A unified description for strange quark matter objects

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Abstract. A unified description for strange quark matter (SQM) objects ranging from strangelets to strange stars is presented, i.e., the UDS model. The important differences on the properties of SQM objects resulted from introducing the UDS model and conventional treatments are discussed. The previously neglected effects such as charge screening, quark depletion, and electrons in conventional treatments are found to be important for the charge properties and stability of strangelets as well as the surface structures of strange stars, which are now well addressed in the UDS model.

1. Introduction
It was proposed decades ago that strange quark matter (SQM) consisting of roughly equal numbers of $u$, $d$, $s$ quarks is the true ground state of QCD [1, 2]. In that case, there may exist stable SQM objects with baryon numbers ranging from a few to $\sim 10^{57}$, e.g., strangelets [3, 4, 5, 6, 7], nuclearites [8, 9], meteorlike compact ultradense objects [10], and strange stars [11, 12, 13].

Extensive efforts were made trying to understand the properties of such objects. For example, adopting the MIT bag model, a strangelet in $\beta$-equilibrium is found to be slightly positively charged [4]. Further investigations indicate that their properties depend strongly on model parameters [14]. Greiner et al. considered the possible formation of strangelets via heavy-ion collisions [15]. They found strangelets that are stable against strong decay are highly negatively charged [16]. The stability of strangelets in various shapes was investigated by Mustafa and Ansari, where a spherically shaped strangelet is found to be more stable than others [17]. Moreover, other effects such as color superconductivity [7, 18, 19, 20], perturbative interactions [21, 22], and external magnetic field [23, 24, 25, 26] on SQM objects were discussed extensively as well.

However, significant simplifications were adopted in those studies. For strangelets, electrons were ignored and quarks were assumed to be uniformly distributed. For strange stars, the local charge neutrality condition was required so their structures can be obtained by solving the Tolman-Oppenheimer-Volkov (TOV) equations. Due to the simplicities, these conventional theoretical treatments for SQM objects do not describe the effects such as charge screening, electron-positron pair creation, and nonzero charge densities in strange stars, which could have important implications on the properties of SQM objects [27]. To incorporate all those effects,
recently we have proposed a unified description [27, 28, 29] for SQM objects ranging from strangelets to strange stars, called the UDS model [30]. In this paper, we present the UDS model and compare it with the conventional treatments for strangelets and strange stars.

The paper is organized as follows. In Sec. 2 the theoretical framework of the UDS model is presented. The differences of introducing the UDS model and more conventional treatments for SQM objects are examined in Sec. 3. Our conclusion is given in Sec. 4.

2. Theoretical framework
In the UDS model, the particle distributions inside SQM objects are obtained by minimizing the mass at given total numbers of particles. For a spherically symmetric SQM object, the local chemical potential \( \mu_i(r) \) follows

\[
\bar{\mu}_i = \mu_i(r) e^{\nu(r)/2} + q_i \varphi(r) = \text{constant.}
\]  

(1)

Here the metric element \( e^{\nu(r)} \) and electric potential \( \varphi(r) \) are obtained by integrating

\[
\frac{d\nu}{dr} = 2G e^\lambda r^2 \left[ 4\pi r^3 \left( P - \frac{\alpha Q^2}{8\pi r^4} \right) + M_i \right], \quad \text{and} \quad \frac{d\varphi}{dr} = -\frac{\alpha Q}{r^2} e^{(\lambda+\nu)/2},
\]

(2)

where \( e^{-\lambda} = 1 - \frac{2G}{r} M_t \) with the total mass \( M_t \) and particle number \( N_i \) determined by

\[
M_i(r) = \int_0^r 4\pi r'^2 \left( E + \frac{\alpha Q^2}{8\pi r'^4} \right) \, dr' \quad \text{and} \quad N_i(r) = \int_0^r 4\pi r'^2 n_i e^{\lambda/2} \, dr'.
\]

(3)

Note that the natural system of units is adopted here, while the gravitational and fine-structure constants are given by \( G = 6.707 \times 10^{-45} \) MeV\(^{-2} \) and \( \alpha = 1/137 \). In Eq. (3), \( n_i(r) \) represents the local number density of particle type \( i \). The total charge can then be obtained with \( Q(r) = \sum_i q_i N_i(r) \) \( (q_u = 2/3, q_d = q_s = -1/3, \text{and} \ q_e = -1) \). Meanwhile, the pressure \( P(r) \) and energy density \( E(r) \) indicate the local properties of SQM, which are obtained based on the bag model at a given chemical potential \( \mu_i(r) \). The thermodynamic potential density of the bag model reads

\[
\Omega = -\sum_i \frac{g_i}{24\pi^2} \left[ \frac{\nu_i}{\sqrt{\nu_i^2 - m_i^2}} \left( \nu_i^2 - \frac{3}{2} m_i^2 \right) + \frac{3}{2} m_i^4 \ln \frac{\mu_i + \nu_i}{m_i} \right] + B,
\]

(4)

where \( \nu_i = \sqrt{\mu_i^2 - m_i^2} \) and \( g_i \) \((g_u = g_d = g_s = 6, \ g_e = 2)\) are the Fermi momentum and degeneracy factor. The quark and electron masses are taken as \( m_u = 2.3 \) MeV, \( m_d = 4.8 \) MeV, \( m_s = 95 \) MeV, and \( m_e = 0.511 \) MeV [31]. Note that for stable SQM objects, the \( \beta \)-equilibrium condition \( \mu_u + \mu_e = \mu_d + \mu_s \) needs to be fulfilled. The bag constant \( B \) is fixed according to the Witten-Bodmer hypothesis, which lies within the stability window \( B^{1/4} = 152 \pm 7 \) MeV and we take its central value. Based on the thermodynamic potential density, the basic thermodynamic relations give the particle number density \( n_i = -\frac{\partial \Omega}{\partial \mu_i} \), energy density \( E = \Omega + \sum_i \mu_i n_i \), and pressure \( P = -\Omega \).

On the surface of an SQM object, the surface effects resulted from quark depletion need to be considered, where we have adopted the multiple reflection expansion (MRE) method [5, 32] with a modification to the density of states

\[
\frac{dN_i^\text{surf}}{dp_i} = n_i^\text{surf} \left( p_i \right) = -\frac{g_i R^2}{\pi} \arctan \left( \frac{m_i}{p_i} \right) + \frac{2g_i R}{3\pi} \left[ 1 - \frac{3p_i}{2m_i} \arctan \left( \frac{m_i}{p_i} \right) \right].
\]

(5)
Table 1. Effects considered in various treatments. For Star II, the electron mass is neglected.

| Model       | Coulomb interaction | Charge screening | Quark depletion | Electron | Gravity |
|-------------|---------------------|------------------|----------------|----------|---------|
| UDS [27, 28, 29] | ✗                   | ✗                | ✗              | ✗        | ✗       |
| Slet I [33, 21]    | ✗                   | ✗                | ✗              |          |         |
| Slet II [34, 35]   |                      | ✗                |                |          |         |
| Star I [11, 13, 22]| ✗                   | ✗                | ✗              |          |         |
| UDS* [29]          | ✗                   | ✗                |                |          |         |
| Star II [12, 36]   | ✗                   |                   |                |          |         |

Here $p_i$ is the momentum of quarks with an upper limit $\nu_i(R)$. The corrections to the total energy and pressure can then be obtained with $E^\text{surf}_i = \int_0^{\nu_i(R)} \sqrt{p_i^2 + m_i^2 n_i^\text{surf}(p_i)} dp_i$ and $P^\text{surf} = -\sum_i \frac{dE^\text{surf}_i}{dV} |_{N^\text{surf}}$. Due to the effects of gravity, the mass of an SQM object is modified by $M^\text{surf} = \sum_i E^\text{surf}_ie^{\nu_i(R)/2}$. Meanwhile, the quark-vacuum interface should meet the requirement of dynamic stability, i.e.,

$$P(R) - P_e(R) + P^\text{surf} = 0.$$  \hfill (6)

The structure of an SQM object is then determined by solving Eq. (1) while fulfilling the boundary conditions $M_t(0) = 0$, $Q(0) = Q(\infty) = 0$, and Eq. (6). For more details of the calculation, please refer to Refs. [29, 30].

3. Properties of SQM objects predicted by various theoretical treatments

To show the differences resulted from introducing various types of treatments, we investigate the properties of SQM objects obtained with the UDS model and other conventional treatments.

3.1. Small SQM objects

For small SQM objects such as strangelets, the conventional treatments can be attained by ignoring the nonuniform internal distribution of quarks, i.e., adopting the particle density profile $n_i(r) = n_i\theta(R - r)$ instead of solving Eq. (1). The structure of a strangelet can then be determined by fulfilling the $\beta$-stability and dynamic stability conditions, i.e., minimizing the mass with respect to the particle numbers and radius at a given total baryon number. Depending on whether or not the Coulomb interaction is considered, we categorize the traditional treatments for strangelets into two types, i.e., Slet I and Slet II. For Slet I, the Coulomb energy $M_C = \frac{\alpha Q^2}{16\pi} + \frac{\alpha Q^2}{2\pi R}$ is included [33], where $Q \equiv \frac{2}{3}\pi R^3 \sum_i q_i n_i$ is the volume term of the total electric charge $Q \equiv Q_e + Q^\text{surf}$. A detailed demonstration of the effects considered in Slet I(II) is indicated in Table 1. For the cases obtained with constant surface tensions, extensive discussions can be found in Ref. [29].

The important differences resulted from introducing different treatments for strangelets are their charge properties. In Fig. 1 we present the charge-to-mass ratio $f_Z \equiv Q/A$ and surface charge density $\sigma \equiv Q/R^2$ obtained with three types of treatments. When the UDS model is adopted, we assume global charge neutrality with $Q(\infty) = 0$. However, it is meaningful to consider the charge carried by the quark part $Q \equiv Q(R)$, i.e., neglecting the surrounding electrons. The obtained properties of a strangelet with various treatments coincide with each other at $A \lesssim 10$. For larger strangelets, the charge-to-mass ratio $f_Z$ predicted by Slet II
approaches to a constant value at $A \gtrsim 10^5$, which deviates from the results obtained with other treatments including Coulomb interaction ($f_Z \to 0$). The UDS model and Slet I give the same charge number for strangelets up to $A \approx 10^5$ ($R \approx 40$ fm). For larger ones, the surface charge density $\sigma$ start to approach to constant values, where more positively charged strangelets are obtained with Slet I comparing with the UDS model. The difference is mainly caused by the charge screening effects of SQM, suggesting the important consequences of nonuniform distribution of quarks on the charge properties of SQM objects with $R \gtrsim 40$ fm.

On the other hand, the effects of electrons should not be neglected for large SQM objects. In fact, as indicated in Ref. [37], the creation of electron-positron pairs in supercritical electric fields plays a crucial role on the maximum net charge an object can carry, which gives $Q_{\text{max}} = 0.71R_{\text{fin}}$ ($400 \lesssim R \lesssim 10^4$ fm) and $7 \times 10^{-5}R_{\text{fin}}^2$ ($R \gtrsim 10^4$ fm). According to Fig. 1, the charge numbers $Q$ of SQM objects predicted by Slet I and Slet II are much larger than $Q_{\text{max}}$, in which case the
electron-positron pair production is inevitable. To show the consequences of neglecting electrons in the conventional treatments, in Fig. 2 we present the electric potential on the quark-vacuum interface at $r = R$. For small strangelets with $R \lesssim 40$ fm, the effects of electrons are not significant, where the electric potentials $\varphi(R)$ predicted by the UDS model and Slet I coincide with each other. For the cases obtained with Slet II, the values of $\varphi(R)$ are much larger because the corresponding strangelets are more positively charged. At $R \gtrsim 40$ fm, $\varphi(R)$ obtained with Slet I starts to increase with radius $R$, while the one with the UDS model approaches to a constant value. The reason is twofold: (1) the two treatments predict different charge numbers for SQM objects; (2) electrons were not considered in the conventional treatments. This indicates the necessity of including electrons for the study of SQM objects.

Aside from the differences on the charge properties for small SQM objects, other quantities such as the mass, radius, and energy per baryon of a strangelet at a given baryon number are insensitive to different theoretical treatments. This is a natural consequence of the dominant effects of quark depletion, which is on the order of 100 MeV for the energy per baryon of strangelets at $A \approx 10$. Correspondingly, the energy reduction by allowing a strangelet to carry positive charge is around 0.2 MeV, which is negligible in comparison. However, this situation can be easily altered if their energy contributions become comparable under certain circumstances. For example, the energy reduction due to the relocation of charged particles on the quark-baryon interface is greatly enhanced for the quark-baryon mixed phase, which supports the existence of various geometrical structures [38, 39, 40, 41, 42, 43, 44]. Alternatively, if the effects of quark depletion are hindered, the charge properties of a strangelet become important. To show this explicitly, we multiply Eq. (5) by a dampening factor $f$, i.e., $n_{\text{surf}} \rightarrow f \times n_{\text{surf}}$. The properties of strangelets at $f = 1, 0.1, 0.01,$ and 0.001 are then investigated with various theoretical treatments, where the corresponding energy per baryon are presented in Fig. 3. Since Coulomb interaction is neglected in Slet II, the obtained masses of strangelets are always smaller than those with other treatments. Meanwhile, the masses predicted by the UDS model are slightly smaller than Slet I, which is attributed to the nonuniform distribution of quarks. For larger SQM objects, the energy per baryon approach to constant values until gravity starts to reduce the energy, which is approximately $0.85 R_m^2$ MeV per baryon for SQM objects with $R \lesssim 3$ km. By decreasing the dampening factor $f$, the energy contribution from quark depletion is reduced. When $f$ is small enough, there exist local minima for the energy per baryon obtained with the UDS model and Slet I, which resemble the cases with small surface tensions [29, 45, 46]. The existence of the local minima has significant implications on the properties of SQM objects, where large strangelets may undergo fission and a strange star’s surface fragments into a crystalline crust [47]. Nevertheless, these cases are quite subtle and sensitive to the theoretical treatments. For example, when Slet II is adopted, there does not exist a strangelet that is more stable than others since the Coulomb energy is neglected. If we take $f = 0.01$, the local minimum in Fig. 3 vanishes for strangelets predicted by Slet I, while it persists when the UDS model is adopted. Moreover, the size of the most stable strangelet is also sensitive to the theoretical treatments. It is thus important to consider the effects of charge screening with nonuniform distributed quarks, which affect the charge properties as well as the stability of small SQM objects.

### 3.2. Large SQM objects

The most important difference between the UDS model and conventional treatments for large SQM objects such as strange stars is the inclusion of nonzero electric charge inside them. According to our previous investigations [27, 28, 29, 30], there exist mainly two types of charge for a large SQM object, i.e., the charge located on the quark-vacuum interface due to the separation of electrons from SQM and the gravity induced charge throughout the object.

To obtain the structure of a strange star, the conventional treatments adopt the TOV equations with the equation of state (EoS) determined by assuming local charge neutrality for
SQM. We refer to such kind of treatments as Star I, where the effects considered are indicated in Table 1. The predicted values for $e^{\nu(r)/2}$ and $\varphi(r)$ are compared with those obtained with the UDS model in Fig. 4, where the central chemical potential of the strange star is taken as $\mu(0) = \mu_u(0) + \mu_d(0) + \mu_s(0) = 1389$ MeV. Since Star I assumes local charge neutrality, the electric potential $\varphi(r)$ remains zero throughout the strange star. However, nonzero values of $\varphi(r)$ are obtained with the UDS model, suggesting the existence of gravity induced charge. In fact, same situation is expected inside neutron stars [48]. The effects of the gravity induced charge on the structures of strange stars are infinitesimal, which accounts for $\sim 10^{-41}$ of the total mass. Note that the density of gravity induced charge will increase if $\frac{\partial n_{ch}}{\partial \varphi} \bigg|_{\nu}$ with $n_{ch} \equiv \sum_i q_i n_i$ is larger, which may become large enough to increase the mass and radius of a strange star [49]. Future investigations on this subject are necessary, where the effects of strong magnetic field and Color Superconducting of SQM may be important.

![Figure 4. The values of the metric element $e^{\nu(r)/2}$ (a) and electric potential $\varphi(r)$ (b) inside a strange star.](image)

![Figure 5. The electric potential $\varphi(r)$ on the surface of a large SQM object.](image)

The structure and charge properties of a strange star’s surface were previously investigated assuming constant charge density for quarks and zero mass for electrons [12, 36]. We name such kind of treatments as Star II. For the cases considered here, the charge density of quarks $n_q$ on the surface is obtained at $P = 0$, which gives $n_q \equiv \frac{\nu_q^3}{3\pi^2}$ with $\nu_q = 7.5$ MeV. The electric potential is then determined by solving

$$\varphi'' = \begin{cases} \frac{4\nu}{3\pi} \left( \varphi^3 - \nu_q^3 \right) & (r \leq R), \\
\frac{4\nu}{3\pi} \varphi^3 & (r > R). \end{cases}$$

To show the differences on the surface charge profiles induced by introducing different treatments, we consider a large SQM object with negligible effects of gravity and present the obtained electric potentials in Fig. 5. The effects considered by Star II, the UDS* and UDS models are indicated in Table 1. Due to the charge screening effects, the electric field predicted by the UDS/UDS* model can penetrate into the SQM by merely $\sim 20$ fm, while much larger value ($\sim 400$ fm) is obtained with Star II. In such cases, the strength of the electric field obtained with the UDS/UDS* model is much larger. Since quark depletion is considered in the UDS model, an additional potential barrier is formed with the height being $\sim 2$ MeV, which is caused by the positive surface charge on the quark-vacuum interface. In such cases, negatively charged particles may be trapped and give a distinct photon spectrum when excited, which is relevant to the experimental searches of
SQM. The surface charge densities of the quark part obtained by Star II, the UDS* and UDS models are $\sigma = 0.00438, 0.00807,$ and 0.01352 fm$^{-2}$, respectively. For strange stars, the effects of gravity cannot be ignored. According to our calculation [27, 28, 29, 30], the electric potential $\varphi(r)$ and the radial coordinate $(r - R)$ should be multiplied by $e^{\varphi(R)/2}$ and $e^{-\lambda(R)/2}$, respectively. The aforementioned differences on the surface structures obtained with various treatments may result in different surface radiation profiles and structures of the thin crusts for strange stars [12]. Note that the masses and radii of strange stars are barely affected by the choice of theoretical treatments, where the differences (within 0.01%) are mainly caused by introducing different conditions for dynamic stability of the surface, i.e., $P = 0$ or Eq. (6). However, a strange star may gain extra mass and radius if it carries net charge on the surface [50]. For a rotating strange star, a magnetic field comparable to the typical strength of pulsars is generated [27, 51]. With the overcritical electric field located on the surface of a strange star, electron-positron pairs can be created, which may be related to some astrophysical events such as supernovae and gamma-ray bursts [52, 53]. Thus, a proper treatment for the surface of a strange star is necessary, where the effects listed in Table 1 should be considered.

4. Conclusion

The UDS model was presented and compared with more conventional treatments on the properties of SQM objects. The bag model was adopted for the local properties of SQM. For strangelets with $R \lesssim 2$ fm, those approaches are equivalent to each other and predict the same results. However, different charge properties were obtained for larger SQM objects. Due to the effects of charge screening, an SQM object obtained with the UDS model is less charged comparing with the conventional treatments. Meanwhile, electrons cannot be neglected for the proper determination of the charge properties of SQM objects. When the effects of quark depletion are hindered, nonuniform distribution of quarks become important and will further reduce the mass of an SQM object. For strange stars, on the contrary with previous assumptions of local charge neutrality, we obtained nonzero gravity induced charge. The surface structure of a strange star was found to be sensitive to the theoretical treatments, where the previously neglected effects of charge screening, quark depletion, and gravity are important.

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