CPC(HEP & NP), 2011, **35**(6): 539–542 Chinese Physics C Vol. 35, No. 6, Jun., 2011

Influences of the bag constant on properties of hybrid stars*

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Abstract: Influences of the bag constant on the properties of hybrid stars are investigated by using relativistic mean field theory and the MIT bag model to describe the hadron phase and quark phase in the interior of neutron stars, respectively. Our results indicate that the onset of hadron-quark phase transition is put off and the appearance of hyperon species is increased with the increase in bag constant. As a result, the hybrid star equation of state for a mixed phase range stiffens whereas that of the quark phase range softens, and the gravitational mass as well as the corresponding radius of hybrid stars are increased obviously. The gravitational mass of a hybrid star is increased from 1.42 $M_\odot$ ($M_\odot$ is solar mass) to 1.63$M_\odot$ and the corresponding radius is changed from 9.1 km to 12.2 km when the bag constant ($B^{1/4}$) is increased from 170 MeV to 200 MeV. It is interesting to find that hybrid star equations of state become non-smooth when the TM2 parameter sets in the framework of relativistic mean field theory used to describe the hadronic matter, and consequently, the third family of compact stars appear in the mass-radius relations of hybrid stars in the narrow scope of the bag constant from 175 MeV to 180 MeV. These show that the choice of the bag constant in the MIT bag model has significant influence on the properties of hybrid stars.

Key words: hybrid stars, bag constant, equations of state, mass-radius relations

PACS: 12.39.Ba, 26.60.-c, 97.60.Jd **DOI:** 10.1088/1674-1137/35/6/005

1 Introduction

Over the four decades since the observation of the first pulsar, known as a rotating neutron star, studies on the properties of neutron stars have been one of the fascinating subjects in astrophysics as well as in nuclear astrophysics. There exist many complex phase structures or degrees of freedom in neutron star matter, especially in the high density core. The hyperon species appear in the neutron star matter at a density of about twice the normal nuclear matter density [1–3]. Phase transition from hadronic matter phase to kaon condensation or deconfined quark matter phases will take place with a further increase in density, which means the formation of hybrid stars [4, 5]. Since the pioneering work by Glendenning in 1992 [6], many authors have studied hybrid stars with various hadronic and quark matter models [7–9]. In many of the studies on hybrid stars, the hadronic phase was often described by relativistic mean field theory (RMFT) [1, 3] and quark matter phase by different models, such as the MIT bag model [10], the Nambu–jona-Lasinio (NJL) model [11], the mass-density-dependent quark model [12] and the effective mass bag model [7, 13]. Since the properties of hybrid stars depend weakly on the hadronic models but mainly on the quark models or model parameters describing quark phases [9], it is significant to adopt a new quark model or to adjust the model parameters to study them. In the MIT bag model, being the pressure difference of internal and external vacua, the bag constant B is an adjustable parameter and the value of B will have a significant impact on the properties of hybrid stars when the bag model is used to descr-

Received 18 October 2010
* Supported by the National Natural Science Foundation of China (10275029, 10675054), Natural Science Foundation of Henan Education Department (2008A140009), Science Foundation of Nanyang Normal University (nytc2006k98) and Natural Science Foundation of Henan Province (112300410187)
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ibe the quark matter phase in the interior of neutron stars. In this paper, we study the influence of the bag constant on the properties of hybrid stars by using relativistic mean field theory and the MIT bag model to describe the hadron phase (HP) and quark phase (QP), respectively. We find that the onset of hadron-quark phase transition is put off and the appearance of hyperon species is increased with the increase of bag constant. As a result, the hybrid star equation of state (EOS) for mixed phase region stiffens whereas that of quark phase region softens and the gravitational mass as well as the corresponding radius of hybrid stars are increased obviously. It is interesting to find that the hybrid star equations of state become non-smooth when we use the TM2 parameter sets [14] in the framework of relativistic mean field theory to describe the hadron phase, and consequently, the third family of compact stars [15] appear in the mass-radius relations of hybrid stars in the narrow scope of the bag constant ($B^{1/4}$) from 175 MeV to 180 MeV.

This paper is organized as follows. In Sec. 2, we discuss the hadron-quark mixed phase. In Sec. 3. our numerical results are presented. Sec. 4 is a short summary.

2 Hadron-quark mixed phase

Since the physics of the hadronic phase of hybrid stars in the framework of RMFT is best understood, we shall discuss the hadron-quark mixed phase in this section. In a thermodynamical system as a mixed phase of hybrid star matter, there exist two independent components or conserved charges, namely, baryon number density and electric charge [6]. For the mixed phase (MP) consisting of hadronic matter and quark matter, we choose $\mu_{\rm e}$, $\mu_{\rm n}$ as independent variables and use the Gibbs condition for phase equilibrium and constraint for global electric charge neutrality to depict the mixed phase. The Gibbs condition for mechanical and chemical equilibrium at zero temperature is

$$p_{\rm HP}(\mu_{\rm n},\mu_{\rm e}) = p_{\rm QP}(\mu_{\rm n},\mu_{\rm e}). \tag{1}$$

In the MP, hadrons and quarks are in chemical equilibrium and satisfy

$$\mu_{\rm n} = \mu_{\rm u} + 2\mu_{\rm d}, \tag{2}$$

which is the joint condition of hadronic phase, hadron-quark MP and pure QP. The MP satisfies the global charge neutral condition,

$$q_{\rm MP} = (1-\gamma)q_{\rm HP} + \gamma q_{\rm QP} = 0, \tag{3}$$

and the total baryon number conservation

$$\rho_{\rm MP} = (1-\gamma)\rho_{\rm HP} + \gamma\rho_{\rm QP}, \tag{4}$$

where $\gamma = V_{\rm Q}/V$ (and $V = V_{\rm Q} + V_{\rm H}$) is the volume fraction of quark matter in the MP ($\gamma = 0$ for the pure hadronic phase, and $\gamma = 1$ for pure quark phase. In the course of the phase transition, γ increases from 0 to 1). The total energy density of the MP is given by

$$E_{\rm MP} = (1-\gamma)E_{\rm HP} + \gamma E_{\rm QP}. \tag{5}$$

Sets of nonlinear transcendental equations of the HP and MP are solved self-consistently at the definite baryon number density, and then the EOS of hadronic phase, mixed phase and quark phase can be obtained. Linking them together, we obtain the total EOS for neutron star matter in the interior of a hybrid star.

3 Numerical results

Using one of the parameter sets, Gl85, in the framework of RMFT to describe the hadronic matter and the MIT bag model with various bag constants to SQM, we calculate the hybrid star particle fractions, the EOS and the corresponding stellar mass-radius relations numerically.

The particle fractions of the hybrid star matter versus the total baryon number density are shown in Fig. 1, where (a), (b), (c) and (d) are the corresponding bag constant $B^{1/4}$ to 170, 180, 190 and 200 MeV, respectively. One can see from Fig. 1 that, in (a), the hadron-quark phase transition begins at ρ=0.15 fm^{-3} and ends at ρ=0.68 fm^{-3}, no hyperon appears, and in (b), the onset and end points of the phase transition are put off to ρ=0.23 fm^{-3} and ρ=0.93 fm^{-3}, with one hyperon, Λ, appearing. In both (c) and (d), the onset and end points are put off to $\rho >$0.3 fm^{-3} and $\rho >$1.1 fm^{-3}, with two (Λ, Σ^-) and three hyperons (Λ, Σ^-,Σ^0) appearing, respectively.

We calculate the EOS, pressure versus energy density, of hybrid star matter with different bag constants. The results are shown in Fig. 2. It is apparent that with an increase in bag constant, the hybrid star equations of state for the mixed phase region stiffen whereas those of the quark phase region soften. In the MIT bag model, being the pressure difference of internal and external vacua, the bag constant is added to the energy density and subtracted from the pressure expression of strange quark matter when the MIT bag model is used to describe the SQM. In hybrid star matter, if $B^{1/4}$ increases, the (SQM) pressure decreases and therefore the condition of hadron-quark phase transition can not be met until a large baryon

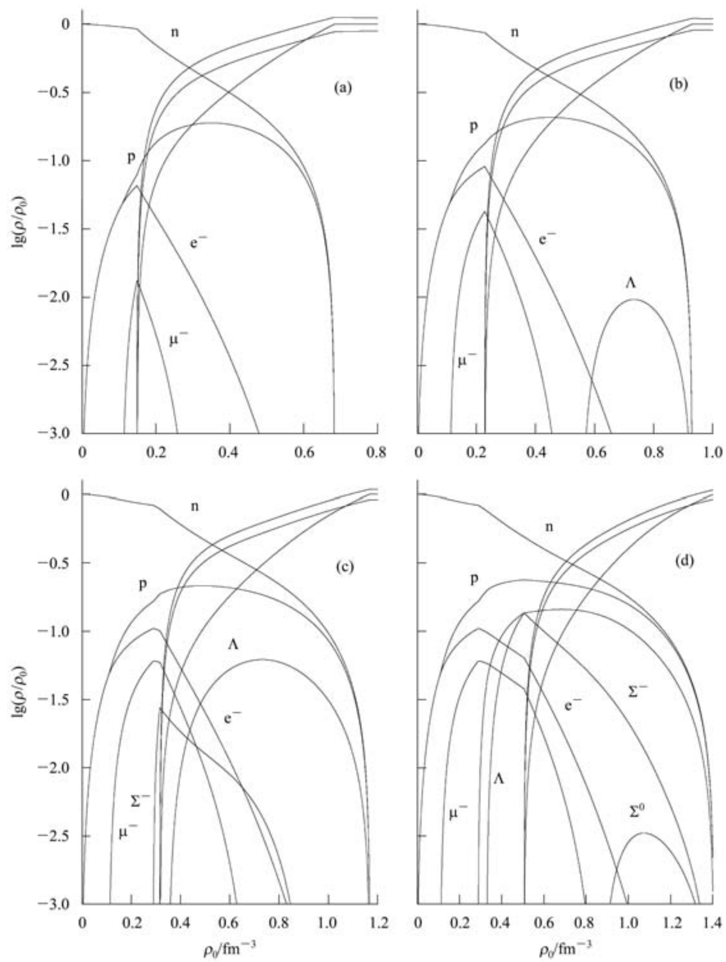

Fig. 1. Particle fractions for Hybrid star matter vs baryon number density ρ. Here, (a), (b), (c) and (d) are the corresponding bag constants, $B^{1/4}$ to 170, 180, 190 and 200 MeV respectively.

number density is reached. As a result, the threshold of phase transition is put off and the hybrid star equation of state for the mixed phase region stiffens, whereas that of the quark phase region softens.

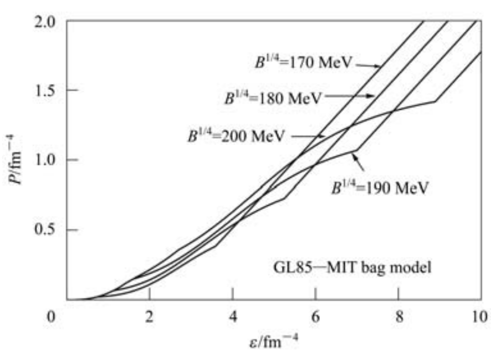

Fig. 2. Hybrid star equations of state.

With the EOS shown in Fig. 2 as the input, we integrate the Telman-Oppenheimer-Volkoff (TOV) equations [16] and calculate the mass-radius relations of hybrid stars numerically. The evaluated results are given in Fig. 3. One can see from Fig. 3 that with the increase in bag constant, the gravitational mass and corresponding radius of the star increase. The star mass is increased from $1.42M_{\odot}$ ($M_{\odot} = 1.99\times10^{33}$ g is the solar mass) to $1.66M_{\odot}$ and the corresponding radius is changed from 9.2 km to 12.1 km when the bag constant ($B^{1/4}$) is increased from 170 MeV to 200 MeV. These results show that the properties of the hybrid star are very sensitive to the choice of the bag constant if the MIT bag model is used to describe the quark matter.

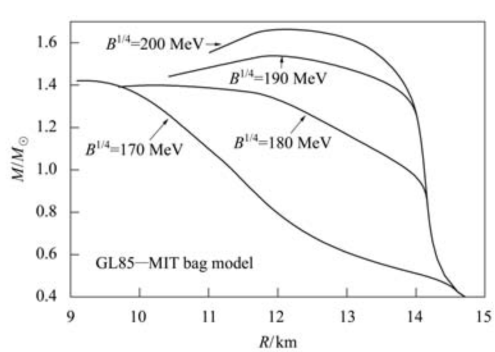

Fig. 3. Hybrid star mass-radius relations for different bag constants.

We have also studied the equations of state and corresponding mass-radius relations of the hybrid star using the TM2 parameter sets in the framework of RMFT to describe the hadron phase. The calculational results are given in Fig. 4 and Fig. 5, respectively. One can see in Fig. 4 that the hybrid star equations of state are non-smooth EOS. This non-smooth EOS will influence the mass-radius relations of hybrid stars further.

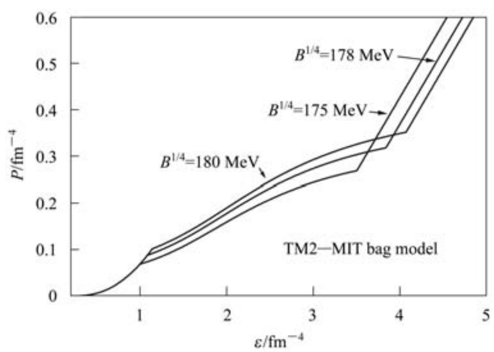

Fig. 4. The hybrid star equations of state, where the TM2 parameter sets are used to describe the hadron phase.

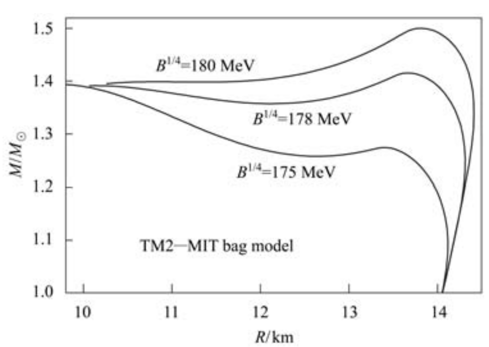

Fig. 5. The hybrid star mass-radius relations corresponding to EOS in Fig. 4. The third family of compact stars appear in these mass-radius curves.

The mass-radius curves in Fig. 5 calculated from the non-smooth EOS in Fig. 4 and the mass-radius curves in Fig. 3 from smooth EOS exhibit very different features of stellar sequence. The latter ones are normal hybrid star mass-radius relations with one segment of stable star, and the former ones are the mass-radius relations of the third family compact stars (TF) with two segments of stable stars [15]. TF only exists in the narrow scope of the bag constant $B^{1/4}$ from 175 MeV to 180 MeV when the TM2 parameter sets are used to describe the hadron phase in the hybrid stars. The existence of the TF is equivalent to the existence of hadron-quark phase transition at large densities. It can be concluded that there would exist more complex phase structures in the interior of a third family compact star owing to its higher central density than that of the neutron stars.

4 Summary

We have studied the influence of the bag constant on the properties of the hybrid star, making use of the MIT bag model with adjusted bag constant to describe the SQM and GL85 parameter sets in the framework of the RMFT to hadronic matter. We find that the onset of the hadron-quark phase transition is put off and the appearance of hyperon species is increased with the increase in the bag constant. As a result, the hybrid star equation of state (EOS) for a mixed phase range stiffens, whereas that of the quark phase range softens and the gravitational mass as well as the corresponding radius of hybrid stars is increased obviously with an increase in bag constant. It is interesting to find that the hybrid star equations of state become non-smooth when we use the TM2 parameter sets in the framework of RMFT to describe the hadron phase, and consequently, the third family of compact stars appears in the mass-radius relations of hybrid stars in the narrow scope of the bag constant ($B^{1/4}$) from 175 MeV to 180 MeV. The existence of the TF is equivalent to the existence of a hadron-quark phase transition at high densities. One can conclude that the choice of the bag constant in the MIT bag model has a significant influence on the properties of hybrid stars.

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