Slowly rotating neutron stars and hadronic stars in chiral SU(3) quark mean field model

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Abstract

The equations of state for neutron matter, strange and non-strange hadronic matter in a chiral SU(3) quark mean field model are applied in the study of slowly rotating neutron stars and hadronic stars. The radius, mass, moment of inertia, and other physical quantities are carefully examined. The effect of nucleon crust for the strange hadronic star is exhibited. Our results show the rotation can increase the maximum mass of compact stars significantly. For big enough mass of pulsar which can not be explained as strange hadronic star, the theoretical approaches to increase the maximum mass are addressed.

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1. INTRODUCTION

Stars are not only the focus of astronomers but also perfect laboratories for theoretical physicists, since extreme stars can supply conditions hard to be realized in earth-based laboratories. The neutron star was one of the most active actors on the stage of astronomy and physics since 1960s, when the first pulsar was observed [1], and is still attracting more concentration. Many different aspects of neutron stars have been examined, such as the moment of inertia [2, 3], the early stage of proto-neutron star [4], the thermodynamic structure [5], etc. However, because of the lack of the knowledge on the details of the matter at high density, the true equation of state (EoS) in such extreme object is still unclear. Great effort to determine the EoS of compact stars at extremely high density have been made by many authors, either by the theoretical calculation [6–8] or by observational constraint [9–11]. At first, considering the extremely heavy mass and strong pressure, people regarded the pulsars as rotating neutron stars for a long time. However, after the pioneer work of Witten [12] that the strange quark matter is comparatively more stable than the normal nucleus, the strange quark star [13–16] have attracted much attention (for a comprehensive review, see Ref. [17]). Up to now, there is still no evidence strong enough to confirm the existence of strange quark star. The question is still open and need more careful study.

In fact, the neutron star and the strange quark star are just very simple categories, and the real components in the star should be much more complicated. It is generally believed that the \( \beta \)-equilibrium can be achieved in the process of neutron-star formation and the hyperons will exist in neutron star. The consideration of hyperons in the EoS of compact star was back to as early as 1960 [18] and got serious discussion in many later references [7, 19–21]. The existence of hyperons can affect the EoS and consequently the mass-radius (\( M-R \)) relation remarkably.

In this paper, we will concentrate on a chiral SU(3) quark mean field model [22, 23], which has been applied successfully to the study of nuclear matter, strange hadronic matter, nuclei and hypernuclei. In this model, quarks are confined within baryons and interact with mesons. The self-interaction of mesons is based on the SU(3) chiral symmetry. This model has been employed by Ref. [24] to discuss the properties of static (non-)strange hadronic stars and neutron stars in \( \beta \)-equilibrium. However, the resulting maximum mass of the strange hadronic star is only 1.45\( M_{\odot} \), which is incapable to explain the existence of some massive stars, such as the recently confirmed data of PSR J1903+0327 with \( M = 1.67 \pm 0.01 M_{\odot} \) [25]. However, we notice that the study in Ref. [24] limited to the static case. But in fact, rotation is a very general property of almost all stellar bodies, for example, PSR J1903+0327 has a very short rotating period 2.15ms. This
motivates us to extend the discussions of Ref. [24] to rotating cases and examine the rotation effect on the maximum mass. In this paper we will utilize Hartle’s method [26] to study the slowly rotating neutron star and hadronic star with the EoS given by Ref. [24]. We will also compare the $M$-$R$ relation and other properties with those of the strange quark star obtained by the quark mass density- and temperature-dependent (QMDTD) model in Ref. [16].

The organization of this paper is as follows. In the next section, we will show the frame of Hartle’s method applied in our calculation. In Sec. III, we will take the strange hadronic EoS of the chiral SU(3) quark mean field model to study the slowly rotating strange hadronic star. The effect of rotation on the maximum mass and moment of inertia will be discussed in detail. In Sec. IV, we will briefly show the numerical results of the non-strange hadronic and neutron star. Together with the results of the strange hadronic star in Sec. III and the strange quark star in Ref. [16], all these results for different stars will be compared. The last section is for summary and discussion.

II. THEORETICAL FORMALISM FOR SLOWLY ROTATING STAR

First we will present the formalism of Hartle’s method on the slowly rotating star. This method treats the slow rotation as a small perturbation to the non-rotating structure. In static frame, the metric of a non-rotating, spherically symmetric star is given by

$$ds^2 = -e^\nu(r) dt^2 + e^\lambda(r) dr^2 + r^2 (d\theta^2 + \sin^2 \theta d\phi^2),$$  

(1)

where $e^{\lambda(r)} = \left(1 - \frac{2m(r)}{r}\right)^{-1}$, $m(r) = \int_0^r 4\pi r'^2 \rho(r') dr'$. In hydrostatic equilibrium, the coefficients $\lambda$ and $\nu$ are governed by the TOV equations:

\begin{align*}
\frac{d\nu(r)}{dr} &= -\frac{2}{\rho(r) + P(r)} \frac{dP(r)}{dr}, \\
\frac{dP(r)}{dr} &= -\frac{[P(r) + \rho(r)][m(r) + 4\pi r^3 P(r)]}{r^2 \left[1 - \frac{2m(r)}{r}\right]},
\end{align*}

(2)

(3)

where $P(r)$ and $\rho(r)$ are the pressure and the energy density of the matter at radius $r$, respectively. The surface of the star $r = R$ is defined by $P(R) = 0$ and the stellar mass is $M = m(R)$. Outside the star, the metric is simply of the Schwarzschild form, $e^{\nu(r)} = 1 - \frac{2M}{r}$, so the inner and outer solution must connect at the surface of the star. These equations can be solved numerically by integrating outward from $r = 0$ with a given center pressure $P(0) = P_c$ till the surface where $P = 0$ is reached, then the main structure of a non-rotating star is obtained.
Now we move ahead to the slowly rotating star with angular velocity $\Omega(r, \theta)$. The metric is not static and isotropic any longer, and the crossing term $g_{t\theta}$ in the metric emerges. We will now apply Hartle’s method. Since this method had been shown in detail in Ref. [26], hereafter we only write down the essential steps which are necessary in our numerical calculation. Following Hartle’s expression, noticing $\Omega$ is very small, the metric can be expanded up to the second order of $\Omega$:

$$ds^2 = -e^{\nu(r)}[1 + 2h(r, \theta)]dt^2 + e^{\lambda(r)} \left[ 1 + \frac{2\tilde{m}(r, \theta)}{r - 2m} \right] dr^2$$

$$+ r^2[1 + 2k(r, \theta)][d\theta^2 + \sin^2 \theta(d\phi - \omega(r, \theta)dt)^2] + O(\Omega^3),$$

where $h$, $\tilde{m}$ and $k$ are corrections to the non-rotating metric of order $\Omega^2$, and $\omega(r, \theta)$ is linear order of $\Omega$ in the $g_{t\theta}$ component, which physically stands for the angular velocity of the local inertial frame. Define $\varpi(r, \theta) = \Omega(r, \theta) - \omega(r, \theta)$, the angular dependence can be studied by the vector spherical harmonics expansion [27]. However, for the uniform rotating case $\Omega(r, \theta) = \Omega$, one can find that $\varpi$ is a function of $r$ alone as required by the boundary condition, so the equation obeyed by $\varpi$ is then simply [26]

$$\frac{1}{r^4} \frac{d}{dr} \left[ r^4 j(r) \frac{d\varpi(r)}{dr} \right] + \frac{4}{r} \frac{dj(r)}{dr} \varpi(r) = 0,$$

where $j(r) = e^{-\nu(r) + \lambda(r)}/2$. The boundary condition at $r = 0$ is $d\varpi/dr = 0$, while outside the star, $j(r) \equiv 1$ and the solution is

$$\varpi(r) = \frac{2J}{r^3},$$

where $J$ is the total angular momentum of the star. The moment of inertia is given by

$$I = \frac{J}{\Omega}.$$ 

Besides the metric, the pressure is also affected by the rotation, which is denoted by a dimensionless parameter $p^*$:

$$p^* = \Delta P/(P + \rho).$$ 

The metric perturbation terms as well as $p^*$ can be expanded in spherical harmonics:

$$h(r, \theta) = h_0(r) + h_2P_2(\theta) + \cdots,$$

$$\tilde{m}(r, \theta) = \tilde{m}_0(r) + \tilde{m}_2P_2(\theta) + \cdots,$$

$$k(r, \theta) = k_0(r) + k_2P_2(\theta) + \cdots,$$

$$p^*(r, \theta) = p^*_0(r) + p^*_2(r)P_2(\theta) + \cdots,$$
where the odd terms automatically vanish because of the symmetry. The field equation together with the TOV equations yields the equations for the \( l = 0 \) correction terms:

\[
\frac{d\tilde{m}_0}{dr} = 4\pi r^2 p_0^*(\rho + P) \frac{d\rho}{dP} + \frac{1}{12} j^2 r^4 \left( \frac{d\varpi}{dr} \right)^2 - \frac{1}{3} r^3 \frac{dj^2}{dr} \varpi^2,
\]

\[
\frac{dp_0^*}{dr} = \frac{1}{12} \frac{r^4 j^2}{r - 2m} \left( \frac{d\varpi}{dr} \right)^2 + \frac{1}{3} \frac{d}{dr} \left( \frac{r^3 j^2 \varpi^2}{r - 2m} \right) - \frac{4\pi (\rho + P) r^2}{r - 2m} p_0^* - \frac{\tilde{m}_0 (1 + 8\pi r^2 P)}{(r - 2m)^2},
\]

where the boundary conditions are \( p_0^*(0) = \tilde{m}(0) = 0 \). Given a center rotating velocity \( \varpi(0) = \varpi_c \), the above formalism is enough to determine the changes on the stellar mass \( \delta M \) and the mean radius \( \delta R \),

\[
\delta M = \tilde{m}_0(R) + \frac{J^2}{R^3},
\]

\[
\delta R = -p_0^*(R)\frac{\rho(R)}{dP(R)} dr.
\]

Higher order terms of the metric corrections are related to the configuration distortion away from an exact spheroid, which is neglected in our study. Under the linear approximation, we can use the relation \( \varpi_c' = \varpi_c \frac{\Omega'}{\Omega} \) to obtain the desired value of \( \varpi_c' \) at the center from any initial value \( \varpi_c \), where \( \Omega' \) and \( \Omega \) are the corresponding angular velocities.

Finally we have to mention the so-called Kepler limit. With the increasing frequency, the tangent velocity of the matter on the stellar surface is also increasing. It is the gravitational force which keeps the matter from escaping. However, when the angular velocity is beyond a critical value, the gravitational attraction becomes insufficient to balance the centrifugal force, and the star becomes dynamically unstable. This onset is the Kepler limit given by the empirical formula

\[
\Omega_K(M) \approx C(M/M_{\text{sun}})^{1/2} (R/10\text{km})^{-3/2},
\]

where \( R \) corresponds to the radius of a non-rotating star with mass \( M \), and \( C = 1.04\text{kHz} \) is a constant independent of the EoS \[28\]. When the rotating frequency approaches the Kepler limit, the stellar equator coincides with the innermost rotating orbit and the surface mass will shed away. Therefore we should always restrict our reasonable results within the Kepler limit.

### III. NUMERICAL RESULTS OF STRANGE HADRONIC STAR

With Hartle’s formalism, we can calculate the physical properties such as the mass, radius and angular momentum of a slowly rotating star with any given EoS. In this section we apply the EoS of strange hadronic matter from the chiral SU(3) quark mean field model \[24\] to examine the properties of slowly rotating strange hadronic star.
Before heading on to the numerical results, we should say a few words about the EoS at lower density. It is commonly believed that the neutron stars or quark stars are enveloped by a nucleon crust at the surface, where the density and pressure are much lower than in the center. The nucleon crust is supposed to be responsible for the glitch of the rotating frequency \[29–31\], and it can also affect the stellar radius significantly. To examine the property of the crust explicitly in the rotating hadronic star, we will compare the results of the strange hadronic star with and without the crust. The crust EoS from different models are generally similar to each other. In order to compare the rotating results with those of the non-rotating case given by Ref.\[24\], for \(\rho_B < 0.1\text{fm}^{-3}\), we still use the same nuclear EoS as that of Ref.\[24\], namely, the EoS first given by Ref.\[32\], though many other good EoS for nuclear matter existed \[6, 33\]. At \(\rho_B > 0.1\text{fm}^{-3}\), the EoS of strange hadronic matter shown in Fig.4 of Ref.\[24\] will be used.

In Fig.1 we show the \(M-R\) curves of crusted strange hadronic stars at different angular velocities. The curve turning over the peak value of \(M\) is kept with only a very short segment, since it is well known that the star becomes unstable at this segment. As can be clearly seen, when the rotation is imposed, the mass and radius are increased significantly. The faster the star rotates, the heavier and larger it can be. The round dot on each curve denotes the minimum stable mass at the corresponding angular velocity, which is obtained by the criterion of the Kepler limit following Eq.(17). Hereafter we will always use such round dots to denote the minimum stable mass on each curve, the segment with mass lower than the dot is unstable because of the violation on the Kepler limit. We also see from Fig.1 that the increase in the radius of the maximum mass at \(\Omega = 5000\text{rad/s}\) from the non-rotating case is about 3.55% only, so the shape deformation is indeed small. This confirms that our application of Hartle’s method is self-consistent. In fact, as was demonstrated by Weber and Glendenning \[34\], Hartle’s method is applicable to stars with the rotation period up to 0.5ms, or in our language \(\Omega = 12566\text{rad/s}\), which is much larger than the fastest rotation speed observed yet.

To illustrate the effect of the crust clearly, we also plot the corresponding results without crust in Fig.2 where the EoS of the chiral SU(3) model is still used when \(\rho_B < 0.1\text{fm}^{-3}\). It is clearly shown that the shape of the \(M-R\) curve is dramatically changed. For a large range of \(M\) about \(0.1 \sim 1.2M_{\odot}\), the \(M-R\) curves have different direction compared to the case with the crust in Fig.1. When the crust of lower density is considered, the radius of the star can be quite large when \(M\) is small, to which the outer crust contributes the most.

Another important property about the crust is its moment of inertia, which is commonly used to explain the glitch of the rotating frequency. The glitch is a sudden change of the angular frequency,
FIG. 1: The $M$-$R$ relation of strange hadronic star with crust at different angular velocities, where the round dots denote the minimum stable mass as required by the Kepler instability.

which can be considered as the transfer of the angular momentum between the crust and inner part of the star. The recent observation requires that the crust must contain at least 1.4% of the total moment of inertia [9]. Now we calculate the ratio of the moment of inertia of the crust to that of the whole strange hadronic star. Since the moment of inertia can be calculated by

$$I = \frac{1}{\Omega} \int T^{0}_{3} \sqrt{-g} dV,$$

in our first order spherical approximation, it can be expressed as

$$I \approx \frac{3\pi}{8} \int_{0}^{R} e^{-\nu(r)/2} r^{4} \left[\left(\rho(r) + p(r)\right) \frac{\left[\Omega - \omega(r)\right]}{\Omega}\right] dr.$$

The crust portion can be easily calculated by substituting the lower limit of the integration from 0 to $R_{\text{crust}}$, which is determined by $\rho_{B}(R_{\text{crust}}) = 0.1\text{fm}^{-3}$. In Fig. we show the crust portion of the moment of inertia in the total star at different rotation speeds. We see that the crust contributes about 3.5% to the total moment of inertia at maximum mass, and this portion is larger at smaller mass. So the requirement of Ref. [9] is well satisfied.

The most important thing we are interested in is the influence of the angular velocity on the maximum mass, which is shown in Fig. where the curve of minimum stable radii vs. the angular velocity is also plotted. The minimum stable radius corresponding to the maximum mass can be
FIG. 2: The same as Fig. 1 but the crust is not considered.

FIG. 3: The crust portion of the moment of inertia as a function of stellar mass at different rotation speeds.

found directly from the $M$-$R$ curve. We find that the minimum stable radius increases with $\Omega$. The dots denote the Kepler limit $\Omega = 6454\text{rad/s}$ obtained from the formula in Eq. (17). It is the maximum rotation speed corresponding to the maximum mass of the non-rotating $M$-$R$ curve. As can be seen from the $M$-$R$ curves in Fig. 1 since the $M$-$R$ curve of rotating star is higher than the
FIG. 4: The maximum mass and the minimum stable radius of strange hadronic star vs. the angular velocity.

non-rotating case, the maximum mass on the $M-R$ curve with such maximum rotation speed does not lie on the boundary of Kepler limit, so this maximum mass can exist safely and lies far from the onset of dynamical instability.

Besides the $M-R$ curve, the $I-M$ curve is also very important because it contains information about the inner property of compact stars. We show the $I-M$ relation at different angular velocities in Fig.5.

IV. COMPARISON BETWEEN DIFFERENT STARS

In previous section we have shown the numerical results of the slowly rotating strange hadronic star in detail. Similarly, we can discuss the properties of the rotating non-strange hadronic star and neutron star. Here “non-strange” means that no hyperon is considered in the EoS, while “neutron” means only the neutron is considered. These EoS are also given in Fig.4 of Ref.24, while the nucleon crust will always be considered from now on. The $M-R$ curves for the non-strange hadronic star and the neutron star are shown in Fig.6 and the $I-M$ curves in Fig.7, respectively. All the Kepler limit points are dotted as in Sec.III. We see from these figures that the qualitative behavior is the same as the strange hadronic star. The masses and moments of inertia in these two cases are larger than the strange hadronic star, and the neutron star has the largest $M$ and $I$ among these three types. Another remarkable property shown in Figs.6 and 7 is that the curves
FIG. 5: The moment of inertia $I$ vs. stellar mass $M$ of strange hadronic star at different angular velocities.

FIG. 6: The $M$-$R$ curves of the non-strange hadronic star and the neutron star at different rotation speeds.

of the same type are closer at bigger mass, while at smaller mass the curves of the same angular velocity are closer. This means that the rotational effect dominates in the lighter star with smaller central pressure.

With all these results, now we can make some comparisons between different stars. They are
the strange hadronic star, non-strange hadronic star and the neutron star obtained by the chiral SU(3) quark mean field model, as well as the strange quark star from the QMDTD model, whose properties are carefully studied in Ref. [16].

A very important consistency check is that these stars have similar behavior according to the effect of the rotation. This is quite reasonable since the dynamical properties of a compact star are qualitatively similar. The centrifugal force from the rotation counteracting the gravitation can help the star bearing more mass and extending to larger radius. The details of these properties have been discussed clearly in Sec. III.

One significant distinctness of the strange quark star is that its $M$-$R$ curve has different direction from the other three types at small $M$, as was shown in Fig.2 of Ref. [16]. The reason is that the crust is not considered in Ref. [16], so similar behavior is observed in our Fig. 2. When the star is very small, the crust thickness becomes important, which will change the shape of the $M$-$R$ curve significantly. Generally, the nucleon crust can increase the radius by about 1km but has very little influence on the maximum mass. One difference between Fig.2 of Ref. [16] and our Fig. 2 is that the radius approaches to zero with decreasing $M$ for the bare strange quark star, while it finally goes very large in our results of bare strange hadronic star. This difference can be understood when we pay attention to their EoS as the pressure approaching zero. In the QMDTD model, the energy density at zero pressure is finite, because of the confinement mechanism, so the pressure vanishes.
much faster than the strange hadronic matter. This property reduces the ability of such strange quark star to support a dilute outer layer as in strange hadronic star.

Different EoS can quantitatively change the mass and radius of a star. The $M-R$ curves of these stars show that, at the same condition, the strange quark star has the smallest radius, which is not changed by about 1km increase from the crust; while the neutron star has the largest radius and mass. The non-strange hadronic star has larger mass and radius than its strange relative. The maximum mass of strange quark star is a little smaller than that of the non-strange hadronic star. For example, at $\Omega = 0$, the neutron star has $M_{\text{max}} = 1.8M_{\odot}$, for the non-strange hadronic star $M_{\text{max}} = 1.7M_{\odot}$, and the strange hadronic star has $M_{\text{max}} = 1.45M_{\odot}$, while the strange quark star has approximately $M_{\text{max}} = 1.7M_{\odot}$. These values are directly related to the EoS of different matter. In general, this property will not change: the steeper the $P-\rho$ curve is, the larger mass the corresponding star will have. The rotation cannot change the order of the physical quantities of these types of stars, either. To make this point clearer, we show the $M_{\text{max}}$ curves as functions of $\Omega$ for different stars together in Fig.8. Similarly, the $R_{\text{min}}$ curves are shown together in Fig.9, where we see that the minimum stellar radius of neutron star is distinctly larger than the other two types.

FIG. 8: The curves of the maximum mass as functions of the angular velocity for the three types of stars.
FIG. 9: The curves of the minimum stable radius as functions of the angular velocity for the three types of stars.

V. SUMMARY AND DISCUSSIONS

In summary, employing the EoS of the chiral SU(3) quark mean field model and Hartle’s method, we have studied the rotation effect on different properties of the strange hadronic star, non-strange hadronic star and neutron star. The most important effect of the rotation is that it can increase the maximum mass, which is listed clearly in Table I where $\Omega_{\text{max}}$ is given by Eq.(17) according to the maximum mass of static star. We see that the range of the mass is significantly enlarged when the rotation is considered. However, the maximum mass of the strange hadronic star is still not large enough to explain the mass of PSR J1903+0327. As can be seen from Fig.8, the point representing the mass and the angular velocity of PSR J1903+0327 lies well below the $M_{\text{max}}$ curves of the non-strange hadronic star and the neutron star but far above the curve of the strange hadronic star. So in the chiral SU(3) quark mean field model this star can not be explained as a strange hadronic star even the rotation effect is considered.

We can easily understand the low mass of the strange hadronic star if we notice that its EoS is very soft. For other mean field hadronic model with hyperons, for example, Refs. [35, 36], the resulting maximum mass $M_{\text{max}} = 1.52M_{\odot}$ for the strange hadronic star and $M_{\text{max}} = 1.84M_{\odot}$ for the neutron star [35] at the static case are just a little larger than those we presented here. Their results still confirm PSR J1903+0327 is not a strange hadronic star, the same as our model.
| Type of Star | Strangeness Hadronic Star | Non-Strangeness Hadronic Star | Neutron Star |
|-------------|--------------------------|-------------------------------|--------------|
| Non-Rotating $M_{\text{max}}$ | $1.45M_{\odot}$ | $1.7M_{\odot}$ | $1.8M_{\odot}$ |
| $M_{\text{max}}$ at $\Omega_{\text{max}}$ | $1.586M_{\odot}$ | $1.877M_{\odot}$ | $1.978M_{\odot}$ |
| $\Omega_{\text{max}}$ | $6454\text{rad/s}$ | $7039\text{rad/s}$ | $6968\text{rad/s}$ |

If we want to increase the $M_{\text{max}}$ of strange hadronic stars, the nonuniform rotation can be considered. As was pointed out in Ref. [37], the uniform rotation can just increase the maximum stellar mass by about 20% at most. Extend the discussion from uniform rotation to differential rotation, the upper limit of the stellar mass will increase remarkably [38–40]. Another possibility is to modify the soft EoS of strange hadronic matter, for example, the mixing phase of hadronic matter and quark matter. It has been proven that the EoS can be significantly steepened and the maximum mass be elevated when the mixing phase is considered [41, 42]. In such case the deconfined quark becomes important and the interior part of the star might be made of quark matter, that is the so-called hybrid star [43–45]. It was shown that the hybrid star with a 2-flavor color-superconducting quark core can support very heavy star [46]. Another interesting question is about the possibility of the “quarkyonic matter” phase [47, 48]. It is of interest to see the influence of such phase on the $M$-$R$ relation if they can be attained in the core of the compact star. However the discussion is beyond the chiral SU(3) mean field model we considered in this paper, because this model cannot provide the deconfinement mechanism.

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