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Constraint on Properties of Rapidly Rotating Neutron Stars from Nuclear Symmetry Energy Slope

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Abstract: During the past decade, theoretical researches and terrestrial nuclear laboratory experiments have made impressive progresses on the researches of symmetry energy of the asymmetric nuclear matters, which is very important in understanding the equation of states and the structures of neutron stars. In this work, by making use of a conservative symmetry energy slope (SES) range (25 MeV $< L <$ 115 MeV), the constraints from the SES on the structures and properties of static and rapid rotating neutron stars are investigated. The constraint properties include the mass-radius relations, the moments of inertia, the redshift, the deformations of the rapid rotating stars, *etc.* According to the conservative SES range, it is shown that the radius of a canonical neutron star (with $M = 1.4M_{\odot}$) can be constrained in a region of $10.28 \sim 13.43$ km, which is consistent with one of the latest constraints on the radius of neutron star in observations. It is also shown that if a sub-millisecond pulsar with a lighter stellar mass is observed in the future, then a softer SES of the asymmetric nuclear matters is preferred. The universal property of the angular momentum provides a way to obtain the upper limit of the moment of inertia of a rapid rotating neutron star with observed mass. Moreover, the results also can provide a constraint on the lower mass limit ($> 1.5M_{\odot}$) of pulsar in low-mass X-ray binary EXO0748-676 if the observed redshift of this star is from the polar direction.

Key words: symmetry energy; neutron star; rotation

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1 Introduction

The density dependent symmetry energy is one of the hot research topics during the past decade, as the symmetry energy is very important both in nuclear physics and astrophysics[1–5]. In nuclear physics, the symmetry energy is essential to understand the structure of the radioactive nuclei, the liquid-gas phase transition in asymmetric nuclear matters, *etc.* In astrophysics, the symmetry energy is the key character to understand the equation of state (EOS) of the asymmetric dense nuclear matters, and thus to comprehend the structure and property of the compact stars, such as the neutron stars. At present, the EOS of the symmetric dense matters (the content of protons and neutrons is equivalent) is understood very well[6], but the EOS of the asymmetric dense matters (the neutron-rich dense matter such as the matter in the core of the neutron stars), especially at the super high densities, is very poorly known, which is essential because of the uncertainties of the density dependent symmetry energy[3–5, 7]. In fact, the theoretical predictions of the symmetry energy at several times of the saturation nuclear densities are rather diverse and unfortunately there is no known first-principle guiding us to close the divarication [3–5, 7–11]. It is gratifying to see that there are still many impressive progresses have been made in understanding the symmetry energy in both theories and experiments during the past decade [2, 5–21].

The first-order coefficient of the Taylor expansion for the symmetry energy at saturated nuclear density is defined as the symmetry energy slope (SES)[5], which provides the dominant baryonic contribution to the pressure around the saturated nuclear density in neutron stars and thus affects the properties of neutron stars, such as the inner crusts and the radii of the neutron stars. In fact, most of the recent effort in constraining the symmetry energy has focused on re-

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ducing the uncertainty of SES [2, 7, 20–22, 24–26]. The SES can be constrained by the nuclear reactions and the nuclear structures. During the last decade, too many efforts have been made to constrain the SES of the asymmetric nuclear matters [2, 7, 21–51].

On the other hand, observations have shown that the neutron stars have rapid spin frequencies and some of them have spin frequencies at an order of their Keplerian frequencies[52–53]. As we know, the Keplerian frequency sets a definite upper limit of the stellar spin frequency and beyond which the matters at equator will be thrown away. In fact, the rapid spin frequency is one of the important dynamical factor to determine the structure and global property of neutron star, such as the mass-radius relation, the redshift, the moment of inertia, the deformation, the gravitational radiation and so on[54–63]. Obviously, above mentioned properties should be investigated in the frame work of general relativity. Generally, these quantities should be the solutions of the Einstein field equations for the static axisymmetric gravitational field, coupled to the equation of hydrostatic equilibrium and the equation of state of the dense matters. Moreover, we only can solve these quantities numerically. In fact, the numerically calculating models for dealing with the rotating neutron stars have been constructed during the past decades by several groups[54–60], among which the scheme of Hartle and Thorne[54–55] is an approximate method to study the slowly rotating neutron star and the others are accurate schemes to deal with the rapidly rotating neutron stars. Based on the rapidly rotating models constructed by Refs. [58–60], one efficacious code RNS was developed and made available to the public by Stergioulas and Friedman[60]. In this work, we will employ the RNS code to calculate the properties of the rapidly rotating neutron stars.

It has been found thirteen years ago that there is a strong correlation between the pressure near the nuclear saturation density and the radius of the neutron star while the stellar radius is not sensitive to the stellar mass[4, 64]. As we know, the mass of the neutron star in binary system can be determined very precisely by the observations nowadays, while the measurement of the radius of neutron star is very hard because of its small figure and the far distance. But many of the properties such as the redshift, the moment of inertia, are related both of the mass and radius of neutron star. Therefore, it is very important to constrain the radius by other methods. As has mentioned above, the SES is the key parameter to determine the EOS of the asymmetric dense matters around the saturation density, and thus is the key parameter to determine the radius of the neutron stars, so it is very interesting to investigate the constraint from the SES, which could/has been constrained by the terrestrial nuclear experiments, on the properties of the rapid rotating neutron stars. By the way, it is worth noting that although the SES at saturation density has a strong correlate with the neutron star radius, it is not the unique important factor in determining the neutron star radius[65–66] In this work, we will use a conservative range of the SES to explore the structures and properties of the rapidly rotating neutron stars, such as the mass-radius relations, the moments of inertia, the redshift, the deformations, *etc.* This paper is organized as follows. After the Introduction, we recall the formalism used to calculate the structure of static and rotating relativistic stars in Sec. 2. The SES and the EOSs are reviewed in Sec. 3. The numerical results and discusses are presented in Sec. 4, Followed by the conclusion in Sec. 5.

2 The equilibrium structure of static and rotating relativistic stars

In the following section, the static and rotating neutron star's equilibrium structure equations deduced in the framework of general relativity are briefly reviewed.

For the static neutron stars, its metric can be described as

$$-\mathrm{d}s^2 = -\mathrm{e}^{2\Phi}\mathrm{d}t^2 + e^{2\Lambda}\mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2) \ , \quad (1)$$

where Φ, Λ are the functions of radius r only.

The energy-momentum tensor of the neutron star matters can be expressed as follows by treating the matters as perfect fluid

$$T^{\alpha\beta} = pg^{\alpha\beta} + (p+\rho)u^\alpha u^\beta \ , \quad (2)$$

where $\alpha, \beta = 0, 1, 2, 3$, and u^α is the four-velocity satisfying $u^\alpha u_\alpha = -1$.

Then according to the Einstein field equation, we can obtain the equilibrium structure equations of static compact stars, namely, the familiar TOV equation[67–68]

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{(p+\rho)[m(r)+4\pi r^3 p]}{r[r-2m(r)]} \ , \quad (3)$$

and

$$\frac{m(r)}{\mathrm{d}r} = 4\pi r^2\rho \ . \quad (4)$$

Providing the EOS and the proper boundary conditions, the structure of a static neutron star can be numerically calculated.

To deal with the rapidly rotating neutron star, the following assumptions are proposed[54]: (1) the matter can be described as a perfect fluid; (2) the matter distribution and the spacetime are in a stationary state and axisymmetric; (3) the matters only have circular rotation motions, and their angular velocity Ω is constant to a distant observer at rest. Under these assumptions, the metric of a rapidly rotating neutron star can be described as

$$-\mathrm{d}s^2 = -\mathrm{e}^{2\nu}\mathrm{d}t^2 + \mathrm{e}^{2\mu}(\mathrm{d}r^2 + r^2\mathrm{d}\theta^2) + \mathrm{e}^{2\psi}r^2\sin^2\theta(\mathrm{d}\phi - \omega\mathrm{d}t)^2 \ , \tag{5}$$

where the metric functions (ν,μ,ω,ψ) are functions of r and θ only. To the rotating stars, the four-velocity u^α in the energy momentum tensor is given by[69]

$$u^\alpha = \frac{\mathrm{e}^{-\nu}}{\sqrt{1-v^2}}(1,0,0,\Omega) \ , \tag{6}$$

where the proper velocity v with respect to a local zero angular momentum observer is defined by

$$v \equiv r\sin\theta\mathrm{e}^{\psi-\nu}(\Omega-\omega). \tag{7}$$

By using the metric of Eq. (5) and the energy momentum tensor based on Eqs. (1), (6) and (7), Einstein field equation can be expressed only by the metric functions, the energy density and the pressure of the matters, and the proper velocity. The detailed expressions please refer to[70].

To numerically calculating the rotating neutron star's structures, excepting for the equations mentioned above, one still need the equation of hydrostatic equilibrium and the appropriate boundary conditions. The equation of hydrostatic equilibrium is derived from the equation of motions and takes the following form[69]:

$$\frac{1}{p+\rho}\nabla p + \nabla\nu - \frac{1}{2}\nabla\ln(1-v^2) = 0 \ . \tag{8}$$

Nowadays, several available numerical codes for calculating the relativistic rotating neutron star structures and properties have been successful developed, the introduction and comparison of these codes please refer to[69]. Here, we will employ the RNS code based on Refs. [58–60] to calculate the structures of the rapidly rotating neutron stars.

To the global properties of rapid rotating neutron stars, except for the mass-radius relation, the moment of inertia, the redshift and the deformation are also interesting quantities to characterize the stellar structures. The moment of inertia is defined by

$$I = \frac{J}{\Omega} \tag{9}$$

where Ω is the star's angular velocity, and J is the angular momentum, which could be calculated by[69]

$$J = 2\pi\int \mathrm{e}^{2\mu+2\psi}\frac{(p+\rho)v}{1-v^2}r^3\sin^2\theta\mathrm{d}r\mathrm{d}\theta \ . \tag{10}$$

For a rapidly rotating neutron star, the redshift of the radiations are from two mechanisms: the gravitational redshift and the Doppler shift (which is a redshift in the backward direction and a blueshift in the forward direction). But at the polar, there is only the gravitational redshift, which is defined as[57, 59]

$$z_p = \sqrt{|g_{\mathrm{tt}}|} - 1 = \mathrm{e}^{-\nu_p} - 1 \ , \tag{11}$$

where the subscript p denotes values at the polar surface. As most of the observed radiation of neutron stars are believed from the polar area, so here we only focus on the redshift at the polar.

Another interesting property is the deformation, which can be described by the ratio of the radius at polar and at equator, that is $R_\mathrm{p}/R_\mathrm{e}$. The deformation is very important in investigating the gravitational radiation.

3 SES and EOS of the asymmetric dense nuclear matters

In numerically calculating the structure of rotating neutron stars, the EOSs of the dense matters are the necessary input. Up to now, the EOS for the symmetric nuclear matter around saturation density is known relatively well, but it is still very poor known in the density regimes far from saturation density and isospin asymmetries δ close to 1 ($\delta = (n_\mathrm{n}-n_\mathrm{p})/(n_\mathrm{n}+n_\mathrm{p})$, where n_n and n_p are the baryon number densities of neutrons and protons, respectively).

In order to describe the EOS of the asymmetric dense nuclear matters mainly made up of neutrons, protons and electrons, the EOS is normally decomposed into two parts according to the isospin asymmetry, that is, the part of the symmetric nuclear matter $E_\mathrm{SNM} = E_0(n,\delta=0)$ and the part of the pure neutron matter $E_\mathrm{PNM} = E(n,\delta=1)$. Then the EOS of the isospin asymmetric nuclear matters can be expanded to the second-order according to the isospin asymmetry as [5, 7, 21]

$$E(n,\delta) = E_0(n) + S(n)\delta^2 + \ldots \ , \tag{12}$$

where n is the baryon density, $S(n)$ is the density dependent symmetry energy. Neglecting the higher-order contribution, as a good approximation which has been verified by many-body theories, the symmetry energy is just the difference between the E_PNM and the E_SNM, that is [5, 7, 21]

$$S(n) = E(n,\delta=1) - E_0(n,\delta=0) \ . \tag{13}$$

Around the saturation density n_0, the symmetry energy can be expanded in a Taylor series as

$$S(n) = S_0 + L\chi + \frac{1}{2}K_{\rm sym}\chi^2 + ... \; ; \qquad (14)$$

where $\chi(=(n-n_0)/(3n_0))$ characterizes the deviations of the density from saturation density, S_0 is the symmetry energy at saturation density, L and $K_{\rm sym}$ are the slope parameter and the curvature parameter, respectively. Through this expanding, the uncertainties of the EOS around saturation density of the asymmetric nuclear matters thus mainly lie in the SES. During the last decade, too many efforts have been made to constrain the SES of the asymmetric nuclear matters [2, 7, 21, 22, 24–50]. The most recent constraints [2, 45–51], coupled with inferences from the theoretical calculations of pure neutron matter[31, 71], the value of L is constrained in a range of $L=(50\pm20)$ MeV. And a community average $L\approx 60$ MeV is obtained through analyzing the recent constraints on the slope[48, 72]. In this work, we will take a conservative range of the SES with 25 MeV $< L <$ 105 MeV from the model analysis of terrestrial nuclear laboratory experiments[2, 7, 21, 22, 24–50] to investigate the constraint from the symmetry energy slope on the properties of the rapidly rotating neutron stars. The Modified Skyrme-Like (MSL) model is adopted to obtain the EOS of the neutron star curst and the lower density region of the core[41], where the MSL interaction involves parameters related to the properties at saturation nuclear density. For each value of L, the magnitude of the symmetry energy at saturation density is adjusted so that the EOS fits the most recent calculations of the EOS of PNM[31, 71] as detailed in Ref. [73]. Furthermore, the EOS of symmetric nuclear matter $E_{\rm SNM}$ is fixed with an incompressibility modulus of $K_0=240$ MeV[22, 73].

The EOS of the neutron star matters adopted in this work is built as the follows. At density below 300 MeV·fm^{-3}, the EOS is obtained from the (MSL) model. At high densities, it is expected that the description of the matter in terms of just neutrons and protons will be broken down, as the exact composition of the inner core is still uncertain. Taking account of our lacking knowledge in this regime, and also to ensure that our complete EOS can support a $2M_\odot$ neutron star as demanded by observations[74–75], we smoothly join the MSL EOS to two polytropic EOSs of the form $P=K\epsilon^{(1+1/n)}$ in a similar way to Ref. [30]. The joins are made at energy densities of 300 and 600 MeV·fm^{-3} by adjusting the constant K to keep the pressure continuous at the join. The lower density polytrope has an index set at $n=0.5$, while the second index takes a range $n=0.5\sim1.5$ for values of L from $25\sim105$ MeV respectively. More details of the description of the EOS adopted in this work please refer Refs. [22, 73].

4 Results and discussion

In this section, we present our numerical results and discussions. Shown in Fig. 1 are the mass-$\rho_{\rm c}$ (central density) relations and mass-radius relations for the static spherically symmetric neutron stars. In the left panel, the rest masses are also plotted, where the rest mass is the mass of all the stellar baryons dispersed at rest at infinity (sometimes also called baryon mass[57]), which is held fixed in the evolutionary sequences for an isolated neutron star as the electromagnetic or gravitational radiation must conserve its total baryon number and thus its rest mass. It is worth noting that for a static neutron star, the difference between the rest mass and the gravitational mass ΔM $(=M_r-M)$ represents the total binding energy, which not only includes the gravitational potential energy, but also contains the work needed to overcome the Fermi pressure and the resistance to compression of supra-dense matters, that is, ΔM is the net energy to assemble the nucleons from infinity to form an equilibrium neutron star. A roughly estimation shows that the pure gravitational potential energy $E_{\rm G}$ per nucleon is about one and half times of the binding energy per nucleon $E_{\rm B}$[76]. It is easy to understand that a larger ΔM corresponds with a tightly bound star and can support a faster spin frequency, which can be confirmed in the right panel of Fig. 2. One can find in the left panel of Fig. 1 that the higher stellar mass corresponds with a larger ΔM and thus a larger binding energy $E_{\rm B}$. It is shown in Fig. 1 that for a softer SES, the neutron star is stronger bound (namely a larger ΔM, see the Fig. 1(a)) and thus has a smaller radius (Fig. 1(b)). To be more quantitative and make it easier to compare with future studies, we list the rest mass $M_{\rm r}$ and the binding energy per nucleon $E_{\rm B}$ of two typical neutron stars ($M=1.4M_\odot$ and $M=2.0M_\odot$) for different symmetry energy slopes in Table 1. As the radius of neutron star is mainly determined by the pressure near the nuclear saturation density[4, 64] and thus mainly determined by the SES, we can conclude that the mass-radius relation of the static neutron star should be constrained in a region between the lines of $L=25$ MeV and $L=105$ MeV in the right panel of Fig. 1. For example, the radius of a $1.4M_\odot$ neutron star should be constrained in a region of $10.28\sim13.43$ km, which is consistent with one of the latest observational constraints on the radius of neutron star: $10.4\sim12.9$ km[77]. If we take a more narrow constraint of the slope such as $43 < L < 52$ MeV[2], the radius of a $1.4M_\odot$ neutron star should be around 11.5 km. Moreover, if we adopt the community average $L \approx 60$ MeV based on the recent slope constraint[48], the radius of a $1.4M_\odot$ neutron star should be about 12.3 km.

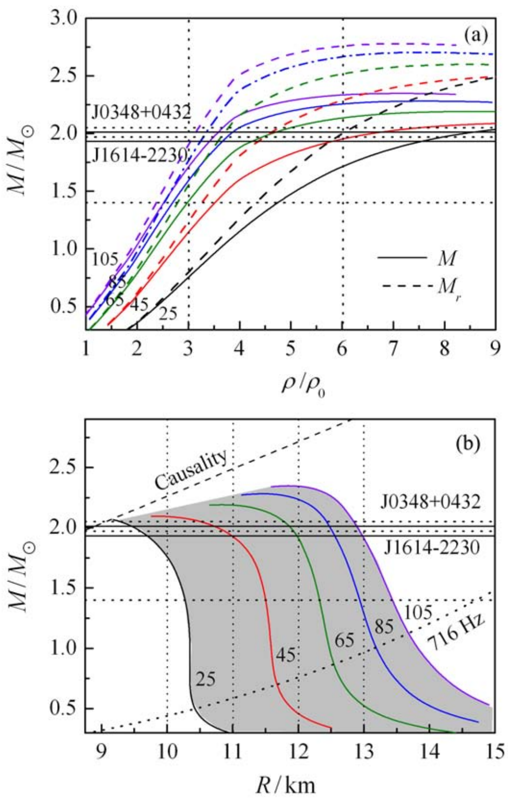

Fig. 1　(color online) (a) The masses of the static neutron stars as a function of the central densities, where M is the gravitational mass (solid lines), and M_r is the rest mass (dashed lines). Here and in the following figures, the numbers marked beside the lines are the SES values of the corresponding EOSs. (b) The mass-radius relations for the static spherically symmetric neutron stars.

Table 1　The rest mass M_r and the binding energy per nucleon E_B of two typical neutron stars ($M = 1.4M_\odot$ and $M = 2.0M_\odot$) for $L = 25$, 65 and 105 MeV, respectively.

L/MeV	$M/M_\odot$		$M_\mathrm{r}/M_\odot$		E_B/MeV	
25	1.4	2.0	1.58	2.44	107	169
65	1.4	2.0	1.54	2.32	85	130
105	1.4	2.0	1.52	2.29	74	119

The mass-radius relations of the Keplerian rotating neutron stars and the corresponding Keplerian frequency are plotted in Fig. 2. As we know, most of the observed neutron stars have far slower spin frequencies than their Keplerian frequencies, so the mass-radius relations of the slowly rotating stars should be located in the static region (among the solid lines in the Fig. 2(a)). According to the observed fastest rotating neutron star J1748−2446ad (with spin frequency 716 Hz $\approx$ 4 500 rad/s)[53], it is shown from the Fig. 2(b) that a lighter neutron star ($< 1.2M_\odot$) with a stiff SES ($\sim$ 105 MeV) will be ruled out, otherwise the matter at the equator will be thrown away. Simultaneously, if a more rapidly rotating neutron star is observed, for example, if the sub-millisecond pulsar XTE J1739-285 (with spin frequency 1 122 Hz)[80] is confirmed in the future, then either a soft symmetry energy slop for the asymmetric nuclear matters or a heavier stellar mass for the pulsar XTE J1739-285 is preferred.

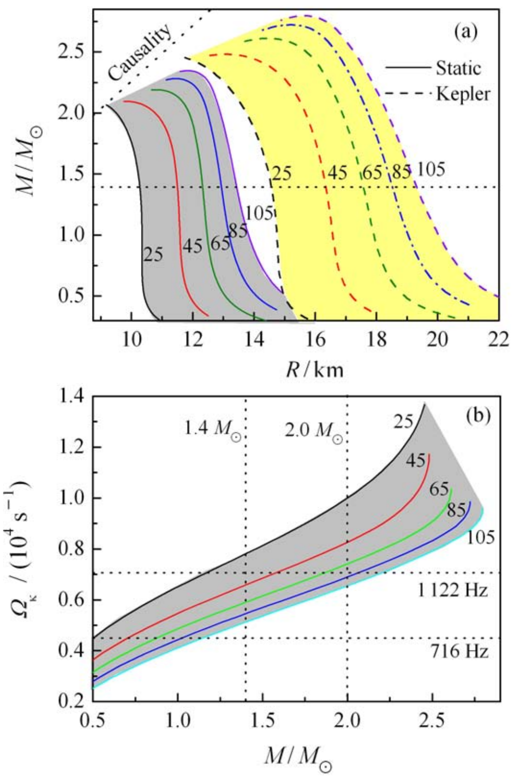

Fig. 2　(color online) (a) The mass-radius relations of the static (solid lines) and the Keplerian rotating neutron stars (dashed lines), where the radius of the Keplerian rotating neutron star is its radius at equator. (b) Keplerian frequency as a function of the neutron star mass.

As we know, the moment of inertia of neutron star is a crucial quantity in understanding the global stellar properties and probing the gravitational radiations. But still now an accurate measurement for the moments of inertia of neutron star, which can place important constraints on the radius and thus on the EOS, is still unavailable. Therefore, it is interesting to investigate the constraint on the moments of inertia from the EOS restricted by the terrestrial nuclear experiments, which may provide a useful reference in the future neutron star observations. Shown in Fig. 3 are the moments of inertia of the slowly rotating and Keplerian rotating neutron stars (Fig. 3(a)) and the angular momentum of the Keplerian rotating neutron stars (Fig. 3(b)). It is obviously that for a normal pulsar with a spin period slower than about 10 ms (which can be looked on as slowly rotating), its moment of inertia should be constrained between the two solid lines marked as 25 and 105 in the left panel, while for a rapid rotating neutron star, its moment of inertia should be located in the shadow region. Recently, there are a few important works focused on the universal relations between the global properties, such as the moment of inertia, the Love number and the quadrupole moment, which are independent of EOS. These universal relations are essential in understanding the neutron star global properties even the EOS of the dense matters is not known very well[78–79]. Here we also find an interesting universal property: the angular momenta of all the Keplerian rotating neutron stars present a perfect universal property which is not affected by the EOSs, as showing in the right panel. This property provides a constraint between the Keplerian frequency and the moment of inertia. For example, for a rapid rotating neutron star, if its stellar mass is determined accurately, according to $J=I\Omega$, one can give a upper limit of the moment of inertia of this neutron star based on the universal property.

In what follows we present two global properties of the Keplerian rotating neutron star: the ratio of rotational energy to gravitational energy T/W and the ration of polar radius to equatorial radius $R_{\rm p}/R_{\rm e}$, as shown in Fig. 4. Obviously, as most of the pulsars are spinning far slower than their Keplerian frequencies, so a real pulsar normally can not reach so larger ratio as shown in the figure. However, these two ratios at Keplerian frequencies still have theoretical significance, such as T/W provides a criterion to determine the gravitational-radiation instability[57], and $R_{\rm p}/R_{\rm e}$ gives a parameter to restrict the maximum deformation. It is shown that a higher stellar mass or a softer SES can support a larger T/W, thus a faster spin frequency, which is consistent with what shows in the right panel in Fig. 2. It is interesting to note that the largest theoretical allowed deformation is not happened at the maximum stellar mass, but at a mass slightly lighter than the maximum mass, as shown in the right panel in Fig. 4. This result may be qualita-

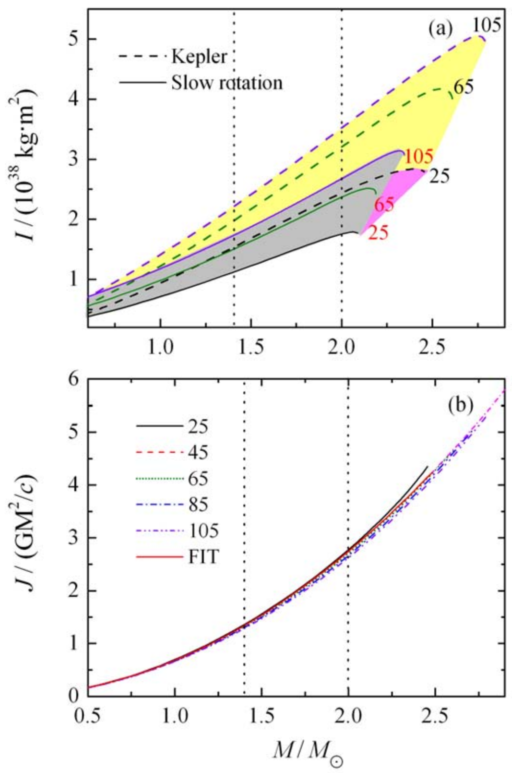

Fig. 3 (color online) (a) The moments of inertia as a function of the mass of the slowly rotating (solid lines) and Keplerian rotating (dashed lines) neutron stars. (b) The angular momentum of the Keplerian rotating neutron stars.

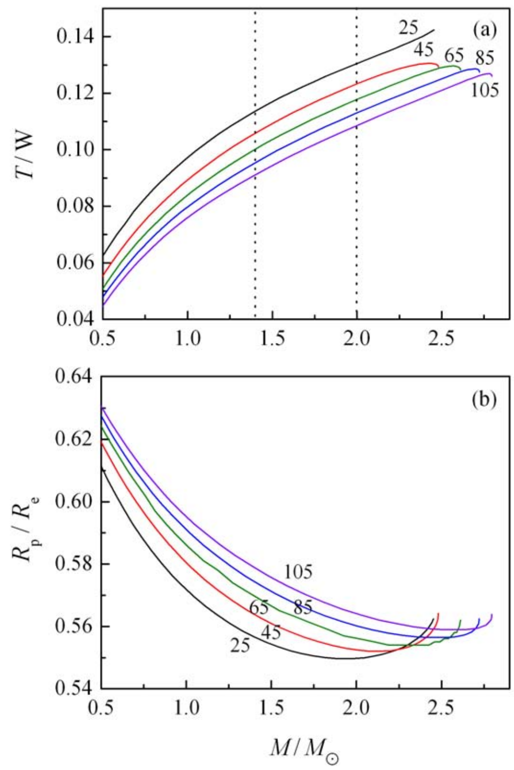

Fig. 4 (color online) (a) The ratio of rotational energy to gravitational energy. (b) The ratio of polar radius to equatorial radius. Both of them are at Keplerian frequencies.

tively explained by the mass-radius relation of the Keplerian rotating stars as shown in Fig. 2, that is, at the maximum mass end, the radius decreases rapidly and it is hard to deform a neutron star with smaller size but with a higher mass, even rotating at a faster Keplerian frequency.

Another interesting quantity of neutron star is the redshift, which is observable and can provide available information on the stellar radius[81]. It is shown in Fig. 5 that excepting the super massive region the static star and the Keplerian rotating star have a similar redshift at a fixed stellar mass. Approximately, according to the definition of the redshift $z=[1-(2M/R)]^{-1/2}-1$ for the static field, one can see that the polar radius of a Keperian rotating neutron star has a similar radius with that of the corresponding static star. This point can also be confirmed by the left panel of Fig. 4. And combining these two figures, we also can qualitatively explain why the static super massive neutron star has a higher redshift than that of the corresponding Keplerian rotating star: it is because that the massive star can support a larger deformation, and a smaller polar radius causes a higher redshift. According to the observational result $z=0.35$ for low-mass X-ray binary EXO0748-676[81], it is shown in Fig. 5 that if the observed radiation is from the polar region, thus the neutron star EXO0748-676 will have a stellar mass at least higher than $1.5M_{\odot}$. As the neutron star EXO0748-676 is spinning rapidly (with spin frequency 552 Hz[82]), if the radiation is from the equator, the situation will become more complicated and will not be discussed here.

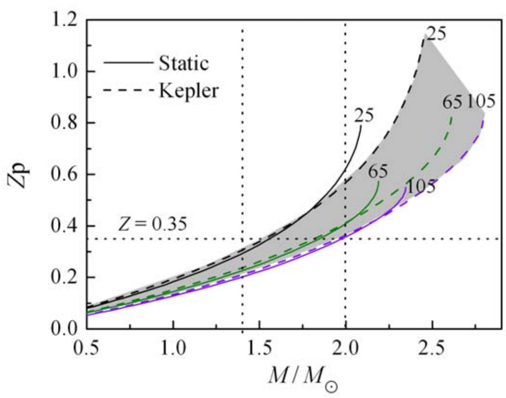

Fig. 5　(color online) The Polar redshift as a function of the stellar mass for static and Keplerian rotating neutron stars, respectively.

5　Conclusions

By making use of a conservative SES constraint, the constraints from the SES on the stellar properties, such as the mass-radius relations, the moments of inertia, the redshift, the deformations of the rapid rotating stars, *etc.*, for the static neutron stars and the rapid rotating neutron stars are investigated and discussed. According to the conservative SES constraint, our calculation shows that the radius of a canonical neutron star (with $M=1.4M_{\odot}$) can be constrained in a region of $10.28\sim13.43$ km, which is consistent with the latest constraint on the radius of neutron star in observations[1]. The results also shows that for a softer SES, the neutron star with a fixed stellar mass is stronger bound and thus can support a faster Keplerian frequency. The quantitative data of the rest mass M_{r} and the binding energy per nucleon E_{B} for two typical neutron stars ($M=1.4M_{\odot}$ and $M=2.0M_{\odot}$) with different symmetry energy slopes are listed in Table 1. It is also shown that if a sub-millisecond pulsar with a lighter stellar mass is observed in the future, then a softer SES of the asymmetric nuclear matters can be concluded. The universal property of the angular momentum provides a way to obtain the upper limit of the moment of inertia of a rapid rotating neutron star with observed mass. In addition, our results also can provide a constraint on the lower mass limit of pulsar in low-mass X-ray binary EXO0748-676 if the observed redshift of this star is from the polar direction.

References:

[1] LATTIMER J. M. Annu Rev Nucl Part Sci, 2012, **62**: 485.
[2] STEINER A W, GANDOLFI S. Phys Rev Lett, 2012, **108**: 081102.
[3] LATTIMER J M, PRAKASH M. Science, 2004, **304**: 536.
[4] LATTIMER J M, PRAKASH M. Phys Rep, 2007, **442**: 109.
[5] LI B A, CHEN L W, KO C M. Phys Rep, 2008, **464**: 113.
[6] DANIELEWICZ P, LACEY R, LYNCH W G. Science, 2002, **298**: 1592.
[7] CHEN L W. In Proceedings of the 14th National Conference on Nuclear Structure in China (NSC2012)[C]. ed. MENG J, SHEN C W, ZHAO E G, *et al.* Singapore: World Scientific, 2012: 43(arXiv:1212.0284).
[8] BROWN B A. Phys Rev Lett, 2000, **85**: 5296.
[9] XIAO Z G, LI B A, CHEN L W, *et al.* Phys Rev Lett, 2009, **102**: 062502.
[10] FENG Z Q, JIN G M. Phys Lett B, 2010, **683**: 140.
[11] XIE W J, SU J, ZHU L, *et al.* Phys Lett B, 2013, **718**: 1510.
[12] LI B A, DAS C B, DAS G S, *et al.* Nucl Phys A, 2004, **735**: 563.
[13] DAS C B, DASGUPTA S, GALE C, *et al.* Phys Rev C, 2003, **67**: 034611.
[14] LI B A, KO C M, BAUER W. Int J Mod Phys E, 1998, **7**: 147.
[15] HOROWITZ C J, PIEKAREWICZ J. Phys Rev Lett, 2001, **86**: 5647.
[16] HOROWITZ C J, PIEKAREWICZ J. Phys Rev C, 2001, **64**:

062802(R).
[17] TYPEL S, BROWN B A. Phys Rev C, 2001, **64**: 027302.
[18] FURNSTAHL R J. Nucl Phys A, 2002, **706**: 85.
[19] KARATAGLIDIS S, AMOS K, BROWN B A, *et al.* Phys Rev C, 2002, **65**: 044306.
[20] ZHANG Y Z, COUPLAND D D S, DANIELEWIC P, *et al.* Phys Rev C, 2012, **85**: 024602.
[21] TSANG M B, STONE J R, CAMERA F, *et al.* Phys Rev C, 2012, **86**: 015803.
[22] WEN D H, NEWTON W G, LI B A. Phys Rev C, 2012, **85**: 025801.
[23] ZHOU Y, WEN D H. Commun Theor Phys, 2014, **61**: 469.
[24] PIEKAREWICE J, AGRAWAL B, COLO G, *et al.* Phys Rev C, 2012, **85**: 041302.
[25] DONG J, ZUO W, GU J, LOMBARDO U. Phys Rev C, 2012, **85**: 034308.
[26] MOLLER P, MYERS W D, SAGAWA H, *et al.* Phys Rev Lett, 2012, **108**: 052501.
[27] GEARHEART M, NEWTON W, HOOKER J, *et al.* Mon Not Roy Astron Soc, 2011, **418**: 2343.
[28] CHEN L W. Phys Rev C, 2011, **83**: 044308.
[29] ZENIHIRO J, SAKAGUCHI H, MURAKAMI T, *et al.* Phys Rev C, 2010, **82**: 044611.
[30] STEINER A W, LATTIMER J M, BROWN E F. Astrophys J, 2010, **722**: 33.
[31] HEBELER K, LATTIMER J M, PETHUCK C J, *et al.* Phys Rev Lett, 2010, **105**: 161102.
[32] CARBONE A, COLO G, BRACCO A, *et al.* Phys Rev C, 2010, **81**: 041301.
[33] NEWTON W G, LI B A. Phys Rev C, 2009, **80**: 065809.
[34] WARDA M, VINAS X, ROCA-MAZA X, *et al.* Phys Rev C, 2009, **80**: 024316.
[35] TSANG M B, ZHANF Y X, DANIELEWICZ P, *et al.* Phys Rev Lett, 2009, **102**: 122701.
[36] DANIELEWICZ P, LEE J. Nucl Phys A, 2009, **818**: 36.
[37] KLIMKIEWICZ A, PAAR N, ADRICH P, *et al.* Phys Rev C, 2007, **76**: 051603.
[38] SHETTY D V, YENNELLO S J, SOULIOTIS G A. Phys Rev C, 2007, **76**: 024606.
[39] FAMIANO M, LIU T, LYNCH W, *et al.* Phys Rev Lett, 2006, **97**: 052701.
[40] CHEN L W, KO C M, LI B A. PHYS Rev Lett, 2005, **94**: 032701.
[41] CHEN L W, CAI B J, KO C M, *et al.* Phys Rev C, 2009, **80**: 014322.
[42] LI B A, CHEN L W. Phys Rev C, 2005, **72**: 064611.
[43] KLIMKIEWICZ A. Phys Rev C, 2007, **76**: 051603(R).
[44] DANIELEWICZ P, LEE J. AIPC Conf Proc, 2007, **947**: 301.
[45] CHEN L W, KO C M, LI B A, *et al.* Phys Rev C, 2010, **82**: 024321.
[46] XU C, LI B A, CHEN L W. Phys Rev C, 2010, **82**: 054607.
[47] NEWTON W G, GEARHEART M, WEN D H, *et al.* J Phys : Conf Ser, 2013, **420**: 012145.
[48] LI B A, HAN X. Phys Lett B, 2013, **727**: 276.
[49] LIU M, WANG N, LI Z X, *et al.* PHYS RRV C, 2010, **82**: 064306.
[50] CENTALLES M, ROCA-MAZA X, VINAS X, *et al.* Phys Rev Lett, 2009, **102**: 122502.
[51] ROCA-MAZA X, CENTALLES M, VINAS X, *et al.* Phys Rev Lett, 2011, **106**: 252501.
[52] THORSETT S E, CHAKRABARTY D. Astrophys J, 1999, **512**: 288.
[53] HESSELS J W T, RANSOM S M, STAIRS I H. Science, 2006, **311**: 1901.
[54] HARELE J B. Astrophys J, 1967, **150**: 1005.
[55] HARTLE J B, THORNE K S. Astrophys J, 1968, **153**: 807.
[56] BUTTERWORTH E M, IPSER J R. Astrophys J L, 1975, **200**: 103.
[57] FRIEDMAN J L, IPSER J R, PARKER L. Astrophys J, 1986, **304**: 115.
[58] KOMATSU H, ERIGUCHI Y, HACHISU I. MNRAS, 1989, **237**: 355.
[59] COOK G B, SHAPIRO S L, TEUKOLSKY S A. Astrophys J, 1994, **422**: 273.
[60] STERGIOULAS N, FRIEDMAN J L. Astrophys J, 1995, **444**: 306.
[61] KRASTEV P G, LI B A, WORLEY A. Astrophys J, 2008, **676**: 1170.
[62] WEN D H. Chin Phys Lett, 2010, **27**: 010401.
[63] WEN D H, CHEN W. Chin Phys B, 2011, **20**: 029701.
[64] LATTIMER J M, PRAKASH M. Astrophys J, 2001, **550**: 426.
[65] FATTOYEV F J, PIEKAREWICZ J. Phys Rev C, 2012, **86**: 015802.
[66] FATTOYEV F J, NEWTON W G, XU J, *et al.* Phys Rev C, 2012 **86**: 025804.
[67] TOLMAN R C. Phys Rev, 1939, **55**: 364.
[68] OPPENHEIMER J R, VOLKOFF G M. Phys Rev, 1939, **55**: 374.
[69] NOZAWA T, STERGIOULAS N, GOURGOULHON E, *et al.* Astron Astrophys, 1998, **132**: 431.
[70] BUTTERWORTH E M, IPSER J R. Astrophys J, 1976, **204**: 200.
[71] GANDOLFI S, CARLSON J, REDDY S. Phys Rev C, 2012, **85**: 032801(R).
[72] NEWTON W G, HOOKER J. Phys J A, 2014, **50**: 41.
[73] NEWTON W G, GEARHEART M, LI B A. Astrophys J S, 2013, **204**: 9.
[74] DEMOREST P B, PENNUCCI T. Nature, 2010, **467**: 1081.
[75] ANTONIADIS J, FREIRE P C C. Science, 2013, **340**: 448.
[76] GLENDENNING N K. Compact Stars: Nuclear Physics, Particle Physics, and General Relativity[M]. New York: Springer, 1997.
[77] STEINER A W, LATTIMER J M, BROWN E F. Astrophys J, 2013, **765**: L5.
[78] YAGI K, YUNES N. Science, 2013, **341**: 365.
[79] YAGI K, YUNES N. Phys Rev D, 2013, **88**: 023009.
[80] KAARET P, PRIEDKORN J, ZAND J J, *et al.* Astrophys J L, 2007, **657**: 97.
[81] COTTAM J, PAERELS F, MENDEA M. Nature, 2002, **420**: 51.
[82] KEEK L, GALLOWAY D K. Astrophys J, 2010, **718**: 292.

核物质对称能斜率对快转中子星性质的约束

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摘要： 在过去的十余年中，对非对称核物质的对称能的研究无论从实验还是理论上都取得了较大的突破，这对中子结构及其物态方程的理解具有十分重要的意义。本研究将采用一个相对保守的对称能斜率范围 (25 MeV $< L <$ 105 MeV) 来研究其对快速转动中子星性质的约束，这些性质包括: 质量-半径关系、转动惯量、引力红移以及转动形变等。通过该对称能斜率的约束，发现典型中子星 ($M = 1.4M_{\odot}$) 的半径约束在 10.28～13.43 km 范围内，这与最近的相关观测相一致。如果观察发现了质量较小的毫秒脉冲星，则将为核物质的对称能较软提供有效的证据。另外还发现，对角动量的一致性可为快转中子星转动惯量的上限提供约束。最后，根据具有低质量伴星的双星 EXO0748-676 的红移观测，给出了该脉冲星的质量下限 ($> 1.5M_{\odot}$)。

关键词： 对称能；中子星；自转

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