A&A 366, 532–537 (2001)
DOI: 10.1051/0004-6361:20000090

Astronomy & Astrophysics

Properties of neutron stars with hyperons in the relativistic mean field theory

Z. X. Ma[1], Z. G. Dai[1,2], and T. Lu[1,2]

[1] Department of Astronomy, Nanjing University, Nanjing 210093, PR China
[2] IHEP, Chinese Academy of Sciences, Beijing 100039, PR China

Received 3 July 2000 / Accepted 30 October 2000

Abstract. We study the equation of state (EOS) of the dense matter in the core of neutron stars with hyperons included and the star structure based on the Zimanyi & Moszkowski (ZM) model in the relativistic mean–field theory with a set of recent satisfactory parameters. The relation between hyperon abundances and baryon number densities is calculated and the distribution of baryons in the core of a typical neutron star of 1.4 $M_{\odot}$ is presented. Our results satisfy the requirements from observations of the mass of binary radio pulsars, and the ratio, $I_{\rm c}/I_{\rm tot}$, of the crustal momentum of inertia to the total one. The actual surface thermal radiation detected seems to indicate that baryons in the core of neutron stars should pair to form a superfluid phase, if hyperons appear in the core of neutron stars.

Key words. stars: neutron – equations of state – elementary particles

1. Introduction

The investigation of properties of hypernuclear matter plays an important role in the knowledge of neutron stars (Balberg et al. 1999). The existence of stable matter at hypernuclear densities is unique to neutron stars, and the macroscopic properties of neutron stars, including some observable quantities, may reveal some physical properties of hypernuclear matter. A notable characteristic of hypernuclear matter is the appearance of new hadronic degrees of freedom in addition to neutrons and protons. One degree of freedom is the formation of hyperons – strange baryons – which is the main subject of this paper. Other possibilities include meson condensation and a deconfined quark phase. The existence of hyperons in neutron stars was first proposed by Ambartsumyan & Saakyan (1960) and has been examined by many authors. For a review, see Glendenning (1996) and Prakash et al. (1997).

To determine the equation of state (EOS) for dense matter through the many body theory of interacting baryons, numerous approaches have been proposed. In recent years, these studies are mainly implemented in the framework of the field theory models, among which the $\sigma-\omega$ model proposed first by Walecka (1974) is of growing interest. The $\sigma-\omega$ model is one kind of relativistic mean field theory. In the standard model of Walecka (1974) the incompressibility of nuclear matter is overestimated. There are two ways to solve this problem. Boguta & Bodmer (1977, hereafter BB) introduced cubic and quartic terms for the scalar field into the Lagrangian and reproduced reasonable incompressibility values in comparison with empirical data. Along this direction, many authors (Kapusta & Olive 1990; Ellis et al. 1991; Sumiyoshi et al. 1992; Sumiyoshi & Toki 1994; Sumiyoshi et al. 1995; Cheng et al. 1996; Schaffner & Mishustin 1996) studied the EOSs for dense matter and the properties of neutron stars. Zimanyi & Moszkowski (1990, hereafter ZM) proposed another nonlinear model, in which the nonlinearity is contained in connection between the effective nucleon mass and the scalar field. The ZM model also gives reasonable incompressibility values. This model has been employed to study the properties of neutron stars (Cheng et al. 1996) and of supernova cores (Dai & Cheng 1998). These theories can be considered as phenomenological, since the coupling constants and meson masses of the effective meson–nucleon Lagrangian are taken as free parameters which are adjusted to fit the properties of nuclear matter and finite nuclei. The ZM model has no extra terms, and consequently deals with fewer parameters as compared with the BB model.

In this paper, we use the ZM model to calculate the relative fractions of the equilibrium composition of dense matter with hyperons as a function of baryon density and the EOSs. The properties of neutron stars are then discussed. This paper is arranged as follows. We describe the framework based on the ZM model in Sect. 2, and present our numerical results in Sect. 3. Section 4 contains conclusions and discussions.

Send offprint requests to: T. Lu, e-mail: tlu@nju.edu.cn

Table 1. Masses, isospins and electric charges of baryon octet

Specices	Masses (MeV)	Charges	I_3
p	938	1	$\frac{1}{2}$
n	938	0	$-\frac{1}{2}$
Λ	1116	0	0
Σ^+	1193	1	1
Σ^0	1193	0	0
Σ^-	1193	-1	-1
Ξ^0	1318	0	$\frac{1}{2}$
Ξ^-	1318	-1	$-\frac{1}{2}$

Table 2. The meson masses (MeV) and the coupling constants

$g_{\rm sn}$	$g_{\rm vn}$	$g_{\rho\rm n}$	$m_{\rm s}$	$m_{\rm v}$	m_ρ
5.824	6.417	2.746	420	783	763

2. The ZM model with hyperons included

To our knowledge, in the ZM model, only nucleons and leptons are included in previous works. In order to describe the properties of dense matter, it is necessary to take hyperons into account. We follow the notations of Walecka (1974). The Lagrangian density of the system is given by

$$\begin{aligned}\mathcal{L} \;=\; & -\sum_{\rm b}\{\overline{\psi}_{\rm b}[\gamma_\mu(i\partial^\mu - g_{\rm vb}V^\mu - g_{\rho\rm b}\tau_{3\rm b}R^\mu) - m_{\rm b}^*]\psi_{\rm b}\} \\ & -\frac{1}{2}(\partial_\mu\phi\partial^\mu\phi + m_{\rm s}^2\phi^2) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{2}m_{\rm v}^2V_\mu V^\mu \\ & -\frac{1}{4}G_{\mu\nu}G^{\mu\nu} - \frac{1}{2}m_\rho^2R_\mu R^\mu, \end{aligned} \quad (1)$$

where

$$F_{\mu\nu} = \partial_\mu V^\nu - \partial_\nu V^\mu \quad (2)$$

$$G_{\mu\nu} = \partial_\mu R^\nu - \partial_\nu R^\mu \quad (3)$$

$$m_{\rm b}^* = \frac{m_{\rm b}}{1 + g_{\rm sb}\phi/m_{\rm b}}\cdot \quad (4)$$

Here $\psi_{\rm b}, \phi, V^\mu$and R^μ denote the fields of baryons, attractive isoscalar–scalar mesons, repulsive isoscalar–vector mesons, and isovector–vector mesons with masses of $m_{\rm b}, m_{\rm s}, m_{\rm v}$ and m_ρ, respectively. We are interested in the baryon octet, of which the masses, electric charges and isospins are listed in Table 1. The masses of the baryon octet are approximately taken to be their mean values of the same family (Glendenning 1985), which will not obviously alter the quantitative results. The meson masses and the constants $g_{\rm vn}, g_{\rm sn}$ and $g_{\rho\rm n}$ (coupling constants for interactions between mesons and nucleons, Cheng et al. 1996) are given in Table 2. Define

$$\chi_{\rm sh} = g_{\rm sn}/g_{\rm sh}, \quad \chi_{\rm vh} = g_{\rm vn}/g_{\rm vh}, \quad \chi_{\rho\rm h} = g_{\rho\rm n}/g_{\rho\rm h}, \quad (5)$$

where $\chi_{\rm vh}^2 = \chi_{\rm sh}^2 = \chi_{\rho\rm h}^2 = 2/3$ for Moszkowski coupling (1974, hereafter MC), and $\chi_{\rm vh}^2 = \chi_{\rm sh}^2 = \chi_{\rho\rm h}^2 = 1$ for universal coupling (hereafter UC). Here the subscript "h" stands for hyperons. The nucleon–related parameters are commendably fitted to the properties of nuclear matter (Dai & Cheng 1998). At present time, we lack the direct comparison between hyperon–related parameters and hypernuclei experimental data in the ZM model, but this should not impede us generalizing the ZM model to include hyperons and investigate the properties of neutron stars. The reasons are as follows. First, the fundamental qualitative result form hypernucleon experiments indicates that hyperon–related interactions are similar in character and in order of magnitude to nucleon–nucleon interactions (Balberg et al. 1999). And observed neutron star masses require that the values of χ should not be much smaller than 1 (Glendenning & Moszkowski 1991). This is one important fundament based on which we generalize the ZM model to include hyperons. Second, the instability of scalar self–interaction at high densities disappear, since the Lagrangian radically does not include the terms of scalar self–interaction in the ZM model. The ZM model always yields positive effective masses even at relatively high densities. After all, the ZM model including hyperons yields reasonable equations of state and properties of neutron stars.

From Eq. (1), we can derive the Euler–Lagrange equations. The Dirac equation for baryons is given by

$$\{\gamma_\mu[\partial^\mu - ig_{\rm vb}V^\mu - ig_{\rho\rm b}\tau_{3\rm b}R^\mu] - m^*\}\psi_{\rm b} = 0, \quad (6)$$

and the Klein–Gordon equations for the meson fields are given by

$$\partial_\mu\partial^\mu\phi - m_{\rm s}^2\phi = \sum_{\rm b}\frac{\partial m_{\rm b}^*}{\partial\phi}\overline{\psi_{\rm b}}\psi_{\rm b}, \quad (7)$$

$$\partial_\mu F^{\mu\nu} - m_{\rm v}^2V^\nu = -i\sum_{\rm b}g_{\rm vb}\overline{\psi_{\rm b}}\gamma^\nu\psi_{\rm b}, \quad (8)$$

$$\partial_\mu G^{\mu\nu} - m_\rho^2R^\nu = -i\sum_{\rm b}g_{\rho\rm b}\overline{\psi_{\rm b}}\gamma^\nu\tau_{3\rm b}\psi_{\rm b}. \quad (9)$$

The matter in neutron stars can be regarded as static uniform ground state matter, where the derivative terms and the space components of the baryon currents vanish automatically, so the space components R^i and V^i vanish. Setting $\phi \to \phi_{0,}$ $V_\mu \to iV_0\delta_{\mu4}$, and $R_\mu \to iR_0\delta_{\mu4}$, we have the meson fields expressed by the expectation values of the ground state,

$$\begin{aligned}\phi_0 \;=\; & \frac{1}{m_{\rm s}^2}\sum_{\rm b}\frac{g_{\rm sb}}{(1 + g_{\rm sb}\phi_0/m_{\rm b})^2}\langle\overline{\psi_{\rm b}}\psi_{\rm b}\rangle \\ =\; & \frac{1}{m_{\rm s}^2}\sum_{\rm b}\frac{g_{\rm sb}}{(1 + g_{\rm sb}\phi_0/m_{\rm b})^2}\rho_{\rm b}, \end{aligned} \quad (10)$$

$$V_0 = \frac{1}{m_{\rm v}^2}\sum_{\rm b}g_{\rm vb}\langle\overline{\psi_{\rm b}}\psi_{\rm b}\rangle = \frac{1}{m_{\rm v}^2}\sum_{\rm b}g_{\rm vb}\rho_{\rm b}, \quad (11)$$

$$R_0 = \frac{1}{m_\rho^2}\sum_{\rm b}g_{\rho\rm b}\langle\overline{\psi_{\rm b}}\tau_{3\rm b}\psi_{\rm b}\rangle = \frac{1}{m_\rho^2}\sum_{\rm b}g_{\rho\rm b}\tau_{3\rm b}\rho_{\rm b}. \quad (12)$$

Following the standard procedure of Walecka (1974), we reduce the energy density and the pressure of the system to

$$\begin{aligned}\epsilon \;=\; & \frac{1}{2}m_{\rm s}^2\phi_0^2+\frac{1}{2m_{\rm v}^2}\left(\sum_{\rm b} g_{\rm vb}\rho_{\rm b}\right)^2 \\ & +\frac{1}{2m_\rho^2}\left(\sum_{\rm b} g_{\rho{\rm b}}\tau_{3{\rm b}}\rho_{\rm b}\right)^2+\frac{1}{8\pi^2}\sum_{\rm b} m_{\rm b}^{*4} f_1(k_{\rm Fb}/m_{\rm b}^*) \\ & + \text{lepton contribution}, \end{aligned} \tag{13}$$

$$\begin{aligned}P \;=\; & -\frac{1}{2}m_{\rm s}^2\phi_0^2+\frac{1}{2m_{\rm v}^2}\left(\sum_{\rm b} g_{\rm vb}\rho_{\rm b}\right)^2 \\ & +\frac{1}{2m_\rho^2}\left(\sum_{\rm b} g_{\rho{\rm b}}\tau_{3{\rm b}}\rho_{\rm b}\right)^2+\frac{1}{24\pi^2}\sum_{\rm b} m_{\rm b}^{*4} f_3(k_{\rm Fb}/m_{\rm b}^*) \\ & + \text{lepton contribution}, \end{aligned} \tag{14}$$

where

$$f_1=2x(x^2+1)^{3/2}-x(x^2+1)^{1/2}-\ln(x+\sqrt{x^2+1}), \tag{15}$$

$$f_3=2x^3(x^2+1)^{1/2}-3x(x^2+1)^{1/2}+3\ln(x+\sqrt{x^2+1}), \tag{16}$$

$$k_{\rm Fb}=(3\pi^2\rho_{\rm b})^{1/3}. \tag{17}$$

Here $k_{\rm Fb}$ and $\rho_{\rm b}$ are the baryon Fermi–energy and number density for species b. The effective baryon masses are calculated through the following equation

$$m_{\rm b}^*=\frac{m_{\rm b}}{1+g_{\rm sb}\phi_0/m_{\rm b}}, \tag{18}$$

and

$$\phi_0=\frac{1}{2\pi^2 m_{\rm s}^2}\sum_{\rm b}\frac{g_{\rm sb}m_{\rm b}^{*3}}{(1+g_{\rm sb}\phi_0/m_{\rm b})^2}f_2(k_{\rm Fb}/m_{\rm b}^*), \tag{19}$$

where

$$f_2=x(x^2+1)^{1/2}-\ln(x+\sqrt{x^2+1}). \tag{20}$$

In following discussion, we assume that the matter in neutron stars is in full beta equilibrium and transparent for neutrinos, and take $T=0$ (ignoring the possible meson condensation and deconfined quark phase). Thus all equilibrium conditions can be given by

$$\mu_{\rm b}=\mu_n-q_{\rm b}\mu_{\rm e}, \tag{21}$$

where

$$\mu_{\rm b}=\frac{g_{\rm vb}}{m_{\rm v}^2}\sum_{\rm b'}g_{\rm vb'}\rho_{\rm b'}+\frac{g_{\rho{\rm b}}}{m_\rho^2}\sum_{\rm b'}g_{\rho{\rm b'}}\tau_{3{\rm b'}}\rho_{\rm b'}+\sqrt{k_{\rm Fb}^2+m_{\rm b}^{*2}}. \tag{22}$$

Here $\mu_{\rm b}$ and $q_{\rm b}$ are the chemical potential and the electric charge of baryon species b respectively, $\mu_{\rm n}$ is the neutron chemical potential, and $\mu_{\rm e}$ is the electron chemical potential. Note that in the case of neutrino transparency, the equilibrium requires

$$\mu_\mu=\mu_{\rm e}. \tag{23}$$

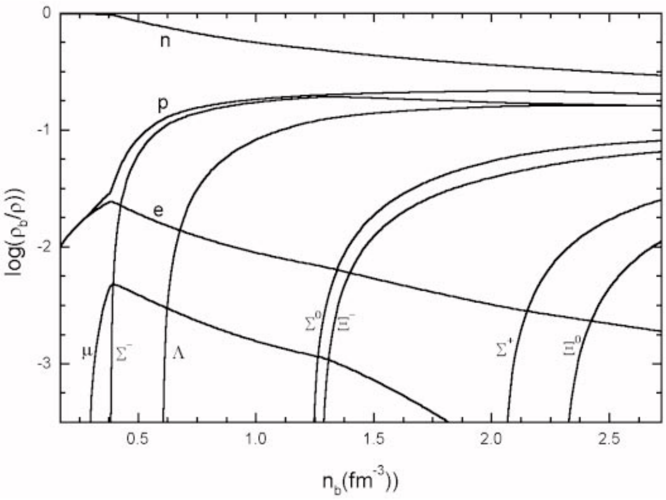

Fig. 1. Relative fractions of neutron star matter as a function of baryon density for UC

The neutron and electron chemical potentials are constrained by the requirements of conservation of total baryon number and electric charge neutrality,

$$\sum_{\rm b}\rho_{\rm b}=\rho, \tag{24}$$

$$\sum_{\rm b}q_{\rm b}\rho_{\rm b}+\sum_{\rm l}q_{\rm l}\rho_{\rm l}=0. \tag{25}$$

Here "l" denotes leptons including electrons and muons. Solving the above equations at various baryon densities, we obtained the relation between the energy density and pressure of the system.

3. Results

3.1. The abundance of hyperons

The number densities at which hyperons appear and the abundances of hyperons are related to their isospins, electric charges, effective masses and coupling constants. Since nuclear matter has an excess of positive charge and negative isospin, the appearance of hyperons with negative charge and positive isospin is favorable. The relative fractions of the equilibrium composition of dense matter as a function of baryon density are shown in Fig. 1 corresponding to UC, and in Fig. 2 corresponding to MC. Some qualitative properties of hyperon formation in dense matter can be deduced from Figs. 1 and 2.

(1) The density at which hyperons appear is 0.38 $\rm fm^{-3}$ for both MC and UC, that is well consistent with resent works (Balberg et al. 1999; Schaffner & Mishustin 1996; Glendenning 1985, 1996) which predict that hyperons will form at a density of $2\sim3\rho_0$ (ρ_0 is the nuclear saturation density);

(2) Companying with hyperon accumulation, the immediate deleptonization, as a common characteristic of dense matter including hyperons (Balberg et al. 1999), is clearly exhibited in Figs. 1 and 2. The relative electron

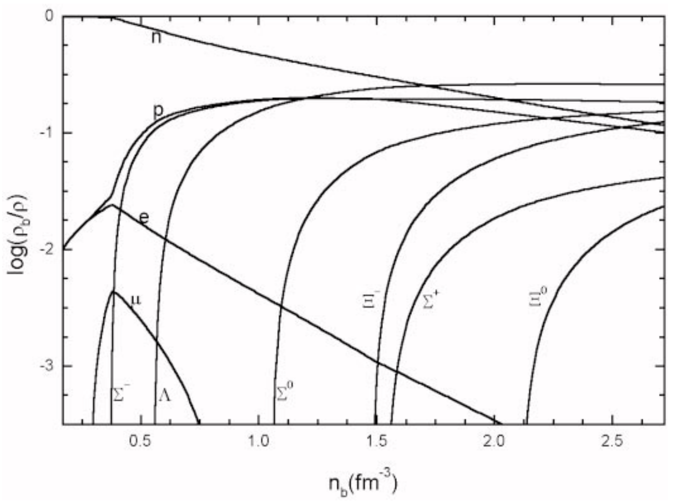

Fig. 2. Relative fractions of neutron star matter as a function of baryon density for MC

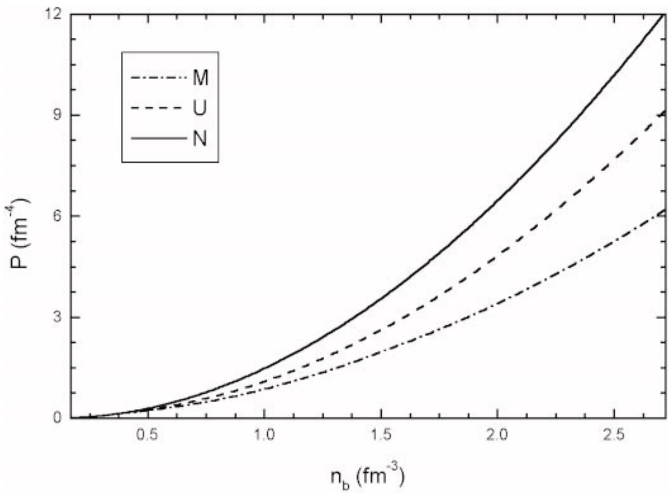

Fig. 3. The pressure vs. baryon number desity for UC, MC and N, N refers to nuclear matter without hyperon

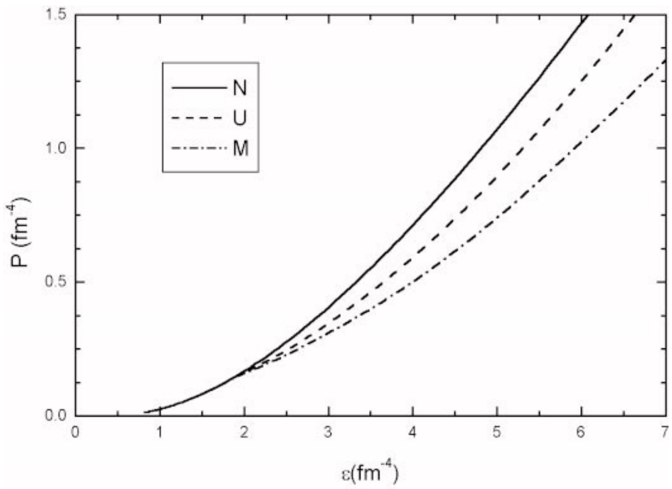

Fig. 4. The pressure vs. energy density for UC, MC and N, N refers to nuclear matter without hyperon

fraction reaches its maximum value of 2.4% for UC and 2.2% for MC both at baryon density 0.38 fm^{-3} (at which Σ^- begins to appear), respectively, and then decreases with increasing of baryon density. The muon populations vanish when the electron fraction drops blow 0.5%;

(3) The first hyperon species that appears is Σ^- followed by Λ. However, the formation of Σ^- is quickly moderated due to its negative isospin, then the Λ abundances exceed the Σ at baryon density 1.19 fm^{-3} for MC and 2.68 fm^{-3} for UC, respectively. For MC, the Λ abundances exceed the proton and neutron abundances at total hadron number density 1.2 fm^{-3} and 1.72 fm^{-3}, respectively;

(4) It is worthwhile to point out that compared to other relativistic field models (Knorren 1995; Schaffner & Mishustin 1996; Glendenning 1996; Balberg 1997), the ZM model yields somewhat smaller lepton and hyperon fractions and high densities at which Σ^0, Σ^+, Ξ^0 and Ξ^- form this is due to the low energy per nucleon predicted by the ZM model.

3.2. Equation of state

In the ZM model, Dai & Cheng (1998) studied the properties of nuclear matter with the parameters given in Tables 1 and 2, but their work doesn't include hyperons. The incompressibility, saturation density, and binding energy per nucleon obtained by Dai & Cheng are 225 MeV, 0.16 fm^{-1}, and -16.0 MeV, respectively. These values are very close to those derived from nuclear experiments. In Figs. 3 and 4, we plot the EOSs based on the ZM model with UC and MC. As a comparison, we also show the EOS based on the ZM model without any hyperon. The inclusion of hyperons softens the EOSs, since hyperons offer new degree of freedom for baryon matter and decrease the degenerate pressure, which has been noticed by some authors (e.g. Glendenning 1996).

4. The structure of neutron stars

After the EOSs are available, we can calculate the hydrostatic structure of a neutron star by solving the Tolman–Oppenheimer–Volkoff equation:

$$\frac{\mathrm{d}p}{\mathrm{d}r} = -\frac{[\rho(r)+p(r)][(M(r)+4\pi r^3\rho(r)]}{[r^2-2rM(r)]}, \tag{26}$$

and

$$\frac{\mathrm{d}M}{\mathrm{d}r} = 4\pi r^2\rho(r), \tag{27}$$

where (in units of $G = c = 1$) $p\,(r)$ and $\rho\,(r)$ are the pressure and energy density, respectively, and $M\,(r)$ is the gravitational mass inside a radius r. In our calculation, we use the EOS of Haensel et al. (1989) for the outer crust, and the EOS of Baym, Bethe and Pethick for the inner crust from the neutron–drip density up to 0.17 fm^{-3}.

The structure of neutron stars is displayed in Figs. 5–8. Figures 5 and 6 show the hyperon abundances as a function of radius for UC and MC, respectively. Figure 7 shows

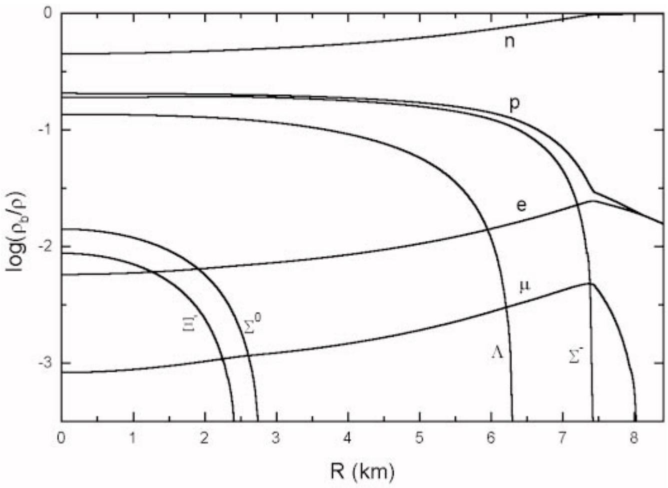

Fig. 5. Relative populations vs. radius in a neutron star of 1.4 $M_\odot$ for UC

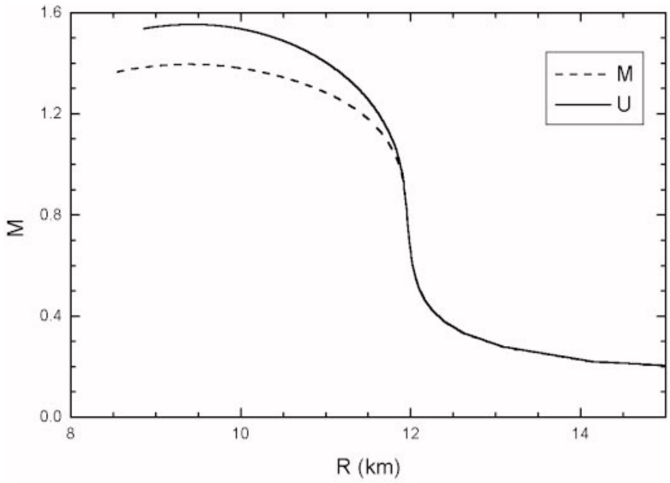

Fig. 7. Gravitational mass (in units of $M_\odot$) versus radius for UC and MC

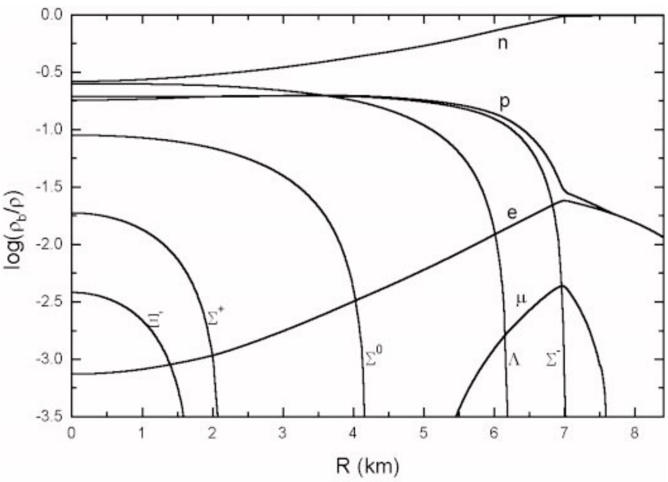

Fig. 6. Relative populations vs. radius in a neutron star of 1.4 $M_\odot$ for MC

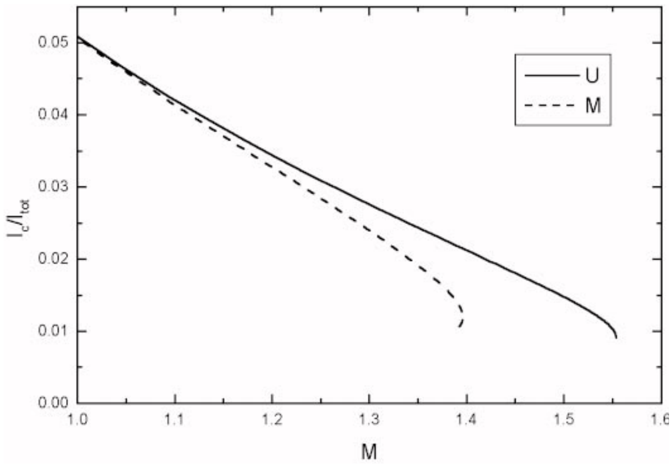

Fig. 8. The ratio of crustal momentum of inertia to the total one as a function of stellar mass for UC and MC

the total mass as a function of radius. For UC, the maximum mass of a neutron star is 1.55 $M_\odot$ with the central density of 3.47 10^{15} g cm^{-3} and the radius $R = 9.44$ km; while for MC, the maximum mass is 1.4 $M_\odot$ with the central density of 3.56 10^{15} g cm^{-3} and the radius of 9.39 km. Here it is clear that compared to other relativistic field model with hyperons the ZM model yields low neutron star maximum mass, which indicates relatively soft equations of state, especially for MC. The neutron star maximum masses yielded by other relativistic field model mainly line in 1.5 $M_\odot \sim 1.8\ M_\odot$ (Balberg 1999; Glendenning 1996, 1985; Schaffner & Mishutin 1995). Figure 8 shows the ratio of the crustal moment of inertia to the total one as a function of stellar mass. The moment of inertia of the neutron stars is calculated in the slow rotation approximation, following Arnett & Bowers (1977). For a typical neutron star of 1.4 $M_\odot$, the ratio is 0.012 and 0.021 for MC and UC, respectively.

5. Conclusions and discussion

By using the ZM model with two sets of coupling constants for interactions between baryons, we have calculated the EOS for dense matter and the properties of neutron stars. Now we discuss astrophysical implications of our results.

First, early observations of binary radio pulsars gave neutron star masses of 1.4 $M_\odot < M_{\max} < 1.85\ M_\odot$ (Joss & Rappaport 1984; Taylor & Weinberg 1989) and recent estimations by Thorsett & Chakrabarty (1999) found 1.05 $M_\odot < M_{\max} < 1.66\ M_\odot$ from double neutron star binaries and 1.26 $M_\odot < M_{\max} < 1.7\ M_\odot$ from neutron star and white dwarf binaries. These observational results are satisfied by our EOSs.

Second, pulsar glitch phenomena have been suggested as a probe of neutron star properties (Link et al. 1992). The postglitch behavior of the pulsar indicates a change in the spindown rate, $\Delta\dot{\Omega}/\dot{\Omega}$, ranging from a fraction of one percent (Crab) to a few percent (2.4% of Vela, Alpar 1993). According to the "two component model" (Shapiro & Teukolsky 1983),

$$\frac{\Delta\dot{\Omega}}{\dot{\Omega}} = \frac{I_c}{I_{tot}}, \quad (28)$$

where I_{tot} is the total moment of inertia of the pulsar and I_c is the moment of inertia of the pulsar crust. Like other relativistic field models, the ZM model simultaneously yield low neutron star maximum masses and large crust (see above section), which just is the requirements of astronomical observations (Alpar 1993; Balberg 1999). The significant difference between UC and MC in terms of the ratio I_c/I_{tot} might provide a possible clue to determine coupling constants and equations of state through astronomical observations.

Third, the implications of hyperon formation for neutron star cooling have been discussed in several studies (Prakash et al. 1992; Prakash 1994; Haensel & Gnedin 1994; Lattimer et al. 1994; Schaab et al. 1996). According to current point of view hyperons will provide direct Urca processes. For more details about the threshold conditions at which hyperon – related direct Urca processes occur see Balberg et al. (1999). If neutron stars cool through direct Urca processes, their temperature should drop too rapidly to be detectable within less than 100 yr after their birth. But in recent years, there is strong evidence that actual surface thermal radiation has been detected for some pulsars, i.e., PSR 0833–45 (Ögelman et al. 1995), PSR 0656+14 (Finley et al. 1992), PSR 0630+178 (Halpern & Holt 1992), PSR 1005–52 (Ögelman & Finley 1993), which indicates that direct Urca processes are suppressed in the core through most of the thermal evolution stages. Fortunately, it was pointed out that the direct Urca processes may be suppressed if the participating baryons pair into a superfluid state, for more details see Schaab et al. (1998). So we are apt to the conclusion that baryons populating in the core of neutron stars should exist in a superfluid state.

Acknowledgements. This work was partly supported by the National Natural Science Foundation of China, grants 19773007, 19973003 and 19825109, and the National 973 Project on Fundamental Researches.

References

Alpar, M. A., Chau, H. F., Cheng, K. S., & Pines, D. 1993, ApJ, 409, 345
Ambartsumyan, V. A., & Saakyan, G. S. 1960, Soviet Astron., 4, 187
Arnett, W. D., & Bowers, R. L. 1977, ApJS, 33, 415
Balberg, S., & Gal, A. 1997, Nucl. Phys. A, 625, 435
Balberg, S., Lichtenstadt, I., & Cook, G. B. 1999, ApJ, 121, 515
Boguta, J., & Bodmer, A. R. 1977, Nucl. Phys. A, 292, 413 (BB)
Cheng, K. S., Dai, Z. G., & Yao, C. C. 1996, ApJ, 464, 348
Chin, S. A. 1977, Ann. Phys., 108, 301
Dai, Z. G., & Cheng, K. S. 1998, A&A, 330, 569
Ellis, J., Kapusta, J. I., & Olive, K. A. 1991, Nucl. Phys. B, 348, 345
Halpern, J. P., & Holt, S. S. 1992, Nature, 357, 222
Finley, J. P., Ögelmann, H., & Kiziloğlu, Ü. 1992, ApJ, 394, L21
Glendenning, N. K. 1985, ApJ, 293, 470
Glendenning, N. K. 1996, Compact Stars (New York: Springer)
Glendenning, N. K., & Moszkowski, S. A. 1991, Phys. Rev. Lett., 67, 2414
Haensel, P., & Gnedin, O. Yu. 1994, A&A, 290, 458
Haensel, P., Zdunik, J. L., & Dobaczewski, J. 1989, A&A, 222, 353
Joss, P. C., & Rappaport, S. A. 1984, ARA&A, 22, 537
Kapusta, J. I., & Olive, K. A. 1990, Phys. Rev. Lett., 64, 13
Lattimer, J. M., Riper, K. A. V., Prakash, M., & Prakash, M. 1994, ApJ, 425, 802
Knorren, R., Prakash, M., & Ellis, P. J. 1995, Phys. Rev. C, 52, 3470
Link, B., Epstein, R. I., & Van Riper, K. A. 1992, Nature, 359, 616
Ögelman, H. 1995, in the lives of the neutron stars, ed. M. A. Alpar, Ü. Kiziloğlu, & J. van Paradjis (Dordrechet: Kluwer), 101
Ögelman, H., & Finley, J. P., ApJ, 413, L31
Ögelman, H., Finley, J. P., & Zimmermann, H. U., Nature, 361, 136
Prakash, M. 1994, Phys. Rep., 242, 297
Prakash, M., et al. 1997, Phys. Rep., 280, 1
Prakash, M., Lattimer, J. M., & Pethick, C. J. 1992, ApJ, 390, L77
Schaffner, F., & Mishustin, I. N. 1996, Phys. Rev. C, 53, 1416
Schaab, Ch., Balberg, S., & Schaffner-Bielich, J. 1998, ApJ, 504, L99
Schaab, Ch., Weber, F., Weigel, M. K., & Glendenning, N. K. 1996, Nucl. Phys. A, 605, 531
Shapiro, S. L., & Teukolsky, S. A. 1983, Black Holes, White Dwarfs, and Neutron stars (New York: Wiley)
Sumiyoshi, K., & Toki, H. 1994, ApJ, 422, 700
Sumiyoshi, K., Kuwabara, H., & Toki, H. 1995, Nucl. Phys. A, 581, 725
Sumiyoshi, K., Toki, H., & Brockmann, R. 1992, Phys. Lett. B, 276, 393
Taylor, J. H., & Weisberg, J. M. 1989, ApJ, 345, 908
Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288
Walecka, J. D. 1974, Ann. Phys., 83, 491
Wolszczan, A. 1991, Nature, 350, 688
Thorsett, S. E., Arzoumanian, Z., Mckinnon, M. M., & Taylor, J. H. 1993, ApJ, 405, L29
Zimanyi, J., & Moszkowski, S. A. 1990, Phys. Rev. C, 42, 416 (ZM)