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Strange star candidates revised within a quark model with chiral mass scaling *

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Abstract We calculate the properties of static strange stars using a quark model with chiral mass scaling. The results are characterized by a large maximum mass ($\sim 1.6\,M_\odot$) and radius (∼10 km). Together with a broad collection of modern neutron star models, we discuss some recent astrophysical observational data that could shed new light on the possible presence of strange quark matter in compact stars. We conclude that none of the present astrophysical observations can prove or confute the existence of strange stars.

Key words: dense matter — elementary particles — equation of state — stars: interiors

1 INTRODUCTION

Nowadays, new instruments with revolutionary techniques have enabled astrophysicists to perform detailed studies of large samples of galactic and extragalactic objects. The possible existence of a new class of compact stars, which is made entirely of deconfined u, d, s quark matter (strange quark matter (SQM)), is one of the most intriguing aspects of modern astrophysics. These compact objects are called strange stars (SSs). Whether or not SSs could truly exist has implications of fundamental importance for astrophysics, and for the physics of strong interactions (strange matter hypothesis) (Witten 1984).

However, most of the observational signatures related to compact stars can be explained by the conventional neutron star (NS) model. The strange star hypothesis is very speculative but it is difficult to conclusively rule them out. In principle, strange and neutron stars could coexist in the universe (Weber 2005), and under suitable physical conditions a neutron star may be converted to a strange star (Bombaci et al. 2004; Staff et al. 2007). Observationally, to distinguish whether a compact star is a neutron star or a strange star, one has to find a clear observational signature. In his recent review, Weber (Weber 2005 and references therein) argued that the unusual small radii exacted from observational data support that the compact objects SAX J1808.4–3658, 4U 1728–34, 4U 1820–30, RX J1856.5–3754 and Her X-1 are strange stars rather than neutron stars.

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These claims were based on an equation of state (EOS) using a "dynamical" density-dependent approach for SQM by Dey et al. (1998). Restoration of chiral quark masses at high density is incorporated in this model. With two different parameterizations considered (both giving an absolutely stable SQM configuration), this quark matter model clearly demonstrates those compact objects mentioned above are more compatible with a quark star model than a neutron star one.

However, from a basic point of view, the EOS for SQM should be calculated by solving the equations of quantum chromodynamics (QCD). As far as we know, such a fundamental approach is presently not available, and it is necessary to rely on non-perturbative QCD models for quark matter which incorporate the basic properties expected for QCD. In studying the EOS of quark matter, the most crucial problem is to treat quark confinement in a proper way. There were a lot of phenomenological models in literature, e.g., the MIT bag model and its variants, where confinement is described in terms of a density-dependent or density-independent bag constant (Farhi & Jaffe 1984; Madsen & Larsen 2003; Schertler et al. 1997; Wen et al. 2009; Wen et al. 2010), the quark-mass-density-dependent model, where the confinement is achieved by the density dependence of quark masses (Fowler et al. 1981; Chakrabarty 1991; Chakrabarty 1993; Chakrabarty 1996; Zhang et al. 2001; Zhang & Su 2002; Zhang & Su 2003; Wang 2000), and the Dey et al. (1998) model with built-in confinement.

In the MIT bag model, to get SS configurations with a mass-radius (MR) relation in agreement with the semiempirical MR relations (Li et al. 1995; Haberl & Titarchuk 1995) for SS candidates (For example: Her X-1 or 4U 1820–30), one must assume that quarks are confined in a large bag with the bag constant $B \simeq 110$ MeV fm^{-3}, much larger than the *standard value* $B = 56$ MeV fm^{-3}, which is able to reproduce the mass spectrum of light hadrons and heavy mesons (DeGrand et al. 1975; Haxton & Heller 1980). The large values of B are also not allowed by the requirement that SQM is stable in bulk (Farhi & Jaffe 1984; Madsen & Larsen 2003), which indicates that the bag model may not be trustworthy for studying the EOS of quark matter.

Besides the bag mechanism, an alternative approach to obtain confinement is based on the density dependence of quark masses (Fowler et al. 1981). Then the real question is how to determine the quark mass scaling that can reasonably produce confinement. The interaction part of the quark masses was originally assumed to be inversely proportional to the density (Fowler et al. 1981; Chakrabarty 1991; Chakrabarty 1993; Chakrabarty 1996). This linear scaling has been extensively applied to studying the properties of SQM (Chakrabarty 1991; Chakrabarty 1993; Chakrabarty 1996; Zhang et al. 2001; Zhang & Su 2002; Zhang & Su 2003). There are also other mass scalings (Dey et al. 1998; Wang 2000; Peng et al. 1999).

To study SQM with these pure phenomenological models is not well justified since they are not based on a convincing derivation. Therefore, a cubic scaling was derived based on the in-medium chiral condensates (Belyaev & Kogan 1984; Born et al. 1989) and linear confinement (Isgur & Paton 1983; Isgur & Paton 1985). In this new cubic treatment, strange quark matter in bulk still has the possibility of absolute stability. With a fully self-consistent thermodynamic treatment of the confinement by the recently developed density-dependent mass model (CDDM) (Peng et al. 2008), one can construct a new EOS for SQM, which has asymptotic freedom built in and describes deconfined quarks at high density and confinement at zero density. Using the model parameter for this confinement, one can study the dependence of quark star properties on the confinement's potential strength (Li et al. 2010).

In this paper, we calculate the properties of static strange stars described by the CDDM model. We study which of these strange star candidates are consistent with the Dey et al. (1998) model and which are also supported by other models described by a self-bound EOS. We calculate the upper limits on observable astrophysical quantities, such as masses and radii. Since the CDDM model comes from the basic feature of the quark confinement potential, it may give referential results on these aspects.

The paper is organized as follows. Section 2 is devoted to the derivation of the EOS for SQM in the quark model with chiral mass scaling. Strange star properties with the new EOS are presented in Section 3. Together with the Dey et al. (1998) model (which is widely used to identify an SS) and a broad collection of modern neutron star models, we discuss some recent astrophysical observational data that could shed new light on the possible identification of the existence of strange stars. This is followed by a brief summary provided in Section 4.

2 THE EQUATION OF STATE OF STRANGE QUARK MATTER

As is usually done, we consider SQM to be a mixture of interacting u, d, s quarks, and electrons, where the mass of the quarks m_q ($q =$u, d, s) is parametrized with the baryon number density n_b as follows:

$$m_q \equiv m_{q0} + m_\mathrm{I} = m_{q0} + \frac{D}{n_\mathrm{b}^z}, \tag{1}$$

where D is a parameter to be determined by stability arguments. The density-dependent mass m_q includes two parts: one is the original mass or current mass m_{q0}, the other is the interacting part m_I. In principle, the quark mass scaling should be determined from QCD, which is obviously impossible at present. As discussed above, we use the cubic scaling z = 1/3. This special choice was first derived at zero temperature (Peng et al. 1999) and then expanded to finite temperature (Wen et al. 2005) based on the linear confinement and in-medium chiral condensates.

In Figure 1, we illustrate this new mass scaling (solid line) of m_d (the system is set lying in the same binding state). Clearly, quark mass varies over a very large range from a very high density region (asymptotic freedom regime) to lower densities, where confinement (hadron formation) takes place. This form of density dependence is justified by its meaningful derivation based on quark chiral condensate and linear confinement potential. It is compared with that of the old linear scale model (dashed line), and that of the Dey et al. (1998) model (dotted line).

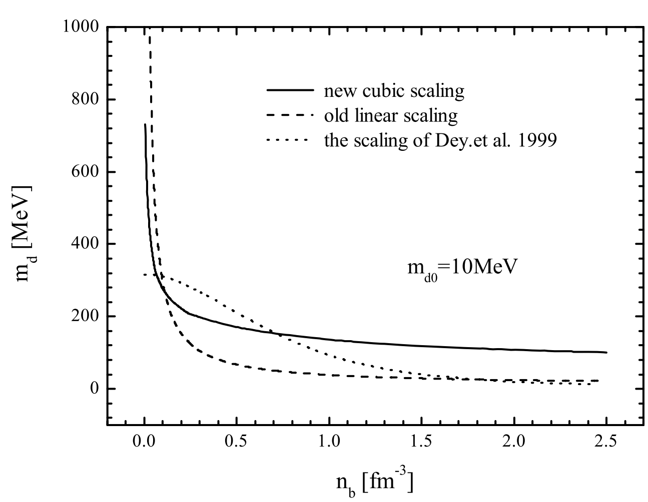

Fig. 1 Density dependence of quark mass $\mathrm{m_d}$ within three quark models is plotted as a function of the baryon number density.

Denoting the Fermi momentum in the phase space by ν_i (i =u, d, s, e$^-$), the particle number densities can then be expressed as

$$n_i = g_i \int \frac{\mathrm{d}^3\mathbf{p}}{(2\pi\hbar)^3} = \frac{g_i}{2\pi^2}\int_0^{\nu_i} p^2\,\mathrm{d}p = \frac{g_i\nu_i^3}{6\pi^2}, \tag{2}$$

and the corresponding energy density as

$$\varepsilon = \sum_i \frac{g_i}{2\pi^2}\int_0^{\nu_i}\sqrt{p^2+m_i^2}\,p^2\,\mathrm{d}p. \tag{3}$$

The relevant chemical potentials μ_u, μ_d, μ_s, and μ_e satisfy the weak-equilibrium condition (we assume that neutrinos freely leave the system)

$$\mu_\mathrm{u} + \mu_\mathrm{e} = \mu_\mathrm{d}, \quad \mu_\mathrm{d} = \mu_\mathrm{s}. \tag{4}$$

For the quark flavor i we have

$$\begin{aligned} \mu_i &= \frac{\mathrm{d}\varepsilon}{\mathrm{d}n_i}|_{\{n_{k\neq i}\}} = \frac{\partial\varepsilon_i}{\partial\nu_i}\frac{\mathrm{d}\nu_i}{\mathrm{d}n_i} + \sum_j \frac{\partial\varepsilon}{\partial m_j}\frac{\partial m_j}{\partial n_i} \\ &= \sqrt{\nu_i^2+m_i^2} + \sum_j n_j \frac{\partial m_j}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right), \end{aligned} \tag{5}$$

where

$$f(a) \equiv \frac{3}{2a^3}\left[a\sqrt{1+a^2} - \ln\left(a+\sqrt{1+a^2}\right)\right]. \tag{6}$$

We clearly see from Equation (5) that since the quark masses are density dependent, the derivatives generate an additional term with respect to the free Fermi gas model.

For electrons, we have

$$\mu_\mathrm{e} = \sqrt{\left(3\pi^2 n_\mathrm{e}\right)^{2/3} + m_\mathrm{e}^2}. \tag{7}$$

The pressure is then given by

$$\begin{aligned} P &= -\varepsilon + \sum_i \mu_i n_i \\ &= -\Omega_0 + \sum_{ij} n_i n_j \frac{\partial m_j}{\partial n_i} f\left(\frac{\nu_j}{m_j}\right) \\ &= -\Omega_0 + n_\mathrm{b}\frac{\mathrm{d}m_\mathrm{I}}{\mathrm{d}n_\mathrm{b}} \sum_{j=\mathrm{u,d,s}} n_j\, f\left(\frac{\nu_j}{m_j}\right), \end{aligned} \tag{8}$$

with Ω_0 being the free-particle contribution

$$\begin{aligned} \Omega_0 = -\sum_i \frac{g_i}{48\pi^2}\Big[&\nu_i\sqrt{\nu_i^2+m_i^2}\left(2\nu_i^2-3m_i^2\right) \\ &+3m_i^4\,\mathrm{arcsinh}\left(\frac{\nu_i}{m_i}\right)\Big]. \end{aligned} \tag{9}$$

Due to the additional term in the chemical potential, the pressure also has an extra term. The inclusion of such a term guarantees that the Hugenholtz-Van Hove theorem is fulfilled in the calculations.

The baryon number density and the charge density can be given as

$$n_{\rm b} = \frac{1}{3}(n_{\rm u} + n_{\rm d} + n_{\rm s}), \tag{10}$$

$$Q_{\rm q} = \frac{2}{3}n_{\rm u} - \frac{1}{3}n_{\rm d} - \frac{1}{3}n_{\rm s} - n_{\rm e}. \tag{11}$$

The charge-neutrality condition requires $Q_{\rm q} = 0$.

Solving Equations (4), (10), and (11), we can determine $n_{\rm u}$, $n_{\rm d}$, $n_{\rm s}$, and $n_{\rm e}$ for a given total baryon number density $n_{\rm b}$. The other quantities are obtained straightforwardly.

In the present model, the parameters are: the electron mass $m_{\rm e} = 0.511\,$MeV, the quark current masses $m_{\rm u0}$, $m_{\rm d0}$, $m_{\rm s0}$, the confinement parameter D and the quark mass scaling x. Although the light-quark masses are not without controversy and remain under active investigation, they are nevertheless very small, and so we simply take $m_{\rm u0} = 5\,$MeV, $m_{\rm d0} = 10\,$MeV. The current mass of strange quarks is $95 \pm 25\,$MeV according to the latest version of the Particle Data Group (Yao et al. 2006).

We now need to establish the conditions under which the SQM is the true strong interaction ground state. Conventionally, the stability of SQM is judged by the minimum energy per baryon. Following Farhi and Jaffe (Farhi & Jaffe 1984), we must require, at $P = 0, E/A \leq M(^{56}{\rm Fe})c^2/56 = 930$ for the SQM and $E/A > 930\,$MeV for two-flavor quark matter (where $M_{^{56}{\rm Fe}}$ is the mass of ^{56}Fe) in order not to contradict standard nuclear physics. The EOS will only describe stable SQM for a set of values of $(D, m_{\rm s0})$ satisfying these two conditions. As seen in figure 1 of Peng et al. (2008), only when the $(D^{1/2}, m_{\rm s0})$ pair is in the range between the full and dashed lines, SQM can be absolutely stable. Therefore, the range of D values is very narrow for a chosen $m_{\rm s0}$ value, if the Bodmer-Witten-Terazawa hypothesis (Bodmer 1971; Witten 1984) is correct. If we take the modest value $m_{\rm s0} = 100\,$MeV, for example, then $D^{1/2}$ is in the range of 156–160 MeV. The value of $D^{1/2}$ of 156 MeV places the energy per baryon number of strange quark matter at $E/A = 908$ MeV (see the upper panel of Fig. 2), which corresponds to strange quark matter strongly bound with respect to ^{56}Fe whose energy per baryon is 930 MeV. The matter tends to be less stable with the increase of D value.

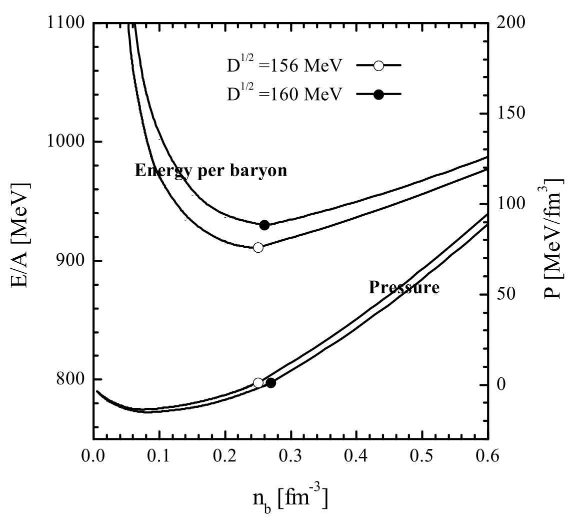

Fig. 2 Equation of state of quark matter in the present quark scale model for $m_{\rm s0}$ = 100 MeV with two values of $D^{1/2}$: 156 and 160 MeV.

The lower panel of Figure 2 shows the pressure of quark matter in the present model for m_{s0} = 100 MeV with two values of $D^{1/2}$: 156 and 160 MeV. The figures imply that in our strange star, the density cannot be less than about 0.24 fm^{-3} because negative pressure is not physically feasible. This means that the strange star has a sharp surface at a density 0.24 fm^{-3} where the pressure goes to zero. This property of the presence of sharp surfaces in strange stars has also been seen in other models. With an increasing value of D, the star's surface becomes even sharper as a result of a stronger confinement potential. Also, each pressure plot has a minimum. When the density is lower than the corresponding density, the derivative $\mathrm{d}P/\mathrm{d}n$ becomes negative, and so quark matter is unstable against phase separation and falls apart at lower densities.

Our EOS is most sensitive to the parameters m_{s0} and D (which rule the density dependence of the quark mass). However, we found that a change within 20% of these parameters, e.g., around the values $D^{1/2} = 156$ MeV and $m_{s0} = 100$ MeV, produces a change of mass and of the corresponding radius which is smaller than 5%.

3 STRANGE STAR PROPERTIES IN THE NEW QUARK SCALE MODEL

As is generally done, we assume the strange star to be a spherically symmetric object. The MR relation is obtained by solving the Tolman-Oppenheimer-Volkov equation. For the detailed calculation process, one may refer to section IV of Peng (2000).

The calculated MR relations of SSs in the present model are plotted in Figure 3 (black lines labeled $D156$ and $D160$), together with the prediction of the Dey et al. (1998) model (black lines labeled ss1 and ss2). SS properties based on the present model are characterized by a larger maximum mass (1.58–1.64 $M_\odot$) and radius (9.7–10.2 km) than those within the Dey et al. (1998) model.

A broad, modern collection of neutron star models is also given, including nucleon stars (dash-dotted lines), hyperon stars (dashed line), and hybrid stars (dotted lines). Each one of these models was combined at sub-nuclear densities with the Baym-Pethick-Sutherland EOS. The nucleon star sequence labeled (NL$\rho\delta$) has been obtained within the relativistic mean-field approach (RMF), allowing for non-linear self-interactions of the σ meson. The isovector part of the interaction is described in terms of both the ρ and δ-meson exchange (Liu et al. 2002). The RMF models contrast with several microscopic models for the EOS of nucleon star matter, such as a relativistic Dirac-Brueckner-Hartree-Fock (DBHF) model (curves labeled DBHF) (Van Dalen et al. 2004; Van Dalen et al. 2005), and a non-relativistic Brueckner-Bethe-Goldstone (BBG) model with both phenomenological and microscopic three-body forces (curves labeled pheno and micro, respectively) (Baldo et al. 2006). The dashed line refers to hyperon stars calculated with the BBG model when hyperons are included with both nucleon-nucleon three-body forces and nucleon-hyperon interactions (Baldo et al. 2006). The dotted line represents hybrid neutron stars (a compact star which possesses a quark matter core) calculated using the BBG model EOS for hyperonic matter to describe the hadronic phase, and a density dependence of the bag constant is introduced to describe the quark phase (Baldo et al. 2006).

In the same figure, we compare the theoretical MR relations of the compact star with the semiempirical MR for three strange star candidates (closed regions labeled SAX J1808, 4U 1820–30 and Her X-1). Clearly, the EOS of the Dey et al. (1998) model was consistent with the explanation of the analysis of semi-empirical MR relations from the observed properties of SAX J1808 (Li et al. 1999; Leahy et al. 2008), 4U 1820–30 (Haberl & Titarchuk 1995; Bombaci 1997) and Her X-1 (Dey et al. 1998; Reynolds et al. 1997; Van Kerkwijk et al. 1995; Wasserman & Shapiro 1983), indicating the existence of an SS with a radius of 6–8 km. However, this conclusion does not hold in the present model, where only 4U 1820–30 may be an SS with a larger radius of 8–10 km. At the same time, this M-R relation can also be fulfilled by a hybrid star model (dotted line), and even a hyperon star model (dashed line). So, one may expect either a large SS associated with 4U 1820–30, or a neutron star containing strangeness in its core. Therefore, it is not decisively proved to be either an SS or a NS. This statement is similar to the case regarding the study of 4U 1728–34 by Bombaci

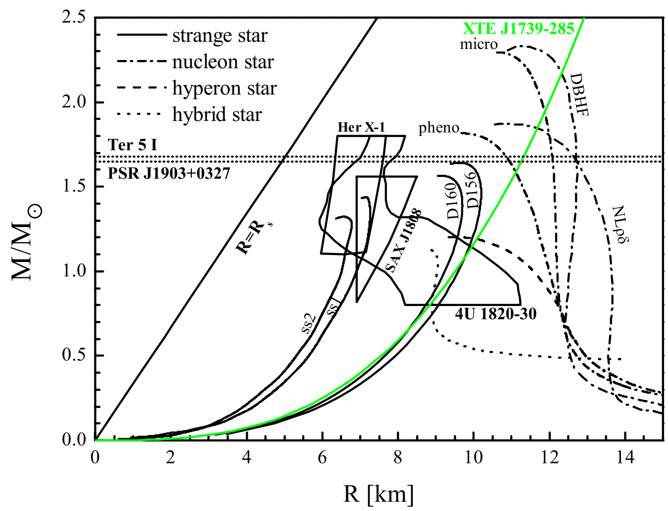

Fig. 3 Mass-radius relation for different theoretical models of compact stars (see text for details). The black solid line labeled $R = R_{\rm s}$ gives the Schwarzschild radius as a function of the stellar mass. The green solid line (*color online*) gives the upper limit, extracted from observational data for the radius of the compact star in XTE J1739–285. Closed regions labeled SAX J1808, 4U 1820–30 and Her X-1 are the semiempirical MR relations analyzed from the observed properties of these objects. The two dotted horizontal lines denote the lower limit (at 99.9% confidence level) for the mass of the compact star in PSR J1903+0327, and the lower limit (at 95% confidence level) for the mass of the compact star in pulsar I of the globular cluster Terzan 5, respectively.

(Bombaci 2003). Although in that paper, since no hyperon interaction was introduced, the hadronic star model (i.e. a neutron star with a core made of different hadron species) cannot reach the small radius where 4U 1728–34 is located, he then demonstrated that a strange star or a hybrid star model is more compatible with 4U 1728–34 than a hadronic star one.

As shown in Figure 3, all the NS models fall above the lower mass limit of 1.6 $M_\odot$ for PSR J1903+0327 (Champion et al. 2008), and also the lower mass limit of Ter 5 (Ransom et al. 2005). The SS model of Dey et al. (1998) cannot support such a large mass. PSR J1903+0327 may have a chance to be an SS in the present new quark scale model, and Terzan 5 is also within an error of less than 5%.

Furthermore, in a recent paper, Kaaret et al. (2007) have reported the discovery of burst oscillations at 1122 Hz in the X-ray transient XTE J1739–285. It is regarded as the most rapidly rotating compact star discovered up to now, and the first with a submillisecond spin period (P = 0.891 ms). The green solid line in Figure 3 gives the upper limit (Lavagetto et al. 2003; Lattimer & Prakash 2004) for the radius of the compact star in XTE J1739–285 extracted from the rotational frequency at 1122 Hz, thus XTE J1739–285 should be located between the Schwarzschild radius $R = R_s$ and this green solid line. From the result of Figure 3, we see that this constraint does not allow for discrimination among different possible types of compact stars.

Here we have considered a limited yet representative set of some of the most recent models for the EOS of dense stellar matter. We have also checked that other models (Bombaci 2003; Blaschke et al. 2008) for neutron stars and strange stars are in agreement with the aforementioned analysis.

4 SUMMARY

Our study clearly reveals that, among all the SS candidates considered here, only one of them (4U 1820–30) is supported by at least two SS models described by a self-bound EOS. However, at the same time, this semi-empirical MR relation for the compact star in 4U 1820–30 can also be fulfilled by models of neutron stars with strangeness in their core. So we conclude that, at the present time, none of the present astrophysical observations can prove or confute the existence of strange stars (or neutron stars), i.e. the presence of SQM compact stars.

However, we should notice that the present quark model with chiral mass scaling is still not well justified, since it has considered only the first-order approximation of the chiral condensates in the medium, which only accounts for the scalar interaction between quarks. Incorporating higher orders of the approximation would non-trivially complicate the quark mass formulas, and is deferred to further work. Nevertheless, the properties of QCD matter at high baryon densities and nonvanishing temperatures will be explored by the heavy-ion program of CBM at the FAIR facility at GSI Darmstadt. On the other hand, mass measurements from pulsars are rapidly accumulating, and other observables (redshifts, QPOs, X-ray bursters and X-ray transient sources, neutron star oscillations, and moments of inertia) could yield simultaneous mass and radius measurements in the coming years.

In addition, the surface electric field could be very strong near the bare quark surface of an SS because of the mass difference of the strange quark and the up (or down) quark, which could play an important role in producing the thermal emission of bare strange stars by the Usov mechanism (Usov 1998; Usov 2001). In the present quark model, although the electric field near the surface is about 10^{18} V cm^{-1}, the outward electric field decreases very rapidly above the quark surface, and at $z \sim 10^{-8}$ cm, the field reduces to $\sim 5 \times 10^{11}$ V cm^{-1}, which is of the order of the rotation-induced electric field for a typical Goldreich-Julian magnetosphere and may allow for some validating astronomical observations. Future experiments can therefore provide a crucial cross-check for the verification of this problem with the theoretical model.

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