Bull. Astr. Soc. India (2013) **41**, 291–298

The surface gravitational redshift of the neutron star PSR B2303+46

Xian-Feng Zhao[1*] and Huan-Yu Jia[2]

[1] *College of Mechanical and Electronic Engineering, Chuzhou University, Chuzhou 239000, China*
[2] *Institute for Modern Physics, Southwest Jiaotong University, Chengdu, 610031, China*

Received 2013 October 07; accepted 2013 December 03

Abstract. The surface gravitational redshift of the neutron star PSR B2303+46 is investigated within the framework of relativistic mean field theory for the baryon octet system through adjusting the hyperon coupling constants. We obtain any models for the neutron star B2303+46 by choosing suitable hyperon coupling constants $x_{\sigma h}$ and $x_{\omega h}$ with $x_{\rho h}$ being determined by SU(6) symmetry and the nucleon coupling constant being chosen as CZ11. Our calculations show that the radius and the surface gravitational redshift of the neutron star PSR B2303+46 are determined as $R = 12.477 \sim 12.493$ km and $z = 0.2184 \sim 0.2187$, respectively. Our results are not consistent with the recent discovery of the massive neutron star PSR J1614−2230 and PSR J0348+0432.

Keywords : gravitation – stars: neutron – pulsars: individual: PSR B2303+46

1. Introduction

The neutron star PSR B2303+46 (Dewey et al. 1985), which is a binary system in eccentric orbits ($e = 0.658$), was first observed by Dewey et al. in 1985 (van Kerkwijk & Kulkarni 1999). Its mass is $M = 1.38^{+0.06}_{-0.10}\ M_\odot$ (Thorsett & Chakrabarty 1999) and its orbital period 12.34 d (Stokes, Taylor & Dewey 1985).

The binary PSR B2303+46 contains a white dwarf as a companion star. For the white dwarf evolving first and not leaving any source of matter for the neutron star to accrete, no recycling takes place in this case (Tauris & Sennels 2000). The mechanism behind this reversal is very different from that of a neutron-neutron star binary system, and especially different from the

*email: zhaopioneer.student@sina.com

recently discovered massive neutron stars PSR J1614−2230 (Demorest et al. 2010) and PSR J0348+0432 (Antoniadis et al. 2013). So a study of the neutron star PSR B2303+46 is useful for understanding of binary evolution.

Being connected to mass, the surface gravitational redshift is an important physical quantity for a neutron star, and hence we study this for the neutron star PSR B2303+46. The relativistic mean field (RMF) theory is a good method to describe the neutron star matter (Zhou 2004). A lot of work has been done on the surface gravitational redshift of neutron stars (Wynn, David & Philip 2007). These results show neutron star matter is very sensitive to the nucleon coupling constants and the hyperon-to-nucleon coupling constants (Prakash et al. 1997).

In this paper, by choosing appropriate parameters of the hyperon coupling the surface gravitational redshift of the neutron star PSR B2303+46 is examined within the RMF approach considering the baryon octet.

2. RMF theory and the surface gravitational redshift of a neutron star

The Lagrangian density of hadron matter reads as follows (Glendenning 1997)

$$\begin{aligned}\mathcal{L} \;=\; & \sum_B \overline{\Psi}_B(i\gamma_\mu\partial^\mu - m_B + g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu\omega^\mu - g_{\rho\ B}\gamma_\mu\tau\cdot\rho^\mu)\Psi_B \\ & +\frac{1}{2}\left(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^2\sigma^2\right) - \frac{1}{4}\omega_{\mu\nu}\omega^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - \frac{1}{4}\rho_{\mu\nu}\cdot\rho^{\mu\nu} \\ & +\frac{1}{2}m_\rho^2\rho_\mu\cdot\rho^\mu - \frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \sum_{\lambda=e,\mu}\overline{\Psi}_\lambda\left(i\gamma_\mu\partial^\mu - m_\lambda\right)\Psi_\lambda. \qquad (1)\end{aligned}$$

The detailed calculation of RMF theory can be seen in (Glendenning 1997) and in the same reference the surface gravitational redshift of a neutron star is given by

$$z = \left(1 - \frac{2M}{R}\right)^{-\frac{1}{2}} - 1. \qquad (2)$$

3. Parameters

In our calculations, the nucleon coupling constant is chosen as CZ11 listed in Table 1 (Zhao 2011).

We define the ratios: $x_{\sigma h} = g_{\sigma h}/g_{\sigma N}$, $x_{\omega h} = g_{\omega h}/g_{\omega N}$, $x_{\rho h} = g_{\rho h}/g_{\rho N}$, with h denoting hyperons.

The $g_{\rho\Lambda}, g_{\rho\Sigma}, g_{\rho\Xi}$ are given by SU(6) symmetry as follows: $g_{\rho\Lambda} = 0$, $g_{\rho\Sigma} = 2g_\rho$, $g_{\rho\Xi} = g_\rho$ (Schaffner & Mishustin 1996). So we choose $x_{\rho\Lambda} = 0, x_{\rho\Sigma} = 2, x_{\rho\Xi} = 1$. The calculations

Table 1. The nucleon coupling constant CZ11.

$(g_\sigma/m_\sigma)^2$ fm^2	$(g_\omega/m_\omega)^2$ fm^2	$(g_\rho/m_\rho)^2$ fm^2	b ×100	c ×100
10.1937	4.8557	4.2090	0.0105	−0.0100

Table 2. The suitable hyperon coupling constants chosen by us.

$U_\Lambda^{(N)}$	$x_{\sigma\Lambda}$	$x_{\omega\Lambda}$	$U_\Sigma^{(N)}$	$x_{\sigma\Sigma}$	$x_{\omega\Sigma}$	$U_\Xi^{(N)}$	$x_{\sigma\Xi}$	$x_{\omega\Xi}$
−31.33	0.50	0.50	20.71	0.33	0.60	−20.68	0.33	0.33
−28.53	0.70	0.80	36.05	0.33	0.70	−25.07	0.40	0.40
			20.93	0.40	0.70	−16.00	0.50	0.60
			36.26	0.40	0.80	−22.27	0.60	0.70
			14.66	0.50	0.80			
			29.99	0.50	0.90			

show that the ratio of hyperon coupling constant to nucleon coupling constant is in the range of ∼ 1/3 to 1 (Glendenning & Moszkowski 1991). Therefore, for x_σ we choose x_σ=0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9. For each x_σ, the x_ω are respectively chosen as 0.33, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9.

The well depth of hyperons Λ, Σ and Ξ in nuclear matter is given as follows (Glendenning 1997)

$$U_h^{(N)} = m_B\left(\frac{m_n^*}{m_n} - 1\right)x_{\sigma h} + \left(\frac{g_{\omega N}}{m_\omega}\right)^2 \rho_0 x_{\omega h}. \tag{3}$$

The experimental data of the well depth respectively are $U_\Lambda^{(N)} = -30$ MeV (Batty, Friedman & Gal 1997), $U_\Xi^{(N)} = -28$ MeV ~ -14 MeV (Fukuda et al. 1998; Khaustov et al. 2000; Dover & Gal 1983; Schaffner-Bielich 2000) and $U_\Sigma^{(N)} = 10 \sim 40$ MeV (Mares et al. 1995; Noumi et al. 2002; Saha et al. 2004; Kohno et al. 2004, 2006; Harada & Hirabayashi 2005, 2006; Friedman & Gal 2007). For the hyperon coupling constants chosen by us, we calculate the corresponding well depth of the hyperons and find that there are several sets of parameters, which are listed in Table 2, being consistent with the experimental data. From the coupling constants in Table 2, we can constitute 48 sets of parameters by successively choosing one set of $x_{\sigma\Lambda}x_{\omega\Lambda}$, $x_{\sigma\Sigma}x_{\omega\Sigma}$ and $x_{\sigma\Xi}x_{\omega\Xi}$.

The maximum mass of the neutron star calculated by us is listed in Table 3 and shown in Fig. 1. We can see that the maximum mass obtained by the sets of parameters No.25–27, 29–31, 33–35, 37–39, 41–43 and 45–47 all are greater than 1.38 $M_\odot$ while that of the neutron star obtained by the parameters No.01–24 are less than that. The former can give the mass of the neutron star PSR B2303+46, and we use these to describe the mass of the neutron star PSR B2303+46.

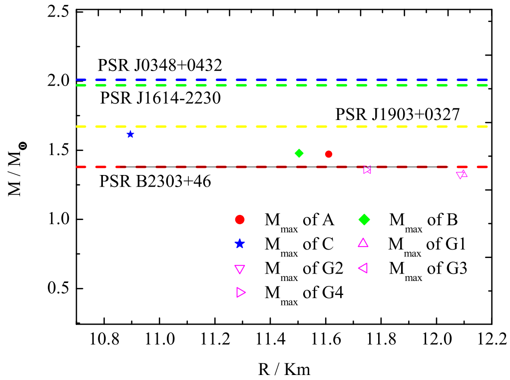

Figure 1. The calculated maximum mass of the neutron star as a function of the radius.

On the other hand, we also see the parameters No.25, 29, 33, 37, 41, 45 (named as A group, one of which is $x_{\sigma\Lambda} = 0.7, x_{\omega\Lambda} = 0.8$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.33$ and $x_{\omega\Xi} = 0.33$) corresponding to the mass 1.4721 M $_{\odot}$, the parameters No.26, 30, 34, 38, 42, 46 (named as B group, one of which is $x_{\sigma\Lambda} = 0.7, x_{\omega\Lambda} = 0.8$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.4$ and $x_{\omega\Xi} = 0.4$) corresponding to the mass 1.4787 M $_{\odot}$ and the parameters No.27, 31, 35, 39, 43, 47 (named as C group, one of which is $x_{\sigma\Lambda} = 0.7, x_{\omega\Lambda} = 0.8$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.5$ and $x_{\omega\Xi} = 0.6$) corresponding to the mass 1.6148 M $_{\odot}$. For the other parameters, we respectively name them as G1 (one of which is $x_{\sigma\Lambda} = 0.5, x_{\omega\Lambda} = 0.5$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.33$ and $x_{\omega\Xi} = 0.33$), G2 (one of which is $x_{\sigma\Lambda} = 0.5, x_{\omega\Lambda} = 0.5$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.4$ and $x_{\omega\Xi} = 0.4$), G3 (one of which is $x_{\sigma\Lambda} = 0.5, x_{\omega\Lambda} = 0.5$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.5$ and $x_{\omega\Xi} = 0.6$) and G4 (one of which is $x_{\sigma\Lambda} = 0.5, x_{\omega\Lambda} = 0.5$, $x_{\sigma\Sigma} = 0.33, x_{\omega\Sigma} = 0.6$, $x_{\sigma\Xi} = 0.6$ and $x_{\omega\Xi} = 0.7$). Then in this work we use the hyperon coupling constants A, B and C to calculate the radius and the surface gravitational redshift of the neutron star PSR B2303+46.

For all the 48 cases, our results cannot give the mass of the massive neutron stars PSR J1614−2230 (1.97 $M_{\odot}$) and PSR J0348+0432 (2.01 $M_{\odot}$). So our calculations cannot describe these two massive neutron stars. And our results also cannot describe the mass of the neutron star PSR J1903+0327 (Champion et al. 2008), which was the first millisecond pulsar and its mass has been determined to be 1.671±0.008 $M_{\odot}$. But in Freire et al. (2013), some equations of state are stiff enough and can give its mass.

4. The radius and the surface gravitational redshift of the neutron star PSR B2303+46

The calculated radius corresponding to the neutron star PSR B2303+46 is given in Fig. 2 and Table 4. We see the radius decreases with the central energy density increase. As the central energy density is larger, corresponding to the same central energy density the parameter A gives

Table 3. The maximum mass of the neutron star calculated in this work.

NO	M_{max} $M_\odot$	NO	M_{max} $M_\odot$	NO	M_{max} $M_\odot$
01	1.3257	17	1.3257	33	1.4721
02	1.3247	18	1.3247	34	1.4787
03	1.3589	19	1.3589	35	1.6150
04	1.3588	20	1.3588	36	—
05	1.3257	21	1.3257	37	1.4721
06	1.3247	22	1.3247	38	1.4787
07	1.3589	23	1.3589	39	1.6150
08	1.3588	24	1.3588	40	—
09	1.3257	25	1.4721	41	1.4721
10	1.3247	26	1.4787	42	1.4787
11	1.3589	27	1.6148	43	1.6150
12	1.3588	28	—	44	—
13	1.3257	29	1.4721	45	1.4721
14	1.3247	30	1.4787	46	1.4787
15	1.3589	31	1.6150	47	1.6150
16	1.3588	32	—	48	—

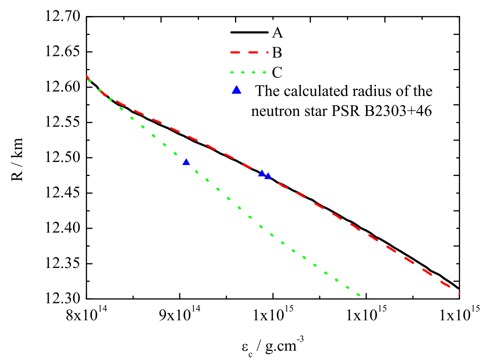

Figure 2. The calculated radius of the neutron star PSR B2303+46 as a function of the central density.

the largest radius while parameter C gives the smallest one. For the mass of the neutron star PSR B2303+46, the parameters A, B and C give the different radii but it can be seen that the difference is very small.

The range of the calculated radius of the neutron star PSR B2303+46 as a function of the central energy density is shown in Fig. 3. From Table 4 we see that for the parameters A, B and C the calculated radii of the neutron star PSR B2303+46 are R = 12.477, 12.473 and 12.493 km respectively, which corresponds to the central energy density $\varepsilon_c = 0.9883 \times 10^{15}$, 0.9949×10^{15}

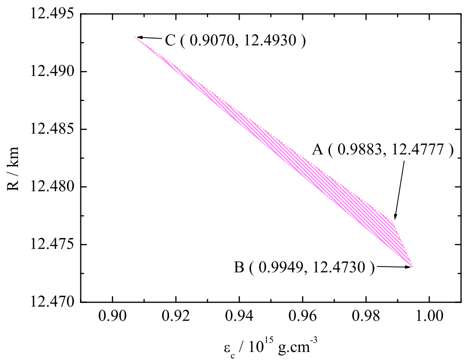

Figure 3. The value range of the calculated radius of the neutron star PSR B2303+46 as a function of the central energy density.

Table 4. The calculated central energy density, the radius and the surface gravitational redshift of the neutron star corresponding to the mass of neutron star PSR B2303+46 $M = 1.38M_{\odot}$.

NO	ε_c 10^{15}g cm^{-3}	R km	z
A	0.9883	12.477	0.2187
B	0.9949	12.473	0.2185
C	0.9070	12.493	0.2184

and 0.9070×10^{15} g cm^{-3} respectively. That is to say the calculated radius of the neutron star PSR B2303+46 is in the range of $R = 12.477-12.493$ km.

The calculated surface gravitational redshift of the neutron star PSR B2303+46 as a function of the central energy density is given in Fig. 4. We see the surface gravitational redshift of the neutron star increases with the central energy density. Corresponding to the same central energy density the parameter C gives the smallest surface gravitational redshift of the neutron star while parameters A gives the largest one. For the mass of the neutron star PSR B2303+46, the parameters A, B and C give different values of surface gravitational redshift of the neutron star although the differences are small.

Fig. 5 and Table 4 show the value range of the calculated surface gravitational redshift of the neutron star PSR B2303+46. We see that for the parameters A, B and C the calculated surface gravitational redshift of the neutron star PSR B2303+46 are respectively $z = 0.2187$, 0.2185 and 0.2184, which respectively correspond to the central energy density ε_c=0.9883×10^{15}, 0.9949×10^{15} and 0.9070×10^{15} g cm^{-3}. Thus, the calculated surface gravitational redshift of the neutron star PSR B2303+46 is in the range of $z = 0.2184 \sim 0.2187$, which is a little smaller than the value range of the gravitational redshift determined by Liang ($z = 0.25-0.35$) (Liang 1986).

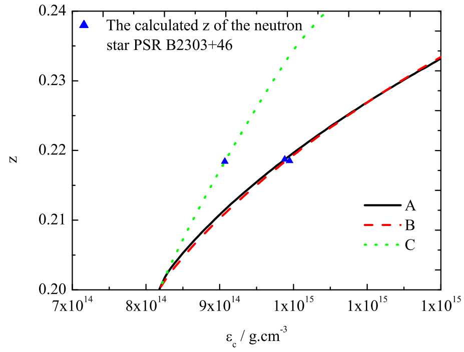

Figure 4. The calculated surface gravitational redshift of the neutron star PSR B2303+46 as a function of the central density.

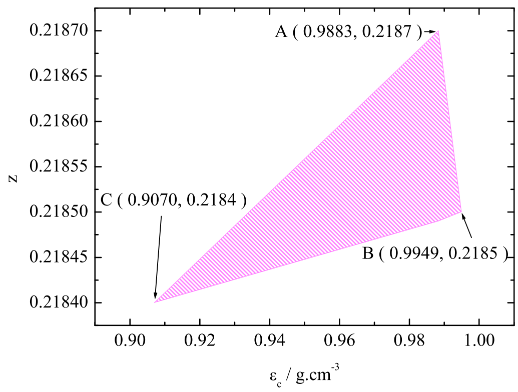

Figure 5. The value range of the calculated surface gravitational redshift of the neutron star PSR B2303+46.

5. Summary

In conclusion, in this paper by adjusting the hyperon coupling constants the surface gravitational redshift of the neutron star PSR B2303+46 is investigated within the framework of RMF theory for the baryon octet system. It is found that we can obtain any model for the neutron star B2303+46 by choosing suitable hyperon coupling constants $x_{\sigma h}$ and $x_{\omega h}$ as $x_{\rho h}$ being determined by the constituent quark model [SU(6) symmetry] and the nucleon coupling constant being chosen as CZ11. According to our calculations, the radius and the surface gravitational redshift of the neutron star PSR B2303+46 are determined as R = 12.477−12.493 km and z = 0.2184−0.2187, respectively. Our results cannot describe the massive neutron star PSR J1614−2230 and PSR J0348+0432.

Acknowledgements

We are thankful to the anonymous referee for many useful comments and suggestions. This work was supported by the Scientific Research Program Foundation of the Higher Education Institutions of Anhui Province "Study on the massive neutron star PSR J0348+0432 in the framework of relativistic mean field theory", the Anhui Provincial Natural Science Foundation under grant 1208085MA09 and the Fundamental Research Funds for the Central Universities under grant SWJTU12ZT11.

References

Antoniadis J., et al., 2013, Science, 340, 448
Batty C. J., Friedman E., Gal A., 1997, Phys. Reports, 287, 385
Champion D. J., et al., 2008, Science, 320, 1390
Demorest P. B., Pennucci T., Ransom S. M., Roberts M. S. E., Hessels J. W. T., 2010, Nature, 467, 1081
Dewey R. J., Taylor J. H., Weisberg J. M., Stokes G. H., 1985, ApJ, 294, L25
Dover C. B., Gal A., 1983, Ann. Phys., 146, 309
Freire P. C., et al., 2009, arxiv.org/pdf/0902.2891
Friedman E., Gal A., 2007, Phys. Rep., 452, 89
Fukuda T., et al., 1998, Phys. Rev. C, 58, 1306
Glendenning N. K., 1997, Compact Stars: Nuclear Physics, Particle Physics, and General Relativity, Springer-Verlag, New York
Glendenning N. K., Moszkowski S. A., 1991, Phys. Rev. Lett., 67, 2414
Harada T., Hirabayashi Y., 2005, Nucl. Phys. A, 759, 143
Harada T., Hirabayashi Y., 2006, Nucl. Phys. A, 767, 206
Khaustov P., et al., 2000, Phys. Rev. C, 61, 054603
Kohno M., et al., 2004, Prog. Theor. Phys., 112, 895
Kohno M., Fujiwara Y., Watanabe Y., Ogata K., Kawai M., 2006, Phys. Rev. C, 74, 064613
Liang E. P., 1986, ApJ, 304, 682
Mares J., et al., 1995, Nucl. Phys. A, 594, 311
Noumi H., et al., 2002, Phys. Rev. Lett., 89, 072301
Prakash M., Bombaci I., Prakash M., Ellis P. J., Lattimer J. M., Knorren R., 1997, Phys. Rep., 280, 1
Saha P.K., et al., 2004, Phys. Rev. C, 70, 044613
Schaffner J., Mishustin I. N., 1996, Phys. Rev. C 53,1416
Schaffner-Bielich J., Gal A., 2000, Phys. Rev. C, 62, 034311
Stokes G., Taylor J., Dewey R., 1985, ApJ, 294, L91
Tauris T. M., Sennels T., 2000, A&A, 355, 236
Thorsett S. E., Chakrabarty D., 1999, ApJ, 512, 288
van Kerkwijk M. H., Kulkarni S. R., 1999, ApJ, 516, L25
Wynn C. G. H., David L. K., Philip C., 2007, MNRAS, 375, 821
Zhao X. F., 2011, Int. J. Theor. Phys., 50, 2951
Zhou S. G., 2004, HEP&NP, 28, 21