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Constraints on the Equation of State of Quark Stars from Compact Object Observations †

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Abstract

Introducing an additional term into the thermodynamic potential density of the quark matter system, as required for thermodynamic consistency, resolves the inconsistency that arises in the conventional perturbative quantum chromodynamics (QCD) model. In this work, we use a revised, thermodynamically consistent perturbative QCD model to compute the stability window and equation of state of up-down (*ud*) quark matter at zero temperature. Our results indicate that the measured tidal deformability for GW170817 places an upper limit on the maximum mass of *ud* quark stars, but does not rule out the possibility of such stars with a mass of about two solar masses. However, when the maximum mass of *ud* quark stars significantly exceeds two solar masses, such as the compact object with a mass in the range of 2.50–2.67$M_{\odot}$ observed in the GW190814 event, it cannot be identified as a *ud* quark star according to the revised perturbative QCD model.

Keywords: perturbative QCD; thermodynamic consistency; equation of state; tidal deformability

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1. Introduction

The study of quark matter properties and its equation of state [1,2] plays a crucial role in understanding the characteristics of quark stars and the behavior of matter under extreme conditions [3–5]. At low energies, effective field theories and QCD phenomenological models serve as essential tools for investigating the properties of dense matter [6–13] and QCD phase transitions [14]. However, for phenomenological models, ensuring thermodynamic self-consistency is a critical issue that must be carefully addressed [15–19]. The conventional perturbative QCD model provides a robust framework for investigating high-energy physical phenomena and the thermodynamic properties of dense matter under high-density conditions [20]. Nevertheless, conventional perturbative approaches to strong interactions between quarks suffer from thermodynamic inconsistencies, which are particularly problematic for describing the equation of state of quark matter at low densities. It is crucial to emphasize that this issue arises from the artificial extrapolation of a perturbative calculation, which does not exhibit thermodynamic problems within its valid perturbative regime, to a non-perturbative system without considering non-perturbative effects.

Recently, it was shown that this issue can be resolved by introducing an additional term to the thermodynamic potential density of the system [21]. After this correction, the density dependence of the sound velocity becomes more reasonable, increasing with density and approaching the ultrarelativistic limit at high densities. In contrast, the pure perturbative expansion overlaps with the ultrarelativistic case throughout the entire density range. At higher densities, the influence of this additional term gradually decreases, ensuring that the equation of state asymptotically approaches that of the conventional perturbative QCD model. Astronomical observational data provide crucial constraints for determining the equation of state of dense matter [22–35], which is important for our understanding of the universe. The main purpose of the present study is to investigate the stability window and equation of state of *ud* quark matter at zero temperature using a revised, thermodynamically consistent perturbative QCD model. In particular, we impose constraints on the equation of state for *ud* quark matter by combining the mass measurement of PSR J0740+6620 [36] and the dimensionless tidal deformability constraint of a 1.4 $M_\odot$ neutron star observed in the GW170817 event [37].

2. Revised Perturbative QCD Model

In the conventional perturbative QCD model, the leading-order perturbative expansion for the thermodynamic potential density of two-flavor cold quark matter is given by

$$\Omega_{\mathrm{pt}} = -\frac{1}{4\pi^2}\left(\mu_{\mathrm{u}}^4 + \mu_{\mathrm{d}}^4\right)\left(1 - \frac{2\alpha_s}{\pi}\right), \tag{1}$$

where μ_u and μ_d denote the quark chemical potentials of the up and down quarks, respectively. At the one-loop level, the explicit expression for the running coupling constant, α_s, can be written as

$$\alpha_{\mathrm{s}} = \frac{1}{c_0 \ln(\Lambda/\Lambda_{\mathrm{QCD}})}, \quad c_0 = \frac{58}{3\pi}, \tag{2}$$

with $\Lambda_{\mathrm{QCD}} = 147$ MeV and $N_f = 2$ [21]. And the number densities of up and down quarks and electrons are, respectively, given by

$$n_{\mathrm{u}} = \frac{1}{\pi^2}\mu_{\mathrm{u}}^3\left(1 - \frac{8\alpha_{\mathrm{s}}}{\pi}\right), \quad n_{\mathrm{d}} = \frac{1}{\pi^2}\mu_{\mathrm{d}}^3\left(1 - \frac{8\alpha_{\mathrm{s}}}{\pi}\right), \quad n_{\mathrm{e}} = \frac{1}{3\pi^2}\mu_{\mathrm{e}}^3. \tag{3}$$

The renormalization subtraction point, Λ, is usually taken to be the typical energy scale of the system. For example, in Ref. [38], it is taken to be proportional to the average chemical potentials, $\Lambda = \sqrt{(\mu_{\mathrm{u}}^2 + \mu_{\mathrm{d}}^2)/2}$. However, the arbitrary choice of the relation between Λ and quark chemical potentials μ_i leads to a thermodynamic inconsistency problem. This inconsistency arises due to non-perturbative effects, which grow increasingly significant as the density decreases. In the revised, thermodynamically consistent perturbative QCD model, the determined explicit expression for Λ is given by [21]

$$\Lambda = C\sqrt[4]{\frac{\mu_{\mathrm{u}}^4 + \mu_{\mathrm{d}}^4}{2}}, \tag{4}$$

where C is introduced as a dimensionless model parameter governing the strength of the strong interaction across different energy scales. Moreover, an additional term determined by meeting the fundamental differential equation of thermodynamics should be added to the thermodynamic potential density, namely

$$\Omega' = \int_{\mu_0}^{\mu} (\mathcal{F}\mathrm{d}\mu_{\mathrm{u}} + \mathcal{Q}\mathrm{d}\mu_{\mathrm{d}}) + B_0, \tag{5}$$

where $\mu_0 = (\mu_{u0}, \mu_{d0})$ denotes the starting point for the integral, for which we take $\mu_{u0} = \mu_{d0} = 300$ MeV in our calculation, while its moving effect is boiled down to the MIT bag constant B_0, and $\mu = (\mu_u, \mu_d)$. The introduced auxiliary functions $\mathcal{F}$ and $\mathcal{Q}$ are given by

$$\mathcal{F} = \frac{2\mu_u^3}{c_0\pi^3}\left[\ln\left(\frac{\Lambda}{\Lambda_{QCD}}\right)\right]^{-2}, \quad \mathcal{Q} = \frac{2\mu_d^3}{c_0\pi^3}\left[\ln\left(\frac{\Lambda}{\Lambda_{QCD}}\right)\right]^{-2}. \tag{6}$$

Putting everything together, the total thermodynamic potential density of the revised perturbative QCD model is

$$\Omega = -\frac{1}{4\pi^2}\left(\mu_u^4 + \mu_d^4\right)\left(1 - \frac{8\alpha_s}{\pi}\right) - \frac{\mu_e^4}{12\pi^2} + \int_{\mu_0}^{\mu}(\mathcal{F}\mathrm{d}\mu_u + \mathcal{Q}\mathrm{d}\mu_d) + B_0. \tag{7}$$

Note that in the above equation, we include the contribution of electrons, $\Omega_e = -\mu_e^4/(12\pi^2)$, to the total thermodynamic potential density of the system, as we are considering stable quark matter in stellar objects. Accordingly, the energy density and pressure of the system are given, respectively, by

$$E = \Omega + \sum_i \mu_i n_i, \quad P = -\Omega, \tag{8}$$

where i runs over the up and down quarks as well as electrons.

3. Numerical Results and Discussions

For a given baryon number density n_b, the chemical potentials of the up quarks, down quarks, and electrons can be determined by solving the charge neutrality and β-equilibrium conditions, namely $2n_u - n_d - 3n_e = 0$ and $\mu_d = \mu_u + \mu_e$. These conditions ensure that the system remains electrically neutral and in chemical equilibrium under weak interactions, which is essential for describing the properties of quark matter in compact stars.

As proved in Ref. [39], any consistent thermodynamic treatment must ensure that

$$\delta = P - n_b^2\frac{\mathrm{d}}{\mathrm{d}n_b}\left(\frac{E}{n_b}\right) = 0 \tag{9}$$

at arbitrary density. In particular, the pressure at the minimum energy per baryon must be zero. In Figure 1, we present a comparison of the pressure versus the energy per baryon for both the conventional and the revised perturbative QCD models. From this figure, it is evident that for the black solid line obtained in the conventional perturbative QCD model with an arbitrary relation $\Lambda = \sqrt{(\mu_u^2 + \mu_d^2)/2}$, the energy minimum does not locate at the zero pressure point. While for the red dash-dotted line obtained in the revised perturbative QCD model using Equation (4), the energy minimum and zero pressure are located at exactly the same position. This confirms that, after the thermodynamic correction, the energy minimum and zero pressure are located at the same position as required by thermodynamic consistency.

Neutron stars are predominantly composed of neutron-rich nuclear matter under normal conditions. However, at extreme densities approaching the nuclear saturation point, nucleons may undergo additional compression, potentially leading to the formation of quark matter [40–42]. In this work, we model compact stellar objects as systems consisting entirely of *ud* quark matter and electrons, hereafter referred to as *ud* quark stars. To illustrate the stability region of *ud* quark matter and its impact on the properties of quark stars, in Figure 2, we show the parameter space for *ud* quark matter in the $C - B_0^{1/4}$ plane. The black shaded region in the bottom right-hand corner denotes a forbidden zone, where the energy per baryon of *ud* quark matter falls below 930 MeV. Conversely, the blue shaded region, enclosed by the red dotted line from below and the blue dotted line from above, signifies stable configurations of *ud* quark matter. This region corresponds to an equation of state that can support *ud* quark stars with a mass of $1.4M_\odot$ and a tidal deformability $\tilde{\Lambda}_{1.4}$ ranging from 70 to 580, consistent with constraints from the GW170817 event [37].

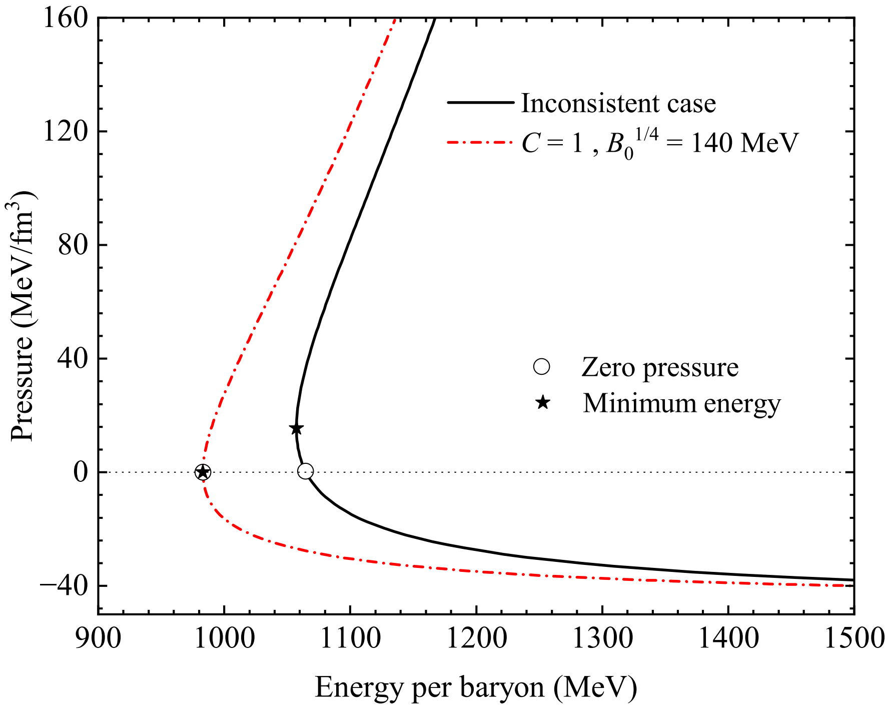

Figure 1. Pressure versus energy per baryon of *ud* quark matter. The energy minimum and the zero pressure are marked by a star and a circle, respectively.

In addition, the measured gravitational mass of PSR J0740+6620 with a lower limit of $2.01M_\odot$ is also translated into the $C - B_0^{1/4}$ plane, as indicated by the red dashed line with star symbols. For the GW170817 event, the observed tidal deformability is $\tilde{\Lambda}_{1.4} = 190^{+390}_{-120}$, where $\tilde{\Lambda}_{1.4}$ represents the dimensionless tidal deformability of a $1.4M_\odot$ star. This value is depicted by the blue shaded region, bounded by the blue dash-dotted and blue dashed lines with star symbols. As can be seen from Figure 2, the blue dashed line with open symbols lies within the blue shaded region, indicating that the revised perturbative QCD model can simultaneously account for the observations of PSR J0740+6620 and the tidal deformability of the GW170817 event. It would be worth mentioning that these results are consistent with those obtained in the quasiparticle model [43]. These results offer valuable theoretical insights into the internal structure of compact stars and their gravitational wave signatures, thereby bridging the gap between quark matter theory and multi-messenger astronomy.

Figure 3 shows the velocity of sound, calculated using the formula $v = \sqrt{|\mathrm{d}P/\mathrm{d}E|}$, as a function of the baryon number density. In the revised perturbative QCD model, the velocity of sound increases with baryon number density, approaching the ultrarelativistic limit $v = 1/\sqrt{3}$ at high densities, consistent with asymptotic freedom. However, the results obtained from the conventional perturbative QCD model are also shown for comparison, as indicated by the horizontal line, which coincides entirely with the ultrarelativistic limit.

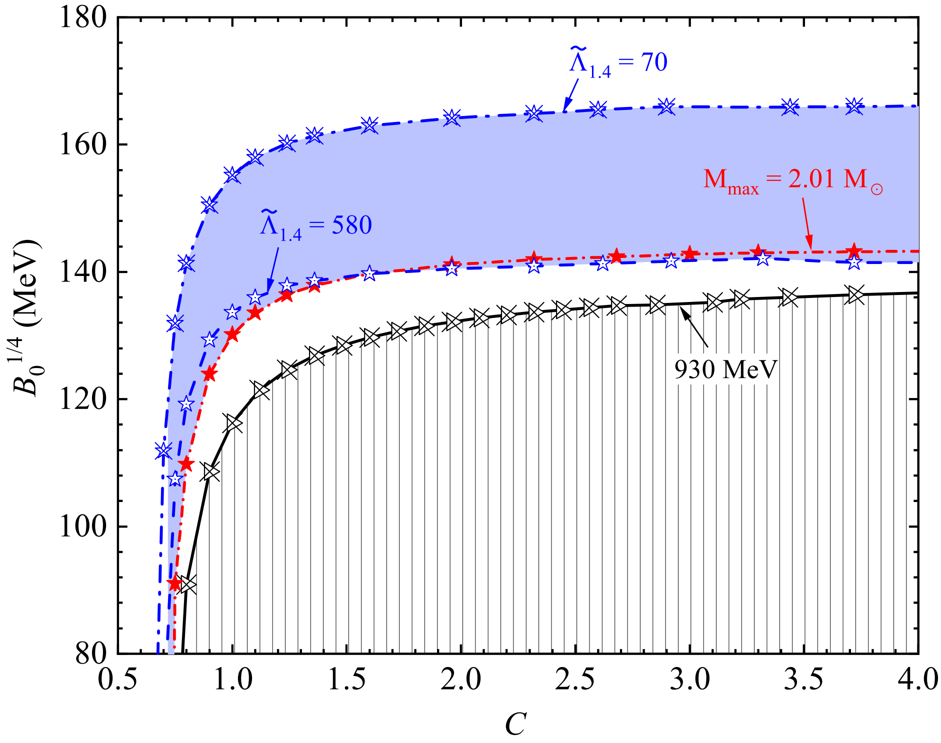

Figure 2. Stability windows for *ud* quark matter in the $C - B_0^{1/4}$ plane. The black shaded area marks the forbidden region with energy per baryon below 930 MeV. The blue shaded region shows stable *ud* quark matter that can support stars with a mass of $1.4M_\odot$ with tidal deformability $70 \leq \tilde{\Lambda}_{1.4} \leq 580$.

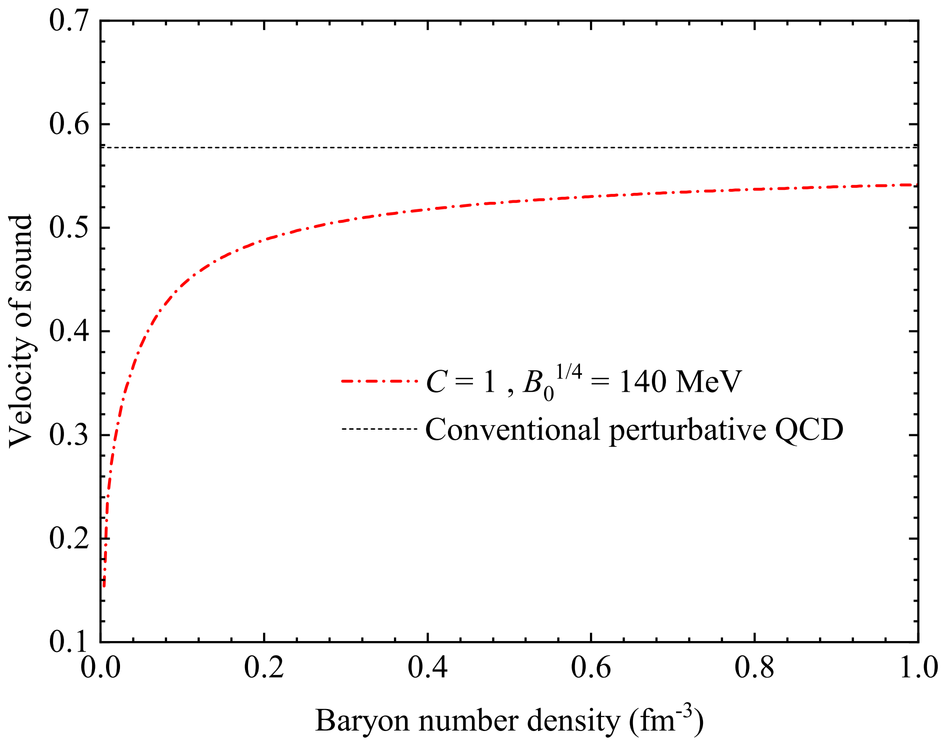

Figure 3. Velocity of sound in *ud* quark matter. The horizontal line corresponds to the result obtained using the conventional perturbation QCD model, which does not consider thermodynamic corrections.

4. Conclusions

The conventional perturbative QCD model provides a robust framework for studying high-energy physical phenomena and characterizing the properties of dense quark matter.

However, the direct extrapolation of the strong interaction between quarks in pure perturbative calculations leads to a problem of thermodynamic inconsistency, due to the running of the QCD coupling. It has been shown that this thermodynamic inconsistency can be resolved by introducing an additional term into the thermodynamic potential density of the system.

We employed the revised perturbative QCD model to study the stability window and equation of state of the *ud* quark star matter at zero temperature. The parameter space of this model was constrained using astronomical observational data, particularly the discovery of massive compact stars and tidal deformation measurements of such objects. We found that, for reasonable model parameters, the maximum mass of an *ud* quark star can reach about two solar masses, and the tidal deformation of a 1.4 solar mass quark star falls within the observational range of tidal deformations, as indicated by the blue region in Figure 2 with $\tilde{\Lambda}_{1.4} = 190^{+390}_{-120}$. Finally, it is worth mentioning that although the revised perturbative QCD model allows for the existence of quark stars with maximum masses exceeding two times the solar mass, i.e., within the white parameter region enclosed by the blue dash and the black solid lines, the corresponding equation of state in this region fails to explain the observed tidal deformability from the GW170817 event.

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