PROCEEDINGS OF SCIENCE

The tension between radius and deformability in quark stars

M. B. Albino[1],[*] **R. Fariello**[2] **and F. S. Navarra**[1]

1 *Instituto de Física, Universidade de São Paulo*
Rua do Matão, 1371, 05508-090, Cidade Universitária, São Paulo, SP, Brazil
2 *Departamento de Ciências da Computação Universidade Estadual de Montes Claros, Avenida Rui Braga, sn, Vila Maurícia, Montes Claros, 39401-089, Minas Gerais, Brazil*

In a recent work, we applied a QCD-based EOS to the study of the stellar structure of self-bound strange stars, obtaining sequences with maximum masses larger than two solar masses and radii ranging from 8 to 12 Km. We have also compared our results with the most recent astrophysical data, including the very recent determination of the mass and radius of the massive pulsar PSR J0740+6620 performed by the NICER and XMM-Newton Collaborations. Our equation of state is similar to the MIT bag model one, but it includes repulsive interactions, which turn out to be essential to reproduce the accumulated experimental information. We find that our EOS is compatible with all astrophysical observations but the parameter window is now narrower. We observe a tension between the radius and the tidal deformability of the star. In this contribution, we expand the discussion of the results found in our previous paper.

XV International Workshop on Hadron Physics (XV Hadron Physics) 13 - 17 September 2021
Online, hosted by Instituto Tecnológico de Aeronáutica, São José dos Campos, Brazil

[*]Speaker

1. Introduction

Nowadays we believe that there is a low temperature deconfined phase of quarks and gluons, the cold QGP, also called quark matter (QM). This phase might exist in the core of dense stars, an idea that has been around already for some decades [1, 2]. It is even possible that a whole star, not only its core, be made of quark matter [2]. This possibility was explored in several works and was be further explored in [3], which is an update of [4].

It was shown in several works that a self-bound star, composed entirely of quark matter, could explain a massive neutron star. In order to obtain a stiff enough quark matter equation of state, several groups introduced repulsive interactions among the quarks, mediated by the exchange of vector particles "effective massive gluons" or "effective vector mesons". Interestingly, most of these developments make use of a mean field approximation for the vector field and arrive at a similar result, which is a quadratic term in the baryon density present both in the pressure and energy density.

From the experimental side, during the last decade, we have witnessed remarkable advances in the observation of neutron stars: the discovery of extremely massive neutron stars; qualitative improvements in X-ray radius measurements, and the famous LIGO/Virgo detection of gravitational waves (GWs) originating from the NS-NS merger GW170817. For references, we refer the reader to Ref. [3], where we made a compilation of all the most recent articles with the relevant experimental data.

Differences between candidate EOS can have a significant effect on the tidal interactions of neutron stars. Recently, new constraints appeared on tidal deformability. It has been realized that the two-solar-mass constraint forces the EOS to be relatively stiff at low densities. At the same time, the constraint on $\Lambda(1.4\,M_{\odot})$ sets an upper limit for the stiffness, constraining the EOS band in a complementary direction. Very recently, the NICER data introduced even more stringent constraints, involving the star radius.

In [3] the calculations published in [4] were updated, showing that the EOS introduced in [5] remains a viable option, satisfying the most recent experimental constraints. Here we review and extend the discussion of the subject.

2. The equation of state

In Ref. [3] we considered a quark star consisting of u, d and s quarks. The derivation of our EOS [5] starts with the assumption that the gluon field can be decomposed into low ("soft") and high ("hard") momentum components. The expectation values of the soft fields were identified with the gluon condensates of dimension two and four, respectively. The former generates a dynamical mass for the hard gluons, and the latter yields an analogue of the "bag constant" term in the energy density and pressure. Given the large number of quark sources, even in the weak coupling regime, the hard gluon fields are strong, the occupation numbers are large, and therefore these fields can be approximated by classical color fields. The effect of the condensates is to soften the EOS whereas the hard gluons significantly stiffen it, by increasing both the energy density and pressure. With these approximations, it was possible to derive [5] an analytical expression for the EOS, called MFTQCD (Mean Field Theory of QCD). The energy density, as a function of the baryon density,

ρ_B, is given by [5]:

$$\varepsilon = \left(\frac{27g^2}{2m_G{}^2}\right)\rho_B{}^2 + \mathcal{B}_{QCD} + \varepsilon_f \tag{1}$$

and the pressure reads:

$$p = \left(\frac{27g^2}{2m_G{}^2}\right)\rho_B{}^2 - \mathcal{B}_{QCD} + p_f \tag{2}$$

where m_G is the dynamical gluon mass, and g is the coupling constant ($\alpha_s = g^2/4\pi$) in QCD. In the above equations, the first term stems from the interaction between a quark and a hard gluon: $g\bar{\psi}\gamma^\mu A_\mu \psi \propto g\rho_B A_0$. Because of the mean field approximation for the gluon field, we can use the equation of motion and integrate it out, obtaining the second power of the baryon density: $A_0 \rightarrow g/m_G^2\, \rho_B$. The second term comes from the four gluon vertex of the QCD Lagrangian. After the separation of the field into soft and hard gluons, the soft component of the four gluon vertex is approximated by its vacuum expectation value, the gluon condensate. This term generates our analogue of the bag constant, called here $\mathcal{B}_{QCD}$, and is given by

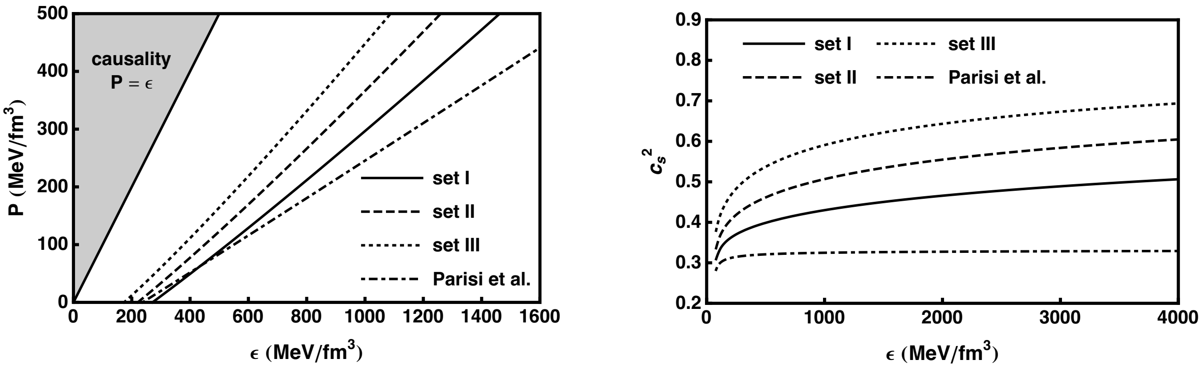
$$\mathcal{B}_{QCD} = \frac{9}{128}\,\phi_0^4 = \langle \frac{1}{4} F^{a\mu\nu} F^a_{\mu\nu} \rangle, \tag{3}$$

where ϕ_0 is an energy scale associated with the energy density of the vacuum and with the gluon condensate [5]. Finally, the third term in Eqs.(1) and (2) is the energy density and pressure of a non-interacting Fermi gas of quarks and electrons. The explicit expressions can be found in many works and also in [3]. In (1) and (2) the summation over quark colors has already been performed. Comparing Eqs. (1) and (2) with the equivalent definitions of energy and pressure in the modified bag model with postulated repulsive vector interactions we observe a similarity. Both EOS have a term proportional to ρ_B^2. In [5] it was derived from QCD, whereas in other works it was postulated.

3. Results and discussion

Once we fix $\mathcal{B}_{QC\mathcal{D}}$ and ξ, we go back to (1) and (2) and, obtaining ε and p for successive values of ρ_B, we construct the EOS in the form $p = p(\varepsilon)$, plotted in Fig. 1a. In the figure, the different lines correspond to the three parameter sets listed in Table I. In this type of plot, the slope is the speed of sound, which, due to causality, can not exceed the unity. In Fig. 1b we show the corresponding values of the speed of sound. As it can be seen, our model yields a much stiffer EOS, with a speed of sound much larger than the conformal value, for which $c_s^2 = 1/3$. The dot-dashed line shows the EOS obtained from a recently updated version of the MIT bag model (for details see [3]). As it can be seen, the MFTQCD EOS generates stronger pressure for larger values of the parameter $\xi = g/m_G$. This combination of parameters appears in the first term of (2), which comes from the repulsive interactions [5].

In order to calculate the mass and radius of the star, we solve numerically the TOV equations for $p(r)$ and $M(r)$ and construct the mass-radius diagram [1]. The pressure and the energy density in the TOV equations are given by the MFTQCD expressions (2) and (1), respectively. We present the obtained results in Fig. 2a. We can see that, with the parameters chosen in the indicated range, our EOS is able to satisfy all the experimental constraints shown in the mass-radius diagram.



(a) (b)

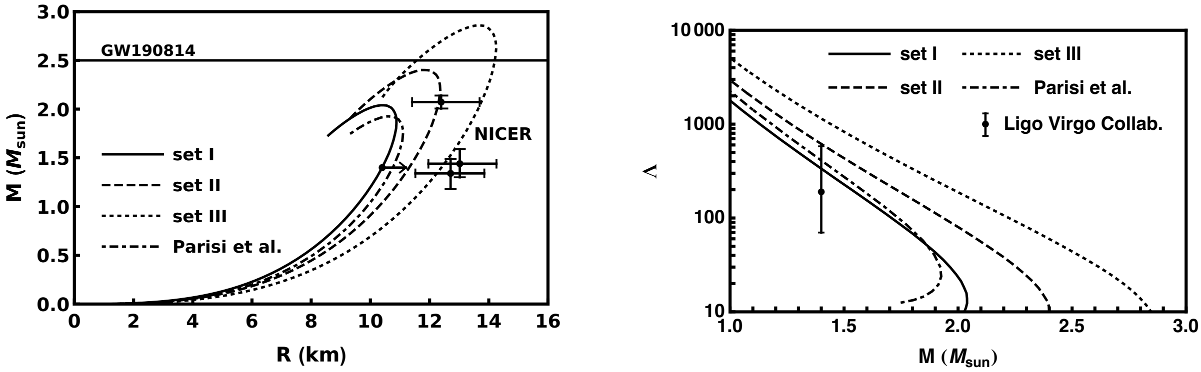
Figure 1: a) Equation of state obtained with MFTQCD. Set I, II and III correspond to the parameter combinations shown in Table I. For comparison, the dot-dashed line shows the updated MIT Bag Model EOS (Parisi et al.). b) Speed of sound for the same parameter choices.

Set	$\mathcal{B}_{QCD}(MeV/fm^3)$	$\xi(MeV^{-1})$
I	70	0.0011
II	60	0.0016
III	50	0.0022

Table 1: Parameters sets used in the figures.

The tidal deformability parameter is given by [6] $\Lambda = \frac{2}{3}k_2 C^{-5}$, where $C \equiv M/R$ is the compactness of the star and k_2 is the tidal Love number. As pointed out in [6], in contrast to the Love number, the tidal deformability has a wide range of values, spanning roughly an order of magnitude over the observed mass range of neutron stars in binary systems. The updated version of the tidal deformability estimate for a 1.4 $M_\odot$ neutron star based on the gravitational-wave event GW170817 implies that $70 < \Lambda_{1.4} < 580$. In Fig. 2b we show our results for Λ as a function of the star mass M. As it can be seen, the experimental constraint can be satisfied. We note, however, the visible tension between this constraint and those shown in the mass-radius plot. The larger values of the radius required to fit the NICER points seem to be somewhat difficult to reconcile with the Λ values required by the GW170817 estimates.

To summarize: in [5] a new equation of state for cold quark matter was presented. It was soon applied to the study of neutron stars, treated as self-bound strange quark stars [4]. In [3], almost ten years later, we have updated the calculations published in [4] and found that the MFTQCD EOS can still account for the most recent astrophysical data. However, we observe that the parameter window is closing. A confirmation of the existing data and the reduction of the error bars in the tidal deformability and in the NICER neutron star radii data will be crucial to rule out strange quark star models and reduce the freedom in the choice of the equation of state.



(a) (b)

Figure 2: a) Mass-radius diagram for combinations of $\mathcal{B}_{QCD}$ and ξ allowed by the stability conditions. Set I, II and III correspond to the parameter combinations shown in Table I. The points represent the region favored by the measurements reported by the NICER and XMM-Newton Collaborations. The horizontal line shows the mass of the compact object observed in the event GW190814. b) The tidal deformability parameter Λ as a function of the star mass. The different lines correspond to the three parameter sets listed in Table I. The vertical bar is the empirical tidal deformability at $M = 1.4M_\odot$ inferred from the Bayesian analysis of the GW170817 data at the 90 % confidence level.

Acknowledgments

We are deeply grateful to G. Lugones for fuitful discussions. This work was partially financed by the Brazilian funding agencies CAPES, CNPq and by the INCT-FNA.

References

[1] N. Glendenning, *Compact stars*, (Springer, New York, 2000).

[2] E. Witten, Phys. Rev. D **30**, 272 (1984).

[3] M. B. Albino, R. Fariello and F. S. Navarra, Phys. Rev. D **104**, 083011 (2021).

[4] B. Franzon, D. A. Fogaca, F. S. Navarra and J. E. Horvath, Phys. Rev. D **86**, 065031 (2012).

[5] D. A. Fogaça, F.S. Navarra, Phys. Lett. B **700**, 236 (2011).

[6] T. Hinderer, arXiv: 0711.2420; E. E. Flanagan and T. Hinderer, Phys. Rev. D **77**, 021502 (2008); T. Hinderer, Astrophys. J. **677**, 1216 (2008).