One-gluon-exchange effect on the properties of quark matter and strange stars*

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Abstract: We present a modified version of quark mass scaling via considering the important one-gluon-exchange interaction between quarks in the quark mass density-dependent model. The properties of strange quark matter and the structure of strange stars are then studied with the new scaling and a self-consistent thermodynamic treatment. It is found that the one-gluon-exchange effect lowers the system energy considerably, makes the equation of state stiffer, and the sound velocity tends to the ultra-relativistic value faster, which make the biggest value of the maximum mass of strange stars become as big as approximately 2 times the solar mass, in accordance with the latest astronomical observations.

Key words: quark matter, one-gluon-exchange, strange stars

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1 Introduction

Strange quark matter (SQM) has long been a hot topic in nuclear physics. Early in 1971, Bodmer supposed that SQM might be the most stable quantum state of hadronic matter [1]. Especially since Witten's conjecture in 1984 that SQM could be the true ground state of quantum chromodynamics (QCD) at finite baryon density [2, 3], many scientists have worked on this subject and obtained many interesting results [4–8].

Because SQM might be absolutely stable, people believe that the so-called pulsars might be strange stars. According to the theory of gravitation, a gravitational collapse may take place in the core of a massive star at the end of its evolutionary path. If the mass of a star is 1.44 times the solar mass ($M_{\odot}$), the star's gravitation will be strong enough to squeeze electrons into protons, and the star could become a neutron star (the previously so-called pulsar). In recent years, many investigations show that some of the young millisecond pulsars are most likely to be strange stars rather than neutron stars [9] because SQM could originate from a first-order hadron-quark phase transition in the core of a massive star.

Presently, and perhaps in the foreseeable future, it is difficult to work out QCD directly and strictly. At the same time, the application of perturbative QCD to a strong-coupling domain is obviously unreliable while the lattice approach faces difficulties. Therefore, one has to rely on phenomenological models in studying the properties of quark matter and strange stars.

There are many phenomenological models, such as the MIT bag model, Nambu-Jona-Lasinio (NJL) model, quasi-particle bag model, quark masses density-dependent (QMDD) model, potential model, etc. The MIT bag model is one of the most famous models, and it has been used to investigate the properties of SQM by many authors [10].

Conventionally, the bag constant was assumed to be density-independent, which can not be justified in general. In chiral models, the bag constant should be given as a function of the chiral condensate, and is thus dependent on the density and/or temperature. Recently, the medium effects on the surface tension of strangelets was studied with an extended quasiparticle approach [8].

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In recent years, the quark model with confinement by the density dependence of quark masses (CDDM) has been developed [11–19]. These kinds of models can be traced back to the 1980s, when an inversely linear scaling of quark masses was suggested [20] and extended to include strange quarks [21]. The linear scaling was derived from the bag conception, and thus gave very similar results as those in the bag model if the thermodynamic treatment was correct [22].

Based on the linear confinement interaction and the in-medium chiral condensate, an inversely cubic-root scaling was later derived at zero temperature [11] and extended to finite temperature [15]. With the cubic scaling and corrected thermodynamic treatment, the properties of strangelets in both ordinary and color-flavor-locked phase have been explored [23, 24].

At lower density, the confinement interaction is dominant. With increasing density, however, the perturbative interaction will become more and more important. On application of the quark mass scaling derivation procedure and the thermodynamic formulas of Wen et al. (WZP model) [15], Modarres and Gholizade calculated the thermodynamic properties of SQM in ordinary phase [25]. They introduced the one-gluon-exchange interaction obtained from the Fermi liquid picture. For the confinement, however, they did not include it, or simply did the same as in the bag model by adding a constant vacuum energy density. In this paper, therefore, we will study the properties of SQM in the quark model considering both the linear confinement and the one-gluon-exchange interactions. We find that the one-gluon-exchange makes SQM more stable, and the sound velocity approaches the ultra-relativistic value faster, which leads to an acceptable maximum mass of strange stars as large as about 2 times the solar mass.

The present paper is arranged as follows. In Section 2, we derive a new quark mass scaling which considers both the linear confinement and the one-gluon-exchange effect. Then in Section 3, we present the thermodynamic formulas and study the equation of state (EoS) of strange quark mass with the newly derived quark mass scaling. And the obtained EoS is applied to investigate the properties of strange stars in Section 4. Section 5 is a short summary.

2 Quark mass scaling considering one-gluon-exchange effect

In Fowler, Raha and Weiner's original paper [20], the density dependence of u and d quarks was given as

$$m_{\mathrm{u/d}}=\frac{B_0}{3n_{\mathrm{b}}}, \tag{1}$$

where n_{b} is the baryon number density, B_0 is interpreted as the vacuum bag constant. For strange quarks, Chakrabarty et al. gave [21]

$$m_{\mathrm{s}}=m_{\mathrm{s0}}+\frac{B_0}{3n_{\mathrm{b}}}, \tag{2}$$

with m_{s0} being the current mass of a s quark.

In order to let the model be able to describe phase transition, Zhang et al. extended the quark mass scaling to finite temperature with the ansatz [14]

$$m_{\mathrm{I}}=\frac{B_0}{3n_{\mathrm{b}}}\left[1-\left(\frac{T}{T_{\mathrm{c}}}\right)^2\right], \tag{3}$$

where T_{c} is the critical temperature. But soon later, they found this parametrization causes an unreasonable result: the radius of a strangelet decreases with increasing temperature. So they added a linear term in temperature, then the parametrization becomes [26]

$$m_{\mathrm{I}}=\frac{B_0}{3n_{\mathrm{b}}}\left[1-a\left(\frac{T}{T_{\mathrm{c}}}\right)+b\left(\frac{T}{T_{\mathrm{c}}}\right)^2\right]. \tag{4}$$

Based on the in-medium chiral condensates and quark confinement, the following quark mass scaling is derived [11],

$$m_{\mathrm{q}}=m_{\mathrm{q0}}+\frac{D}{n_{\mathrm{b}}^{1/3}} \quad (\mathrm{q}=\mathrm{u,d,s}), \tag{5}$$

where D is a parameter determined by stability arguments. Later, in order to describe phase transition, the quark mass scaling expression (5) was extended to finite temperature [15],

$$m_{\mathrm{q}}=m_{\mathrm{q0}}+\frac{D}{n_{\mathrm{b}}^{1/3}}\left[1-\frac{8T}{\lambda T_{\mathrm{c}}}\exp\left(-\lambda\frac{T_{\mathrm{c}}}{T}\right)\right], \tag{6}$$

in which T_{c} is also the critical temperature of phase transition, and $\lambda=\mathrm{LambertW}(8)$.

The above scalings consider only the interaction of confinement. They are, in principle, merely correct at lower density. With increasing density, the perturbative interactions between quarks will become more and more important. So in this paper, we consider the one-gluon-exchange interaction which is the first-order approximation of perturbative interactions between quarks.

In terms of the QMDD model, the strong interaction between quarks is included within the appropriate variation of quark masses with density. We define an equivalent mass of quark as

$$m_{\mathrm{q}}=m_{\mathrm{q0}}+m_{\mathrm{I}}, \tag{7}$$

where m_{q0} is the quark current mass, and m_I is the interaction part. The interaction part of the quark mass can be expressed as [11, 15]

$$m_I = \frac{\langle H_I \rangle}{\sum\limits_{q=u,d,s} [\langle \bar{q}q \rangle_{n_b} - \langle \bar{q}q \rangle_0]}, \tag{8}$$

in which $\langle H_I \rangle$ is the interacting part of the energy density from interactions. It is linked to density n_b by [27]

$$\langle H_I \rangle = 3 n_b v(r), \tag{9}$$

where

$$r = \left(\frac{2}{\pi n_b} \right)^{1/3} \tag{10}$$

is the average distance between quarks at the density n_b, $v(r)$ is the quark-quark interaction. To include the perturbative interaction, we first consider one-gluon-exchange interaction between quarks as the first-order approximation, i.e., the inter-quark interaction is expressed as

$$v(r) = \sigma r - \frac{4}{3} \frac{\alpha_s}{r}, \tag{11}$$

where σ is the string tension, α_s is the running coupling constant of QCD.

The relative quark condensate in Eq. (8) can be expanded to a Taylor series. For the first order approximation, we have the model-independent result

$$\frac{\langle \bar{q}q \rangle_{n_b}}{\langle \bar{q}q \rangle_0} = 1 - \frac{n_b}{\rho^*}, \tag{12}$$

where

$$\rho^* = \frac{m_\pi^2 f_\pi^2}{\sigma_N}. \tag{13}$$

Taking the pion mass $m_\pi = 140$ MeV, the pion decay constant $f_\pi = 93.3$ MeV, and the pion-nucleon sigma term $\sigma_N = 45$ MeV, we then have $\rho^* \approx 3.79 \times 10^6$ MeV^3.

Substituting (9)–(13) into (8), we get a new quark mass scaling as

$$m_I = \frac{D}{n_b^{1/3}} - C n_b^{1/3}, \tag{14}$$

where the first term stands for linear confinement interaction, the second term presents the one-gluon-exchange effect, and

$$D = \frac{3(2/\pi)^{1/3} \sigma_0 \rho^*}{-\sum\limits_q \langle \bar{q}q \rangle_0}, \tag{15}$$

$$C = \frac{4(\pi/2)^{1/3} \alpha_s \rho^*}{-\sum\limits_q \langle \bar{q}q \rangle_0}. \tag{16}$$

One may find that the m_I in Eq. (14) will finally go to zero and even become negative at some extremely high density. This is caused by the divergence in Eq. (11) at small distance. This can be eliminated by adding a damping factor, as has been done in Ref. [28]. The concrete form of the damping factor should not matter because it influences only the behavior of quark matter at extremely high densities while in that case quark matter has the important characteristic of asymptotic freedom.

Here we use another treatment approach. Suppose the m_I is zero at a specific value n_0 which can be determined by letting m_I in Eq. (14) be zero, i.e.,

$$n_0 = \left(\frac{D}{C} \right)^{3/2}. \tag{17}$$

If the density is less than n_0, m_I as given by Eq. (14). If the density is larger than n_0, the quark has merely the corresponding current mass and does not change further with the density. Normally, n_0 is a very high density.

3 Thermodynamic formulas and properties of strange quark matter

In the previous section, we have discussed quark mass scaling. A self-consistent thermodynamic treatment is also very important when quark masses are density-dependent. There are many discussions in the literature on thermodynamic treatment [12, 14, 15, 18, 19, 21, 22]. Because other treatments suffer from the drawback that the lowest energy state does not correspond to zero pressure, we use the thermodynamic treatment in Refs. [12] and [15]. The full thermodynamic consistency has been represented in Ref. [19].

At zero temperature, the energy density and pressure are expressed as

$$E = \sum_i m_i n_i F(x_i), \tag{18}$$

$$P = \sum_i m_i n_i x_i^2 G(x_i) - \sum_i m_i n_i f(x_i), \tag{19}$$

where the auxiliary functions $F(x_i)$, $G(x_i)$ and $f(x_i)$ are defined by

$$F(x_i) \equiv \frac{3}{8x_i^3} \left[x_i \sqrt{x_i^2+1}(2x_i^2+1) - \text{arcsinh}(x_i) \right], \tag{20}$$

$$G(x_i) \equiv \frac{1}{8x_i^5} \left[x_i \sqrt{x_i^2+1}(2x_i^2-3) + 3\text{arcsinh}(x_i) \right], \tag{21}$$

$$f(x_i) \equiv -\frac{3}{2x_i^3}\frac{n_b}{m_i}\frac{dm_i}{dn_i}\left[x_i\sqrt{x_i^2+1}-\text{arcsinh}(x_i)\right]. \tag{22}$$

In the above three functions,

$$x_i \equiv \frac{\nu_i}{m_i} = \frac{\sqrt{\mu_i^2-m_i^2}}{m_i} \tag{23}$$

is the ratio of Fermi momentum to the corresponding quark mass for particle type i (i=u, d, s, e), while the hyperbolic function is given by arcsinh $(x) \equiv \ln(x+\sqrt{x^2+1})$.

Following the previous authors [3], we assume the SQM to be a Fermi gas mixture of u, d, s quarks and electrons with chemical equilibrium maintained by the weak-interaction processes: $d(s) \leftrightarrow u+e^-+\bar{\nu}_e$, $u+d \leftrightarrow u+s$, and so on.

For a given baryon number density n_b and total electric charge density Q, the relationships between chemical potentials and number densities of quarks and electrons are determined by the following equations,

$$\mu_d = \mu_s \equiv \mu, \tag{24}$$

$$\mu_u + \mu_e = \mu, \tag{25}$$

$$n_b = \frac{1}{3}(n_u+n_d+n_s), \tag{26}$$

$$\frac{2}{3}n_u - \frac{1}{3}n_d - \frac{1}{3}n_s - n_e = Q. \tag{27}$$

Here, we consider only neutral SQM, so we take $Q=0$ in Eq. (27).

The particle number density n_i (i = u, d, s, e) can be expressed as

$$n_i = \frac{g_i}{6\pi^2}(\mu_i^2-m_i^2)^{3/2}, \tag{28}$$

where g_i is the degeneracy factor with the value 6 for quarks and 2 for electrons.

The quark masses m_u, m_d, and m_s in the above equations should be replaced by the density-dependent expression in Eq. (7) with the interaction part m_I given by Eq. (14) in order to include the one-gluon-exchange interaction between quarks. The electron mass, m_e, is 0.511 MeV. Once n_b is given, the effective chemical potentials μ_i (i=u, d, s, e) can be obtained by solving the equation group (24)–(27). The number densities n_u, n_d, n_s and n_e can be easily calculated, and then the energy density and pressure are obtained from Eqs. (18)–(23).

The velocity of sound c represents one of the most important properties of SQM, which is defined by

$$c = \sqrt{\left|\frac{dP}{dE}\right|}. \tag{29}$$

In the following calculations, due to the current masses of u and d quarks being so small that their value uncertainties are unimportant, we take the fixed values $m_{u0} = 5$ MeV and $m_{d0} = 10$ MeV. As for s quarks, the value range is about 95 ± 25 MeV [29], we adopt $m_{s0} = 100$ MeV. The range of D has been discussed in detail before, such as in Refs. [12, 19]. In Ref. [19], $D^{1/2}$ was found to be in the range (156, 270) MeV. Here, we employ the values $D^{1/2} =$ 160, 180 MeV.

Naturally, we mainly investigate the effect of one-gluon-exchange as the first-level approximation of a quark's perturbative interaction in the present work. To study the properties of SQM, we should further determine the values of parameter C. Of course, it is not arbitrary. The running coupling constant of QCD with the correction of the analytic perturbation theory in the case of one-loop order is [30]

$$\alpha_s(Q^2) = \frac{1}{\beta_0}\left[\frac{1}{\lg(Q^2/\Lambda^2)} + \frac{\Lambda^2}{\Lambda^2-Q^2}\right], \tag{30}$$

where $\beta_0 = (11-2N_f/3)/4\pi$, N_f is the number of flavors. We take $\Lambda = 300$ MeV here. In this condition the α_s value is in the range of $(0, 1.25)$. From Eq. (16) we know that C value is in the range of (0, 0.918) when $-\sum_q\langle\bar{q}q\rangle_0$ varies from $3\times(300\ \text{MeV})^3$ to $3\times(200\ \text{MeV})^3$. In this paper, we take $C = 0.1$, 0.6 as examples. To compare with the previous results, we also give the results for taking $C = 0$.

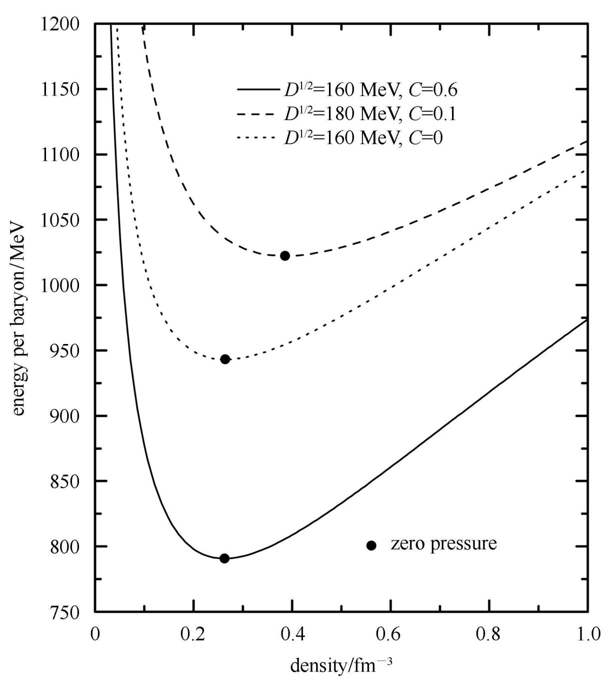

Fig. 1. The energy per baryon vs baryon number density for different parameters. The zero pressure points are exactly coincident with the lowest energy state.

In Fig. 1, we give the energy per baryon E/n_b versus the baryon number density n_b for the three pairs of parameters.

It is found from the figure that SQM can be more stable if the one-gluon-exchange effect is taken into account. The points marked with solid points ('•') are the zero pressure points where the pressure within SQM is zero. Due to the density dependence of quark masses, we have adopted the thermodynamic treatment in Refs. [12, 15, 19], which ensures that the zero pressure point is exactly coincident with the minimum energy per baryon.

In Fig. 2, we show the corresponding EoS of SQM for diferent parameter sets, as in Fig. 1. One can see that all of the three lines approach the free gas EoS at high density as expected. To show the one-gluon-exchange effect, we give also the curve for $C = 0$. Obviously, the EoS becomes stiffer with increasing C value for the same D value. Therefore, the one-gluon-exchange interaction makes the EoS stiffer, which means that it increases the maximum mass of strange stars.

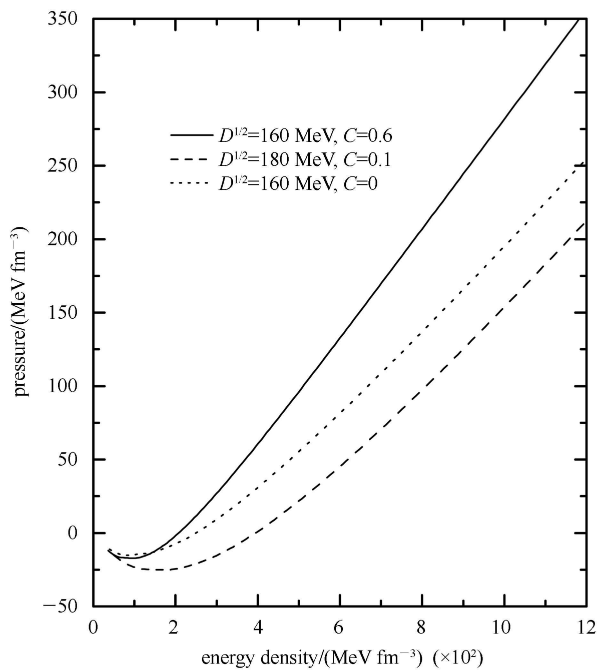

Fig. 2. The EoS of SQM for different parameter groups. All curves approach the altra-relativistic case at higher density. The stiffer EoS will correspond to a bigger maximum mass of strange stars.

In Fig. 3, we plot the velocity of sound in SQM versus the baryon density for the same groups of parameters. The velocity of sound asymptotically tends to the ultra-relativistic value $1/\sqrt{3}$, as has happened in other models due to the asymptotic freedom. At lower density, they are significantly different because of the density-dependence of quark masses.

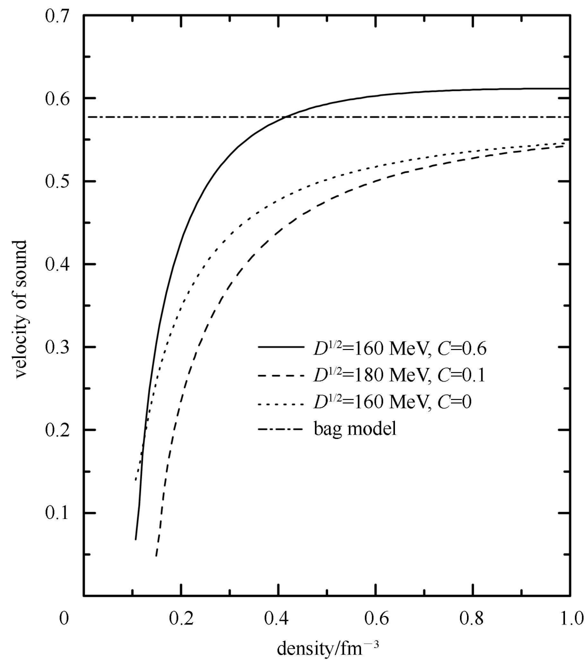

Fig. 3. The velocity of sound in SQM. The solid asymptotical horizontal line is for the MIT Bag model case, while the other three lines are the results of the present model.

4 Properties of strange stars

Strange stars have been studied by many authors with their obtained EoS. For example, different models [31, 32] have been used to investigate the possible EoS of solid quark matter and to explain the stiffness required by observed massive pulsars [33]. Recently, the properties of strange stars have been researched by adopting the QMDD model [34] where the quark mass scaling is employed as $m_\mathrm{q} = m_{\mathrm{q}0} + D/n_\mathrm{b}^x$ for a wide range values of x=1/10, 1/5, 1/3, 1, 2. Their calculations show that the resulting maximum mass always lies between $1.5M_\odot$ and $1.8M_\odot$ for all the scalings chosen there. In this section, we study the mass-radius relation of strange stars using the EoS obtained in this paper, which includes the important one-gluon-exchange effect.

As usual, we assume the strange star to be a spherically symmetric object. Its stability is determined by the Tolman-Oppenheimer-Volkov (TOV) equation

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{GmE}{r^2}\left(1+\frac{P}{E}\right)\left(1+\frac{4\pi r^3 P}{m}\right)\left(1-\frac{2Gm}{r}\right)^{-1}, \quad (31)$$

which is a general relativistic equilibrium equation of an ideal spherically symmetric hydrostatic object under the action of gravitational field. In Eq. (31),

$$m \equiv \int_0^r 4\pi E r'^2 \mathrm{d}r', \tag{32}$$

or

$$\mathrm{d}m/\mathrm{d}r = 4\pi r^2 E, \tag{33}$$

and r is the distance from the core of the star to its surface, $G = 6.707\times10^{-45}$ MeV^{-2} is the gravitational constant, $m = m(r)$ is the mass within the radius r, $E = E(r)$ is the local energy density and $P = P(r)$ is the local pressure at the distance r.

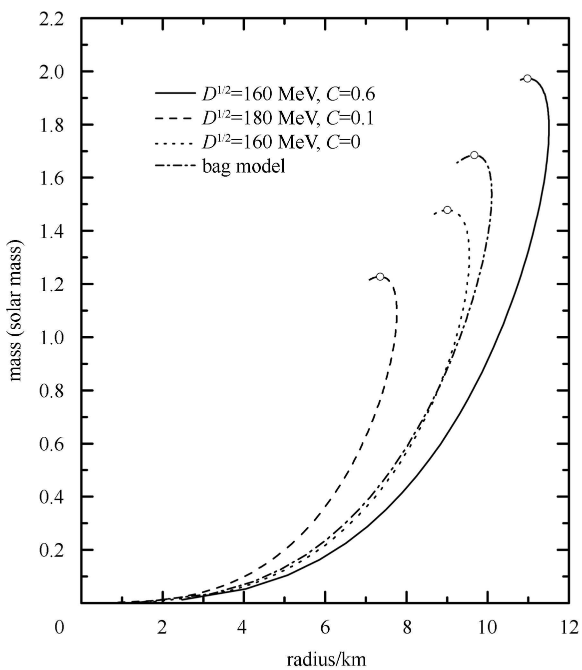

Fig. 4. The mass-radius relationship of strange stars. The points marked with a circle ('○') represent the maximum acceptable masses. For the bag model, $B^{1/4}$=150 MeV has been used.

If the EoS

$$P = P(E) \tag{34}$$

is given, then the structure of strange stars is obtained by solving Eqs. (31), (32) or (33), and (34). In the above section, we have presented the EoS of the SQM with the one-gluon-exchange effect. For an initial baryon number density, and accordingly an initial energy density and pressure, we can numerically solve Eq. (31) with the aid of the auxiliary Eq. (32) or (33). And then the mass and radius of strange stars can be obtained.

With the above sets of parameters, we plot the mass-radius relation in Fig. 4. The result for the bag model with a bag constant $B^{1/4} = 150$ MeV has also been plotted for comparison. The points marked with a circle ('○') stand for the largest acceptable masses $M_{\max}$. The biggest value of the acceptable mass is approximately 2 times the solar mass (the solid line). For that case, the corresponding EoS is the stiffest EoS as shown in Fig. 2. So our parametrization can provide a strange star with maximum mass close to $2M_\odot$ which is in accordance with the observed maximum mass [33]. We can find from the graph that the strange stars in this model are dimensionally bigger and more massive than the result in Ref. [12] if the important one-gluon-exchange effect is included in the EoS of SQM.

5 Summary

We have presented a new version of quark mass scaling in the QMDD model of SQM, and applied it to the investigation of strange stars. With increasing densities, the perturbative interaction between quarks becomes more and more important, so we have considered the one-gluon-exchange interaction between quarks as a first-order approximation. It is found that when one-gluon-exchange effect is considered, SQM can be more stable, and the velocity of sound can tend to the ultra-relativistic value faster. Our parametrization can lead to stable strange stars with maximum mass as big as approximately 2 times the solar mass, which is in accordance with the newly observed maximum mass [35].

Naturally, the matter in a compact star can undergo deconfinement phase transition from hadronic matter to quark matter. Therefore, some compact stars could in fact be a strange hadronic star with a quark core. It is thus interesting to further study the structure of hybrid stars with mixed phase in the future.

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