + \bar{n}_i). \]

(4)

Here, \( \gamma \) is the spin-isospin degeneracy. \( M_B^* = M_B - g_{\sigma B} \sigma - g_{\omega B} \omega \) is the effective mass of the baryon species \( B = (p, n, \Lambda, \Sigma^\pm, \Xi^\pm) \), \( k_B \) is its Fermi momentum and \( \tau_{3B} \) denotes the isospin projections of baryon \( B \).

The thermal distribution function in these expression are defined by

\[ n_i = \frac{1}{e^{\beta (\epsilon_i^* - v_i)} + 1} \quad \bar{n}_i = \frac{1}{e^{\beta (\epsilon_i^* + v_i)} + 1} \]

(5)

where

\[ \epsilon_i^* = \sqrt{k^2 + M_B^{*2}} \quad v_i = \mu - g_{\omega N} \omega \pm g_{\rho N} \rho \frac{\rho}{2} \quad (i = n, p) \]

are the effective energy and effective chemical potential respectively.

The energy density of the uniform matter in the ERMF models is given by

\[ \mathcal{E} = \sum_{j=p,n} \frac{1}{\pi^2} \int_0^{k_B} \epsilon_j^0 (k) k^2 dk (n_i + \bar{n}_i) + \sum_B g_{\omega B} \omega \rho_B + \sum_B g_{\rho B} \rho_B \tau_{3B} + \frac{1}{2} m_{\sigma}^2 \sigma^2 \]

\[ \frac{k}{6} g_{\sigma N}^3 \sigma^3 + \frac{1}{24} g_{\sigma N}^4 \sigma^4 - \frac{\xi}{24} g_{\omega N}^4 \omega^4 - \frac{\xi}{24} g_{\rho N}^4 \rho^4 - \frac{1}{2} m_{\omega}^2 \omega^2 - \frac{1}{2} m_{\rho}^2 \rho^2 \]

\[ - \frac{1}{2} \alpha_1 g_{\sigma N} g_{\omega N} \sigma \omega^2 - \frac{1}{2} \alpha_1 g_{\sigma N} g_{\omega N} \sigma \rho^2 - \frac{1}{2} \alpha_2 g_{\sigma N} g_{\rho N} \sigma \rho^2 - \frac{1}{2} \alpha_2 g_{\sigma N} g_{\rho N} \omega^2 \]

\[ - \frac{1}{2} \alpha_3 g_{\omega N} g_{\rho N} \rho^2 + \frac{1}{2} m_{\sigma}^2 \sigma^2 + \sum_B g_{\phi B} \phi \rho_B - \frac{1}{2} m_{\phi}^2 \phi^2. \]

(7)
The pressure of the uniform matter is given by

\[ P = \sum_{j=p,n} \frac{1}{3\pi^2} \int_0^{k_j} \frac{k^4 \, dk}{\sqrt{k^2 + M_j^2}} (n_j + \bar{n}_j) - \frac{1}{2} m_\sigma^2 \sigma^2 - \frac{\pi}{6} g_{\sigma N}^4 \sigma^3 - \frac{1}{24} g_{\sigma N}^4 \sigma^4 + \frac{\xi}{24} g_{\omega N}^4 \omega^4 + \frac{\xi}{24} g_{\rho N}^4 \rho^4 + \frac{1}{2} m_\omega^2 \omega^2 + \frac{1}{2} m_\rho^2 \rho^2 + \frac{\alpha_1}{2} g_{\sigma N}^2 g_{\omega N}^2 \omega \sigma^2 + \frac{1}{2} \alpha_2 g_{\sigma N}^2 g_{\rho N}^2 \sigma \rho^2 + \frac{1}{2} \alpha_3 g_{\omega N}^2 g_{\rho N}^2 \omega^2 \rho^2 - \frac{1}{2} m_\sigma \sigma^2 - \frac{1}{2} m_\omega \omega^2 - \frac{1}{2} m_\rho \rho^2. \]  

The symmetry energy \( E_{\text{sym}} \), the slope \( L \), and the incompressibility \( K \) can be evaluated as

\[
E_{\text{sym}}(\rho) = \frac{1}{2} \frac{d^2 E(\rho, \delta)}{d \delta^2} \bigg|_{\delta=0} \quad (9)
\]

\[
L = 3 \rho_0 \frac{d E_{\text{sym}}(\rho)}{d \rho} \bigg|_{\delta=\rho_0} \quad (10)
\]

\[
K = 9 \rho_0^2 \frac{d^2 E(\rho)}{d \rho^2} \bigg|_{\rho=\rho_0} \quad (11)
\]

where \( \rho_0 \) is the saturation density, \( E(\rho, \delta) \) is the energy per nucleons at a given density \( \rho \) and asymmetry parameter \( \delta = \left( \frac{n_p - n_n}{n_n + n_p} \right) \) and \( E_0(\rho) = E(\rho, \delta = 0) \) is the energy per nucleon for symmetric matter.

**III. RESULT AND DISCUSSIONS**

In the present work we have employed parametrization sets of the ERMF model, BSR1 - BSR21 [24, 26], generated by varying the \( \omega \) meson self-coupling \( \zeta \) and neutron skin thickness \( \Delta r \) for the \(^{208}\text{Pb} \) nucleus. These parametrizations have been obtained so as to reproduce the nuclear structure properties in finite nuclei and bulk properties of nuclear matter at nuclear saturation density [24]. The parametrization sets BSR1-BSR7 correspond to the value of \( \omega \) meson self-coupling \( \zeta = 0.0 \), sets BSR8-BSR14 correspond to \( \zeta = 0.03 \), and sets BSR15-BSR21 correspond to \( \zeta = 0.06 \), and for each parametrization set the value of neutron skin thickness of \(^{208}\text{Pb} \) varies from 0.16 to 0.28 fm in intervals of 0.02 fm. Further, the hyperon-meson coupling parameters are expressed in terms of the nucleon-meson coupling using the SU(6) model. The coupling parameters of \( \sigma \)-meson-hyperon and \( \omega \)-meson-hyperon are very sensitive to structural properties of compact stars, so these parameters have been fitted to the hyperon-nucleon potential depth the same as in Ref.
and its value $X_{\omega Y}$ varies from 0.5 to 0.8, where $X_{\omega Y}$ is defined as,

$$X_{\omega Y} = \begin{cases} \frac{g_{\omega Y}}{g_{\omega N}} & \text{for } \Lambda \text{ and } \Sigma \text{ hyperons} \\ 2 \left( \frac{g_{\omega Y}}{g_{\omega N}} \right) & \text{for } \Xi \text{ hyperons}, \end{cases}$$

(12)

where $g_{\omega Y}$ and $g_{\omega N}$ are the $\omega$-meson-hyperon and $\omega$-meson-nucleon coupling parameters.

### A. Nuclear Matter Properties

We study the properties of symmetric and asymmetric nuclear matter for different parametrizations of the ERMF model at temperatures of 0 to 30 MeV. In Table I we present the results for the bulk properties of nuclear matter at saturation density for the parameters BSR1, BSR7, BSR8, BSR14, BSR15, and BSR21 at temperatures $T = 0$, 10, 20, and 30 MeV. It is found that the bulk properties at saturation densities remain almost the same up to 20 MeV, but as temperature increases further these properties start varying significantly. The results for the saturation density ($\rho_0$), energy per nucleon ($E/A$), incompressibility coefficient for symmetric nuclear matter ($K$), symmetry energy ($E_{\text{sym}}(\rho_0)$), linear density dependence of symmetry energy slope ($L$) and effective nucleon mass ($M^*$) for the various parametrizations at saturation density are given in Table I. It can be seen from Table I that the nuclear matter properties at saturation density such as energy per nucleon, symmetry energy and value of its slope, and the effective mass of the nucleons get changed beyond $T \geq 20$ MeV by a very small amount with respect to $T = 0$ MeV for the all parametrizations of the ERMF model. However, the incompressibility coefficient for symmetric nuclear matter decreases up to a maximum of 12.5% at $T = 30$ MeV with respect to $T = 0$ MeV for the BSR1 parametrization, which provides the stiffest EOS with neutron star gravitational mass $M = 2.5M_\odot$ [24]. The variation in the values of $K$ is a minimum of 7% for the BSR21 parametrization, which provides the softest EOS with neutron star gravitational mass $M = 1.74M_\odot$ [24].

The nuclear symmetry energy is a fundamental input to understand the exotic nuclei, heavy ion collision data and many other astrophysical phenomena. Therefore recently many efforts have been made to extract the information on the magnitude and density dependence of symmetry energy of nuclear matter. In Fig. 1 we present the values of $E_{\text{sym}}(\rho_0)$ at saturation density as a function of $\Delta r$, the neutron skin thickness in the $^{208}Pb$ nucleus for various model parametrizations, the square represent the parametrizations BSR1-BSR7 with $\zeta = 0.00$, the triangles represent the parametrizations BSR8-BSR14 with $\zeta = 0.03$, and the circles represent the parametrizations BSR15-BSR21 with $\zeta = 0.06$. In Fig. 2 in the lower panel we present the slope of symmetry
energy and in the upper panel we present the incompressibility coefficient for nuclear matter as a function of $\Delta r$. In Figs. 1 and 2, the red symbols represent the results at $T = 0$ MeV and the blue symbols represent the results at $T = 30$ MeV. It is found that variation in the values of symmetry energy becomes reasonably large as the value of neutron skin thickness increases, where as the value for the slope of symmetry energy remains unaffected at temperature $T = 0$ and $30$ MeV. The value of incompressibility coefficient is sensitive to $\zeta$ and indicates the change at $T = 30$ MeV.

In Fig. 3 we compare the density dependence of the incompressibility coefficient at finite temperatures for various parametrizations with cold nuclear matter. It is found that the incompressibility coefficient at finite temperature has shown change below neutron saturation densities $\rho_0 = 0.15$ fm$^{-3}$ only, and $K$ gain maximum value in the range of densities of $\sim 0.4$ to $0.5$ fm$^{-3}$. The maximum value is very sensitive to $\zeta$, remains almost same on varying $\Delta r$, and decreases with increasing temperature. Further, we explore the effect of density on energy per nucleon ($E/A$) for symmetric nuclear matter and pure neutron matter at finite temperatures as shown in Fig. 4 computed by employing the BSR1, BSR7, BSR15, and BSR21 parametrizations. At the finite temperature the $E/A$ for symmetric nuclear matter decreases sharply as compared to the $E/A$ for pure neutron matter in the low density regime, and with the increase of $\zeta$ from 0.00 to 0.06, the $E/A$ of both symmetric nuclear matter and pure neutron matter decreases moderately. The value of $E/A$ remains almost unchanged for the variation in values of $\Delta r$ in $^{208}$Pb. In Fig. 5 we present the variation of $E/A$ as a function of density at the different values of the asymmetry parameter $\delta$ at $T = 0, 5, 10,$ and $20$ MeV for the BSR15 parametrization. The value of $E/A$ increases reasonably well with the increase in value of $\delta$. Fig. 5 shows that the $E/A$ changes in the higher density region due to the change in the asymmetry parameter $\delta$, whereas in the low density region $E/A$ varies with increases in temperature.

In Fig. 6 we present the variation of the equation of state of symmetric nuclear matter as a function of nuclear matter density at various temperatures for the BSR1, BSR7, BSR15, and BSR21 parametrization, in the very low density region. The pressure varies with temperatures at small values of densities and has negligible effect at higher densities. The variation in pressure for a given density depends mostly on the choice of parametrizations and temperature. The pressure become negative for BSR7 and BSR21 parametrizations with $\Delta r = 0.28$fm, in the low density regime ($\rho \leq 0.04$ fm$^{-3}$). In Fig. 7 the pressure of asymmetric nuclear matter is plotted as a function of density in the low density region for various values of the asymmetry parameter $\delta$. The solid line represents $T = 0$ MeV and the dashed line represent $T = 20$ MeV. The black line,
red line, green line, and blue line represent the BSR1, BSR7, BSR15, and BSR21 parametrization respectively. The EOS becomes stiff with the increase in the asymmetry parameter $\delta$ and trend continues till it becomes pure neutron matter.

We study the density dependence of symmetry energy, nuclear matter pressure density, and energy per nucleon at low density and the nuclear matter incompressibility coefficient as a function of density, with different RMF models. The comparison of the theoretical results for $E_{sym}$, $P$, $E/A$ and $K$ computed with BSR11 with NL3[27] and TM1[28] parametrizations of RMF theory at temperatures of 0 and 30 MeV as a function of density are presented in Fig. 8. The solid and dashed black lines represent the results of the BSR11 parametrization, the red lines represent the NL3 parametrization, and the blue lines represent the TM1 parametrization. The solid lines and dashed lines represent temperatures of 0 MeV and 30 MeV, respectively. It is found that the values of $E_{sym}$, $P$, $E/A$ and $K$ are very sensitive to temperatures at lower densities ($\sim 0 - 0.1 \text{fm}^{-3}$) and, are independent of temperature at higher densities. Further, we find a reasonable change in the behavior of symmetry energy for small values of $\Delta r$. However, the symmetry energy decreases at 30 MeV, and at very low density ($\sim 0.02 \text{fm}^{-3}$) for the value of $E_{sym}$ the trend reverses as shown in Fig. 8. It is noteworthy from Fig. 8 that, except for nuclear matter incompressibility computed with the NL3 parametrization, all other RMF parametrizations yield almost the same values of bulk properties.

B. Non Rotating PNS

We discuss the properties of protoneutron star composed of charge neutral nuclear matter at different temperatures. The fixed total baryon density is given as,

$$\rho = \sum_B \rho_B, \quad (13)$$

the charge neutrality condition is given as

$$\sum_B q_B \rho_B + \sum_L q_L \rho_L = 0, \quad (14)$$

and the chemical equilibrium conditions,

$$\mu_B = \mu_N - q_B \mu_e, \quad (15)$$

$$\mu_\mu = \mu_e \quad (16)$$
are satisfied. For density higher than 0.5\(\rho_0\) the baryonic part of the EOS is evaluated within the ERMF model, whereas the contributions of the electrons and muons to the EOS are evaluated within the Fermi gas approximation. At densities lower than 0.5\(\rho_0\) down to \(0.4 \times 10^{-10}\rho_0\) we use the EOS of Baym et al. [29]. The properties of nonrotating compact star are obtained by integrating the Tolman-Oppenheimer-Volkoff equations [30].

Fig. 9 shows the relative particle fraction calculated at different temperatures for the BSR15 parametrization as a function of density. At finite temperature, neutrons, protons, \(\Lambda\) hyperons, and electrons become abundant at baryon density lower than their particle threshold density in the cold nuclear matter, where as \(\Xi\) hyperons disappears even at \(T = 3\) MeV and the particle threshold densities of muons and \(\Sigma\) hyperons increase to 0.902 and 0.5\(fm^{-3}\), respectively, as compared with their threshold densities in cold nuclear matter. In our calculation, the threshold densities of hyperons in cold matter are as follows: for \(\Lambda\)-hyperons the threshold density is 0.376 \(fm^{-3}\), for \(\Sigma^-\) hyperons it is 0.482 \(fm^{-3}\) and for \(\Xi^-\) hyperons it is 0.490 \(fm^{-3}\), but at \(T = 10\) MeV the threshold density of \(\Lambda\) hyperons decreases to 0.112 \(fm^{-3}\), of \(\Sigma^-\) hyperons it increases to 0.902 \(fm^{-3}\) and for \(\Xi^-\) it disappears as shown in Fig. 9. We also observed the effect of temperature on relative particle fraction in compact stars without hyperons. It is found that with the increase in temperature the neutrons, protons and leptons become abundant at lower densities however, at higher densities for protons, electrons, and muons, the magnitude of the particle fraction slightly decreases. The pressure density is plotted as a function of baryon density by employing BSR1, BSR8 and BSR15 parametrizations as shown in Fig. 10. The dashed lines represent EOS with hyperons having hyperon-meson coupling parameter \(X_{\omega\gamma}=0.50\) and the solid lines represent EOS without hyperons at temperatures of \(T = 0, 3, 5,\) and 10\(MeV\). The EOS become sti at higher temperature with and without inclusion of hyperons and, subsequently, there is an increase in the gravitational mass of the CS.

In Fig. 11 we present the gravitational mass and radius relationship for the PNS. The dashed lines represent mass for EOS with hyperons at \(X_{\omega\gamma}=0.50\) and the solid lines represent mass for EOS without hyperons at temperatures of 0, 3, 5, and 10 MeV. The region excluded by causality (green solid line) and rotation constrains of compact star XTE J1739-285 (maroon solid line) are shown in the upper left panel. The mass and radius limit estimate from Vela pulsar glitches \(\Delta I/I=0.014\) is shown as the magenta solid line in the upper left panel. The recent mass measurement of the PSR J1614-2230 pulsar of 1.97\(\pm\)0.04 [31] is displayed in Fig. 11 as another constrain to the nuclear matter EOS, computed by our group in Ref.[24]. The EOS that contain exotic hadronic
matter of hyperons does not satisfy the mass constrain of the PSR J1614-2230 as shown in Fig. 11 and also as discussed similar in Ref. ?? that the model of EOS includes the appearance of hyperons or kaon condensates. However the EOS computed without hyperons for ζ = 0.00 and ζ = 0.03 satisfy the constraint of the PSR J1614-2230 pulsar mass measurement and the prediction of its radius 11-15 km, where ζ is the ω-meson self-coupling parameter, and mainly affects the high density behavior of the EOS and cannot be constrained by the structural properties of finite nuclei measurements and bulk properties of nuclear matter at saturation density. From the argument of Tolman VII solution of Einstein’s equations for the relationship between maximum gravitational mass and its upper limit on the central energy density, we get the value [32] of εc = 1.92 \times 10^{15} \text{gcm}^{-3} and 2.73\times 10^{15} \text{gcm}^{-3} for BSR1 and BSR15 parametrization respectively. The EOSs of warm dense nuclear matter becomes stiffer than the EOS of cold dense nuclear matter of the compact stars, even in the presence of exotic matter.

In Fig.12 the maximum gravitational mass of protoneutron star is plotted as a function of neutron skin thickness Δr in the 208Pb nucleus at temperature of 0, 3, 5, and 10 MeV. The color blue represents the mass computed with EOS without hyperons whereas red represents gravitational masses of EOS including hyperon, at Xωy = 0.50. Green and black represent masses of EOS with hyperon, the values of Xωy are equal to 0.60 and 0.70, respectively. The circles, triangles, and squares represent the values of maximum gravitational mass for the ω-meson self-coupling ζ = 0.0, 0.03 and 0.06, respectively. We varied the hyperon meson coupling parameter Xωy from 0.50 to 0.70 at all temperatures and found that on increasing the coupling parameter the maximum gravitational mass of the PNS increased. It is noticed that the increase in gravitational mass of the compact star is large at ζ=0.00 and reasonably small at ζ=0.06. Further, Fig.12 shows that the cold compact star with hyperons can have gravitational mass \( M \geq 2M_\odot \) if \( \zeta = 0.00 \) and \( X_{\omega y} \geq 0.70 \), whereas the protoneutron star with hyperons can have mass \( M \geq 2M_\odot \) if the chosen parameters are \( \zeta = 0.00 \) or 0.03 and \( X_{\omega y} \geq 0.50 \), and the compact star satisfies the constraint of the mass measurement of the PSR J1614-2230 pulsar [31].

In Tables II-IV we have presented the key structural properties of compact stars at finite temperature; properties such as maximum gravitational mass, radius at maximum gravitational mass, radius for star with canonical mass (1.4M_\odot), and gravitational redshift of the photon Z_{surf} emitted from the compact star surface for a star with maximum mass and canonical mass using BSR1-BSR21 parametrizations at temperatures of 0, 3, 5, and 10 MeV without and with the inclusion of hyperons for \( X_{\omega y} = 0.50 \) only. It is observed from the Tables II-IV that with an increase in the value
of the $\zeta$ parameter the mass of the compact star decreases, whereas with a rise in temperature the mass of the compact star increases. Further with increasing $\Delta r$ the mass increases for all temperatures. It is also observed that when the temperature changes from 0 to 3 MeV there is an increase in the mass of the compact star by $\sim 0.2$ to $0.4M_\odot$, but on further increasing temperature $T \geq 5$ MeV this increase in mass of compact star becomes very small. Also the increase in the radius at maximum mass and canonical mass ($M_{\text{max}}$ and $M_{1.4}$) with temperature is $\sim 1.5 - 2$ km initially but becomes smaller with further increase in temperature. The radius also increased on increasing $\Delta r$ for all temperatures but decreased with increase in the value of the $\zeta$ parameter. The results for gravitational redshift of the photon $Z_{\text{surf}}$ emitted from the surface of the compact star, can be computed as:

$$Z_{\text{surf}} = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2} - 1,$$

(17)

where $R$ is the radius and $M$ is the gravitational mass of the compact star. It is clear from Tables II-IV that, with an increase in the $\zeta$ or $\Delta r$ parameter, the gravitational redshift $Z_{\text{surf}}$ and $Z_{1.4}$ decrease, whereas with an increase in temperature $Z_{\text{surf}}$ and $Z_{1.4}$ decrease further. It is observed that the inclusion of hyperons in PNS decreases the magnitude of the mass, the radius and the gravitational redshift for all RMF parametrizations. In comparison with cold compact star, we obtained that the gravitational mass of the PNS with and without hyperons increases by $\sim 0.4M_\odot$, its radius increases by $\sim 3$km, and the radius $R_{1.4}$ at the canonical mass of the computed data increases by 3-6km, whereas the value of the gravitational red shift at finite temperature decreases approximately 0.03-0.07.

C. Rotating PNS

The keplerian configurations of rapidly rotating PNS have been computed in the framework of general relativity by solving the Einstein field equations for stationary axisymmetric space time (e.g., see Ref.[33] and references therein). The numerical calculations have been performed by employing the rotating neutron star (RNS) code [34]. In Fig.13 the mass shedding limit (Kepler) is plotted for EOS obtained by using the BSR1, BSR8, and BSR15 parametrizations at 0, 5, and 10 MeV in terms of gravitational mass $M$ as a function of central energy density $\epsilon_c$. The upper panel contains EOS without hyperons, whereas the lower panel contain EOS with hyperons at $X_{\omega y} = 0.50$. Keplerian configurations terminate at the central energy density where equilibrium solutions are stable with respect to the small axisymmetric perturbations; the slanting dotted (blue) line
corresponds to the axisymmetric instability limit. In the Kepler limit sequences, the gravitational maximum mass of the PNS increase with increases in temperature by 20% – 23% and its corresponding equitorial radius increases by 25% – 46%, with respect to its non rotating gravitational maximum mass and radius, respectively. These observations are reasonably well within the predictions provided in Refs. [33, 35] and are slightly higher in the case of the PNS with hyperons. Compared with the cold nuclear matter compact star, the Keplerian angular velocity of the PNS decreases by 5% – 8% in the case of the PNS without hyperons, and it is 14% – 20% for the PNS with hyperons.

IV. CONCLUSION

The effect of temperature and density dependence of the asymmetric nuclear matter properties is studied within the ERMF model which includes the contribution from the self and mixed interaction terms by using different parametrizations obtained by varying the neutron skin thickness Δr and the ω-meson self coupling (ζ). We studied the bulk properties of cold and warm nuclear dense matter at finite temperature, and compared the structural properties of non rotating and rotating cold compact stars with PNS, constructed within ERMF model.

We observed that the changes in bulk properties at saturation densities are negligible till a temperature of 20 MeV but as temperatures increase further these properties start varying significantly. It is found that variation in the values of symmetry energy becomes reasonably large as the value of the neutron skin thickness increases, where as the value for the slope of symmetry energy remains unaffected at T = 0 and 30 MeV. The value of the incompressibility coefficient is sensitive to ζ and indicates the change at T = 30 MeV. the energy per nucleon for symmetric nuclear matter decreases sharply as compared to the energy for pure neutron matter at very low densities, and upon increasing the ζ the decrease becomes moderate whereas upon increasing Δr the value remains almost the same. It is observed that with the increase in the asymmetry parameter δ, the EOS become stiff and the trend continues until it becomes pure neutron matter. It is found that the temperature dependence of the symmetry energy is more sensitive to the small values of Δr. Although the symmetry energy decreases with increases in temperature, at very low density (∼ 0.02 fm⁻³) the trend reverses.

In our calculations at finite temperature, neutrons, protons, Λ hyperons, and electrons become abundant at baryon density lower than their particle threshold density in the cold nuclear matter,
where as $\Xi$ hyperons disappears even at $T = 3$ MeV. The EOS of warm dense nuclear matter becomes stiffer than the EOS of the cold dense nuclear matter of the compact stars, even if we include the exotic matter. We varied the hyperon meson coupling parameter $X_{\omega\Xi}$ from 0.50 to 0.70 at all temperatures and found that on increasing the coupling parameter the maximum gravitational mass of the star increased and this increase was large for the smaller values of $\zeta$ and small for the larger values of $\zeta$. Values of all the properties such as mass, radius, and gravitational redshift decreased upon inclusion of hyperons for all the parametrizations. We obtained that the gravitational mass of the PNS with and without hyperons increased by $\sim 0.4M_\odot$ and its radius increased by $\sim 3$km, and the radius $R_{1,4}$ at the canonical mass of the computed data increased by 3-6 km, where as the value of the gravitational red shift at finite temperature decreased approximately 0.03-0.07. In the Kepler limit sequences, the gravitational maximum mass of PNS increase with increase in temperature by 20$\%$ – 23$\%$ and its corresponding equitorial radius increased by 25$\%$ – 46$\%$, with respect to its non rotating gravitational maximum mass and radius, respectively. The Keplerian angular velocity of PNS without hyperons decreased by 5$\%$- 8$\%$ and it decreased by 14$\%$-20$\%$ for PNS with hyperons, in comparison to the cold CS without and with hyperons, respectively.
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FIG. 1: (Color online) The symmetry energy $E_{\text{sym}}(\rho_0)$ plotted as a function of the neutron skin thickness $\Delta r$ in the $^{208}\text{Pb}$ nucleus for 21 different parametrizations of the ERMF model. The squares, triangles and circles represent results for the parametrizations BSR1-BSR7, BSR8-BSR14 and BSR15-BSR21 respectively. The red symbols represent the results at $T = 0$ MeV and the blue symbols represent the results at $T = 30$ MeV.
TABLE I: The bulk properties of the nuclear matter at the saturation density ($\rho_0$) for the different temperatures, saturation density ($\rho_0$), energy per nucleon (E/A), incompressibility coefficient for symmetric nuclear matter (K), symmetry energy ($E_{sym}(\rho_0)$), linear density dependence of symmetry energy (L) and effective nucleon mass/nucleon mass ($M^*_N/M_N$)

| Force | $\zeta$ | $\Delta r$ | T | $\rho_0$ | E/A | K | $E_{sym}(\rho_0)$ | L | $M^*_N/M_N$ |
|-------|--------|-----------|---|--------|-----|---|-----------------|---|-------------|
|       | (fm)   | (MeV)     | (fm$^{-3}$) | (MeV) | (MeV) | (MeV) | (MeV) | (MeV) | (MeV) |
| BSR1  | 0.00   | 0.16      | 0 | 0.1481 | -16.0192 | 240.0477 | 30.9841 | 59.6144 | 0.6052 |
|       |        |           | 10 | 0.1481 | -16.0192 | 240.0477 | 30.9841 | 59.6144 | 0.6052 |
|       |        |           | 20 | 0.1481 | -16.0194 | 239.7282 | 30.9838 | 59.6240 | 0.6052 |
|       |        |           | 30 | 0.1464 | -16.0483 | 211.0066 | 30.7468 | 59.3789 | 0.6088 |
| BSR7  | 0.00   | 0.28      | 0 | 0.1493 | -16.1753 | 231.8574 | 36.9894 | 98.7838 | 0.6014 |
|       |        |           | 10 | 0.1493 | -16.1753 | 231.8574 | 36.9894 | 98.7838 | 0.6014 |
|       |        |           | 20 | 0.1493 | -16.1755 | 231.5692 | 36.9890 | 98.7972 | 0.6014 |
|       |        |           | 30 | 0.1478 | -16.2010 | 204.8214 | 36.6289 | 98.4333 | 0.6048 |
| BSR8  | 0.03   | 0.16      | 0 | 0.1469 | -16.0351 | 230.8656 | 31.0094 | 60.3747 | 0.6059 |
|       |        |           | 10 | 0.1469 | -16.0351 | 230.8656 | 31.0094 | 60.3747 | 0.6059 |
|       |        |           | 20 | 0.1469 | -16.0353 | 230.5972 | 31.0092 | 60.3831 | 0.6059 |
|       |        |           | 30 | 0.1455 | -16.0643 | 207.6021 | 30.8013 | 60.2005 | 0.6087 |
| BSR14 | 0.03   | 0.28      | 0 | 0.1474 | -16.1838 | 235.4955 | 36.0527 | 93.4748 | 0.6078 |
|       |        |           | 10 | 0.1474 | -16.1838 | 235.4955 | 36.0527 | 93.4748 | 0.6078 |
|       |        |           | 20 | 0.1474 | -16.1840 | 235.2218 | 36.0523 | 93.4878 | 0.6078 |
|       |        |           | 30 | 0.1459 | -16.2150 | 212.2077 | 35.7080 | 93.2011 | 0.6106 |
| BSR15 | 0.06   | 0.16      | 0 | 0.1456 | -16.0320 | 226.9275 | 30.9177 | 61.8943 | 0.6075 |
|       |        |           | 10 | 0.1456 | -16.0320 | 226.9275 | 30.9177 | 61.8943 | 0.6075 |
|       |        |           | 20 | 0.1455 | -16.0322 | 226.4806 | 30.9002 | 61.8556 | 0.6077 |
|       |        |           | 30 | 0.1442 | -16.0621 | 209.2170 | 30.7094 | 61.7048 | 0.6098 |
| BSR21 | 0.06   | 0.28      | 0 | 0.1452 | -16.1235 | 220.4414 | 35.7123 | 92.5457 | 0.6017 |
|       |        |           | 10 | 0.1452 | -16.1235 | 220.4414 | 35.7123 | 92.5457 | 0.6017 |
|       |        |           | 20 | 0.1451 | -16.1236 | 220.0422 | 35.6861 | 92.4886 | 0.6019 |
|       |        |           | 30 | 0.1441 | -16.1486 | 205.8949 | 35.4542 | 92.3135 | 0.6036 |
TABLE II: The values of maximum gravitational mass $M_{\text{max}}$, radius $R_{\text{max}}$, radius $R_{1.4}$ corresponding to canonical mass $1.4M_\odot$, and the gravitational redshift of the photon emitted from the surface of the compact star at maximum mass $Z_{\text{max}}$ and at canonical mass $Z_{1.4}$ for different values of the neutron skin thickness $\Delta r$ at different temperatures for the $\omega$-meson self-coupling $\zeta = 0.0$ with and without hyperons. The hyperon meson coupling is $X_{\omega y} = 0.50$.

| Force  | $\Delta r$ | T      | $M_{\text{max}}$ | $R_{\text{max}}$ | $R_{1.4}$ | $Z_{\text{max}}$ | $Z_{1.4}$ | $M_{\text{max}}$ | $R_{\text{max}}$ | $R_{1.4}$ | $Z_{\text{max}}$ | $Z_{1.4}$ |
|--------|------------|--------|------------------|------------------|---------|------------------|---------|------------------|------------------|---------|------------------|---------|
|        | (fm)      | (MeV)  |                  |                  |         |                  |         |                  |                  |         |                  |         |
|        |           |        | without hyperons | with hyperons    |         |                  |         |                  |                  |         |                  |         |
| BSR1   | 0.16      | 0      | 2.43             | 11.74            | 12.37   | 0.61             | 0.23    | 1.81             | 11.87            | 13.64   | 0.35             | 0.20    |
|        |           | 3      | 2.65             | 13.11            | 14.12   | 0.58             | 0.19    | 2.14             | 12.53            | 14.49   | 0.42             | 0.18    |
|        |           | 5      | 2.66             | 13.21            | 14.49   | 0.57             | 0.18    | 2.16             | 12.82            | 14.89   | 0.42             | 0.18    |
|        |           | 10     | 2.78             | 14.61            | 18.82   | 0.51             | 0.13    | 2.28             | 14.81            | 19.30   | 0.35             | 0.13    |
| BSR3   | 0.20      | 0      | 2.33             | 11.79            | 13.48   | 0.55             | 0.20    | 1.73             | 11.65            | 13.60   | 0.33             | 0.20    |
|        |           | 3      | 2.59             | 13.43            | 15.62   | 0.52             | 0.17    | 2.13             | 13.16            | 16.03   | 0.38             | 0.16    |
|        |           | 5      | 2.59             | 13.46            | 15.72   | 0.52             | 0.16    | 2.14             | 13.25            | 16.16   | 0.38             | 0.16    |
|        |           | 10     | 2.65             | 14.11            | 17.06   | 0.50             | 0.15    | 2.23             | 14.30            | 17.56   | 0.36             | 0.14    |
| BSR5   | 0.24      | 0      | 2.45             | 12.11            | 13.75   | 0.58             | 0.20    | 1.82             | 11.80            | 13.88   | 0.35             | 0.19    |
|        |           | 3      | 2.73             | 13.83            | 16.00   | 0.55             | 0.16    | 2.15             | 13.26            | 16.19   | 0.39             | 0.16    |
|        |           | 5      | 2.73             | 13.84            | 16.08   | 0.55             | 0.16    | 2.16             | 13.33            | 16.29   | 0.38             | 0.16    |
|        |           | 10     | 2.78             | 14.30            | 17.22   | 0.53             | 0.15    | 2.23             | 14.30            | 17.56   | 0.36             | 0.14    |
| BSR7   | 0.28      | 0      | 2.47             | 12.23            | 14.00   | 0.58             | 0.19    | 1.81             | 11.91            | 14.13   | 0.35             | 0.19    |
|        |           | 3      | 2.80             | 14.29            | 16.57   | 0.54             | 0.15    | 2.19             | 13.71            | 16.69   | 0.38             | 0.15    |
|        |           | 5      | 2.80             | 14.30            | 16.62   | 0.54             | 0.15    | 2.19             | 13.78            | 16.77   | 0.37             | 0.15    |
|        |           | 10     | 2.83             | 14.60            | 17.47   | 0.53             | 0.14    | 2.26             | 14.59            | 17.77   | 0.37             | 0.14    |
TABLE III: Same as Table II but with ω-meson self-coupling ζ = 0.03.

| Force | Δr | T | $M_{\text{max}}$ | $R_{\text{max}}$ | $R_{1.4}$ | $Z_{\text{max}}$ | $Z_{1.4}$ | $M_{\text{max}}$ | $R_{\text{max}}$ | $R_{1.4}$ | $Z_{\text{max}}$ | $Z_{1.4}$ |
|-------|----|---|-----------------|-----------------|----------|-----------------|----------|-----------------|-----------------|----------|-----------------|----------|
|       | (fm) | (MeV) | ($M_\odot$) | (km) | (km) | ($M_\odot$) | (km) | ($M_\odot$) | (km) | (km) |
| BSR8  | 0.16 | 0  | 1.94 | 11.43 | 13.08 | 0.42 | 0.21 | 1.54 | 11.82 | 13.14 | 0.28 | 0.21 |
|       |     | 3  | 2.18 | 12.99 | 15.07 | 0.41 | 0.17 | 1.84 | 12.92 | 15.50 | 0.31 | 0.17 |
|       |     | 5  | 2.19 | 13.05 | 15.21 | 0.41 | 0.17 | 1.85 | 13.07 | 15.68 | 0.31 | 0.17 |
|       |     | 10 | 2.28 | 13.96 | 16.78 | 0.39 | 0.15 | 1.96 | 14.39 | 17.24 | 0.30 | 0.15 |
| BSR10 | 0.20 | 0  | 1.94 | 11.46 | 13.19 | 0.41 | 0.21 | 1.54 | 11.80 | 13.24 | 0.28 | 0.21 |
|       |     | 3  | 2.21 | 13.20 | 15.43 | 0.41 | 0.17 | 1.85 | 13.04 | 15.72 | 0.31 | 0.17 |
|       |     | 5  | 2.21 | 13.24 | 15.53 | 0.41 | 0.17 | 1.86 | 13.16 | 15.86 | 0.31 | 0.16 |
|       |     | 10 | 2.27 | 13.91 | 16.86 | 0.39 | 0.15 | 1.96 | 14.31 | 17.32 | 0.30 | 0.15 |
| BSR12 | 0.24 | 0  | 1.95 | 11.49 | 13.29 | 0.42 | 0.21 | 1.54 | 11.84 | 13.33 | 0.27 | 0.20 |
|       |     | 3  | 2.25 | 13.43 | 15.73 | 0.41 | 0.16 | 1.87 | 13.23 | 15.92 | 0.31 | 0.16 |
|       |     | 5  | 2.25 | 13.45 | 15.80 | 0.41 | 0.16 | 1.88 | 13.31 | 16.03 | 0.31 | 0.16 |
|       |     | 10 | 2.29 | 14.00 | 16.94 | 0.39 | 0.15 | 1.95 | 14.30 | 17.35 | 0.29 | 0.15 |
| BSR14 | 0.28 | 0  | 1.94 | 11.54 | 13.51 | 0.41 | 0.20 | 1.54 | 11.89 | 13.53 | 0.27 | 0.20 |
|       |     | 3  | 2.30 | 13.82 | 16.20 | 0.40 | 0.16 | 1.89 | 13.45 | 16.21 | 0.31 | 0.16 |
|       |     | 5  | 2.30 | 13.84 | 16.25 | 0.40 | 0.16 | 1.89 | 13.48 | 16.29 | 0.31 | 0.16 |
|       |     | 10 | 2.32 | 14.25 | 17.15 | 0.39 | 0.15 | 1.95 | 14.36 | 17.44 | 0.29 | 0.15 |
TABLE IV: Same as Table II but with $\omega$-meson self-coupling $\zeta = 0.06$.

| Force | $\Delta r$ | $T$ | $M_{max}$ | $R_{max}$ | $R_{1.4}$ | $Z_{max}$ | $Z_{1.4}$ | $M_{max}$ | $R_{max}$ | $R_{1.4}$ | $Z_{max}$ | $Z_{1.4}$ |
|-------|------------|----|------------|------------|-----------|------------|------------|------------|------------|-----------|------------|------------|
|       | (fm) | (MeV) | ($M_\odot$) | (km) | (km) | ($M_\odot$) | (km) | (km) | ($M_\odot$) | (km) | (km) |
| BSR15 | 0.16 | 0   | 1.73       | 10.92     | 12.62     | 0.37       | 0.22       | 1.41       | 11.52     | 12.15     | 0.25       | 0.23       |
|       |      | 3   | 1.97       | 12.53     | 14.73     | 0.37       | 0.18       | 1.67       | 12.14     | 14.64     | 0.30       | 0.18       |
|       |      | 5   | 1.97       | 12.60     | 14.86     | 0.36       | 0.18       | 1.68       | 12.31     | 14.85     | 0.30       | 0.18       |
|       |      | 10  | 2.03       | 13.41     | 16.36     | 0.35       | 0.16       | 1.76       | 13.54     | 16.64     | 0.27       | 0.15       |
| BSR17 | 0.20 | 0   | 1.73       | 10.93     | 12.66     | 0.37       | 0.22       | 1.41       | 11.49     | 12.09     | 0.25       | 0.23       |
|       |      | 3   | 1.99       | 12.66     | 14.95     | 0.37       | 0.18       | 1.69       | 12.33     | 14.88     | 0.30       | 0.18       |
|       |      | 5   | 1.99       | 12.70     | 15.04     | 0.36       | 0.17       | 1.69       | 12.44     | 15.03     | 0.29       | 0.17       |
|       |      | 10  | 2.04       | 13.38     | 16.40     | 0.35       | 0.16       | 1.76       | 13.56     | 16.71     | 0.27       | 0.15       |
| BSR19 | 0.24 | 0   | 1.73       | 11.01     | 12.83     | 0.37       | 0.22       | 1.41       | 11.56     | 12.24     | 0.25       | 0.23       |
|       |      | 3   | 2.03       | 12.99     | 15.41     | 0.36       | 0.17       | 1.71       | 12.61     | 15.26     | 0.29       | 0.17       |
|       |      | 5   | 2.03       | 13.04     | 15.48     | 0.36       | 0.17       | 1.71       | 12.69     | 15.38     | 0.29       | 0.17       |
|       |      | 10  | 2.06       | 13.56     | 16.62     | 0.35       | 0.15       | 1.77       | 13.73     | 16.90     | 0.27       | 0.15       |
| BSR21 | 0.28 | 0   | 1.75       | 11.17     | 13.13     | 0.36       | 0.21       | 1.43       | 11.69     | 12.68     | 0.25       | 0.22       |
|       |      | 3   | 2.09       | 13.49     | 15.97     | 0.36       | 0.16       | 1.75       | 12.96     | 15.77     | 0.29       | 0.16       |
|       |      | 5   | 2.09       | 13.51     | 16.02     | 0.36       | 0.16       | 1.75       | 13.02     | 15.84     | 0.29       | 0.16       |
|       |      | 10  | 2.12       | 13.91     | 16.92     | 0.35       | 0.15       | 1.80       | 13.88     | 17.11     | 0.27       | 0.15       |
FIG. 2: (Color online) Same as Fig. 1, but for the slope of the symmetry energy (L) and incompressibility coefficient (K) of nuclear matter.
FIG. 3: (Color online) The density dependence of the incompressibility coefficient is plotted at temperatures of 0, 10, 20, and 30 MeV for various parametrizations.
FIG. 4: (Color online) The variation in energy per nucleon (E/A) for symmetric nuclear matter (solid lines) and for pure neutron matter (dashed lines) calculated with the BSR1, BSR7, BSR15, and BSR21 parametrizations is plotted as a function of density at temperatures of 0, 5, 10, and 20 MeV.
FIG. 5: (Color online) The variation in energy per nucleon (E/A) for asymmetric nuclear matter at temperatures of 0, 5, 10, and 20 MeV with various values of $\delta$ calculated with the BSR15 parametrization.
FIG. 6: (Color online) The pressure for symmetric nuclear matter for the BSR1, BSR7, BSR15, and BSR21 parametrizations is plotted as a function of density at temperatures of 0, 5, 10, and 20 MeV.
FIG. 7: (Color online) The pressure of asymmetric nuclear matter plotted as a function of density in low density regions for various values of the asymmetry parameter $\delta$. The solid line represents $T = 0$ MeV and the dashed line represents $T = 20$ MeV. The black line, red line, green line, and blue line represent the BSR1, BSR7, BSR15, and BSR21 parametrizations respectively.
FIG. 8: (Color online) The comparison of the theoretical results for symmetry energy ($E_{\text{sym}}$), the incompressibility coefficient ($K$), pressure ($P$) and energy per nucleon ($E/A$) computed with the BSR11, NL3, [27] and TM1 [28] parametrizations of relativistic mean field theory at temperatures of 0 and 30 MeV as a function of density. The black lines represent the results of the BSR11 parametrization, the red lines represent the NL3 parametrization, and the blue lines represent the TM1 parametrization. The solid lines and the dashed lines represent temperatures of 0 and 30 MeV, respectively.
FIG. 9: (Color online) Relative particle fraction as a function of baryon density of the compact stars obtained for the BSR15 parametrization with the hyperon meson coupling parameter $X_{\omega\gamma} = 0.50$ at different temperatures.
FIG. 10: (Color online) The pressure density is plotted as a function of density employing using the BSR1, BSR8, and BSR15 parametrizations. The dashed lines represent EOS with hyperons having the hyperon-meson coupling parameter $X_{\omega \gamma} = 0.50$ and solid lines represent EOS without hyperons at temperatures of 0, 3, 5, and 10 MeV.
FIG. 11: (Color online) The mass and radius relationship of protoneutron stars. The dashed lines represent mass for EOS with hyperons having the hyperon-meson coupling parameter $X_{\omega\pi} = 0.50$, and the solid lines represent mass for EOS without hyperons at temperatures of 0, 3, 5, and 10 MeV. The colors blue, red, and black represent the BSR1, BSR8 and BSR15 parametrizations respectively. The recent mass measurement of the PSR J1614-2230 pulsar is also displayed.
FIG. 12: (Color online) The maximum gravitational mass of protoneutron star is plotted as function of neutron skin thickness ($\Delta r$) in the $^{208}\text{Pb}$ nucleus at temperatures of 0, 3, 5, and 10 MeV. The color blue represents the masses of EOS without hyperons whereas the color red represents masses of EOS having hyperons with hyperon-meson coupling parameter $X_{\omega y} = 0.50$. The colors green and black represent masses of EOS having hyperons with $X_{\omega y}$ 0.60 and 0.70, respectively. The circles, triangles, and squares represent the values of maximum gravitational mass for the $\omega$-meson self-coupling $\zeta = 0.0$, 0.03, and 0.06, respectively.
FIG. 13: (Color online) The mass shedding limit (Kepler) is plotted for EOS obtained using BSR1, BSR8, and BSR15 parametrizations at temperatures of 0, 5, and 10 MeV in terms of gravitational mass $M$ as a function of central energy density $\epsilon_c$. The upper panels contain EOS without hyperons, whereas the lower panels contain EOS with hyperons having the hyperon-meson coupling parameter $X_{\omega y} = 0.50$. The slanting dotted (blue) line corresponds to the axisymmetric instability limit.