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Strangeons constitute strong matter in bulk

– To test using GW 170817

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Abstract. The fundamental strong interaction determines the nature of pulsar-like compact stars which are essentially in the form of strong matter in bulk. From an observational point of view, it is proposed that strong matter in bulk could be composed of strangeons, i.e. quark-clusters with there-light-flavor symmetry of quarks, and therefore pulsar-like compact objects could actually be strangeon stars. The equation of state (EOS) of strangeon stars is described in a Lennard-Jones model for the purpose of constraining the EOS by both the tidal deformability Λ of GW 170817 and $M_{\rm TOV}$. It is found that the allowed parameter space is quite large as most of the Lennard-Jones EOS models satisfy the tidal deformability constraint by GW170817. The future GW detections for smaller values of Λ and mass measurement for larger values of $M_{\rm TOV}$ will help a better constraint on the strangeon star model.

PACS. 97.60.Gb Pulsars – 97.60.Jd Neutron stars – 95.30.Cq Elementary particle processes

1 Introduction

The strong matter we concentrate on in this paper refers to the strongly interacting matter whose nature is determined by the strong force [1]. The most familiar form of strong matter to us is that of atomic nuclei. In normal matter, nuclei are far way from each other, but the overall properties of normal matter are controlled by the electromagnetic force; however, this is not the whole story about the baryonic matter in the Universe. The strong matter in bulk, which is macroscopic and whose surface effect is negligible, could be produced by core-collapse supernovae of evolved stars. After core-collapsing of a massive star, the supernova-produced rump is left behind, where normal nuclei are intensely compressed by gravity to form the strong matter in bulk, which could manifest in the form of a pulsar-like compact object.

Nevertheless, the true nature of strong matter in bulk is still uncertain, which is essentially related to the ignorance about the behavior of strong interaction at low energy scales. The neutron star and quark star are two models that have attracted most attentions. The former one originates from the concept of "gigantic nucleus" initiated by Landau [2], and the latter compares the whole star to a gigantic hadron composed of deconfined quarks, based on the conjecture of Witten [3]. From astrophysical points of view, however, it is proposed that "strangeons", which are formerly named as quark-clusters with strangeness, could constitute strong matter in bulk, and the pulsar-like compact stars could actually be "strangeon stars" composed totally of strangeons. The observational consequences of strangeon stars show that different manifestations of pulsar-like compact stars could be understood in the regime of strangeon stars (see the review by [4] and references therein). More observational evidences to verify or disaffirm this proposal are needed.

The gravitational wave event GW170817 [5] and its multiwavelength electromagnetic counterparts (e.g., [6]) open a new era in which the nature of pulsar-like compact stars could be crucially tested. The tidal deformability from the detection of gravitational waves (GWs) from binary merger could put a clean and strong constraint on the equation of state (EOS) of compact stars. We have found that the tidal deformability of GW170817 and the bolometric radiation could be understood if the signals come from the merge of two strangeon stars in a binary [7], where the tidal deformability is derived from the EOS in [8]. Further, it will be interesting and important to study what the GW observation of tidal deformability means for EOS of strangeon stars and properties of strangeon matter, by the constraints on model parameters.

This paper is organized as follows: In §2 we briefly introduce the concept of strangons constituting the strong matter in bulk, and the EOS of strangeon stars in a Lennard-Jones model. In §3 we derive the dependence of tidal deformability of merging strangeon stars on the parameters in the Lennard-Jones model [8], and the constraint by GW170817. Conclusions and discussions are made in §4.

2 Strong matter in bulk

The dense matter inside pulsar-like compact stars is strong matter because the average density should be supra-nuclear density (a few nuclear saturation densities) due to gravity. The Fermi energy of electrons are significant in compressed baryonic matter, and it is very essential to cancel the energetic electrons by weak interaction in order to make a lower energy state. There are two ways to eliminate electrons. The conventional way is via $e^- + p \to n + \nu_e$ as suggested in popular neutron star models (i.e., *neutronization*). On the other hand, a 3-flavor symmetry of quark could be restored in strong matter, since the energy scale ($>\sim$ 400 MeV) is much larger than the mass difference between s and u/d quarks. Consequently, another possible way to eliminate electrons could be through the so-called *strangenization*, which is related to the flavor symmetry of strong-interaction matter. Strangenization has both the advantages of minimizing the electron's contribution of kinetic energy and maximizing the quark-flavor number.

2.1 Strangeon and strangeon star

If dense matter changes from a hadronic phase to a deconfined phase as baryon density increases, the strong matter in compact stars could be strange quark matter. As stated by Witten [3], if strange quark matter in bulk may constitute the true ground state of strong matter rather than ^{56}Fe, then compact stars could actually be strange quark stars instead of neutron stars. However, the problem is: can the density of realistic compact stars be high/low enough for quarks to become deconfined/confined?

The state of compressed baryonic matter is essentially relevant to the non-perturbative chromodynamics (QCD) problem, and at the realistic density of compact stars the quarks should neither be free nor weakly coupled. Although some efforts have been made to understand the state of pulsar-like compact stars in the framework of conventional quark stars, including the MIT bag model with almost free quarks [9] and the color-superconductivity state model [10], realistic stellar densities cannot be high enough to justify the use of perturbative QCD which most of compact star models rely on.

Inside compact stars, the strong coupling between quarks may naturally render quarks grouped in quark-clusters [11, 4], and each quark-cluster is composed of several quarks condensating in position space rather than in momentum space. Quark-cluster with three-light-flavor symmetry is renamed "strangeon", being coined by combining "strange nucleon" for the sake of simplicity. It is the *strangeonization* to convert nucleons into strangeons during compressing normal baryonic matter of core-collapse supernova.

Strangeon matter in bulk may constitutes the true ground state of strong-interacting matter rather than nuclear matter [17]. This proposal could be regarded as a *general Witten's conjecture*: strange matter in bulk could be absolutely stable, in which quarks are either free (for strange quark matter) or localized (for strangeon matter). Due to both the strong coupling between quarks and the weak interaction, the pulsar-like compact stars could be actually strangeon stars which are totally composed of strangeons. A strangeon star can then be thought as a 3-flavored gigantic nucleus, and strangeons are its constituent as an analogy of nucleons which are the constituent of a normal (micro) nucleus.

Different manifestations of pulsar-like compact objects have been discussed previously (see a review by [4] and references therein) in the strangeon star model. Strangeon stars could help us to naturally understand the observations of pulsar-like compact stars, both their surface and global properties, for example, the drifting and bi-drifting sub-pulses [13], the clean fireball for core-collapse supernovae and cosmic gamma-ray bursts (GRBs) [14], the neutrino burst during SN 1987A [15], the spectra of XDINSs from optical to X-ray bands [16], the high-mass pulsars [8, 17,18], the radiation of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) [19,20], and the glitch behavior of pulsars [21]. It is also worth noting that, although the the EOS is very stiff, the causality condition is still satisfied for strangeon matter [22].

Moreover, the recently observed gravitational waves GW170817 [5] as well as the electromagnetic radiation (e.g., [6]) could be understood if the signals come from the merge of two strangeon stars in a binary [7]. The tidal deformability is derived in the Lennard-Jones model [8], where the interaction between strangeons are assumed to be similar to that between molecules of inert gas.

2.2 EOS of strangeon stars in Lennard-Jones model

As stated above, pulsar-like compact stars could actually be strangeon stars, where strangeons form due to both the strong and weak interactions and become the dominant components inside those stars. Strangeons are composed of several quarks, similar to nucleons, but the number of quarks in each strangeon is unknow. Although we have proposed that H-dibaryons (with structure $uuddss$) could be a possible kind of strangeons [17], what could be the realistic strangeons inside compact stars is uncertain due to the difficulties in QCD calculations. In this paper, we use a more general and phenomenological model, the Lennard-Jones model [8], to describe the EOS of strangeon stars and to find out the constraints from the tidal deformability of GW170817.

In the Lennard-Jones model, the interaction between strangeons are assumed to similar to that between molecules of iner gas, and the dependence of the potential u on the distance between strangeons r is

$$u(r) = 4U_0[(\frac{r_0}{r})^{12} - (\frac{r_0}{r})^6], \tag{1}$$

where U_0 is the depth of the potential and r_0 can be considered as the order of interaction range. This form of potential has the property of short-distance repulsion and long-distance attraction, like the interaction between nucleons which stems from the residual chromo-interaction. By the approximation that only the two nearby strangeons have interaction to each other, the EOS of strangeon stars can be derived under the above potential, and the details are given in [8].

At the late stage of merging strangeon stars, the temperature should be $>\sim 10$ MeV due to the tidal heating. As a result, although an isolate strangeon star could be in the solid state [23] at low temperature, the strangeon stars in a binary just before merger could be in the fluid state. Consequently, to calculate the tidal deformability in the next section, we neglect the contribution from the lattice vibrations [8] to the EOS.

The energy density is then

$$\epsilon = 2U_0(A_{12}r_0^{12}n^5 - A_6 r_0^6 n^3) + nmc^2, \tag{2}$$

and the pressure is

$$P = 4U_0(2A_{12}r_0^{12}n^5 - A_6 r_0^6 n^3), \tag{3}$$

where n is the number density of strangeons, m is the mass of each strangeon. If the number of quarks inside each strangeon is N_q, then we could approximate that $m \simeq N_q \cdot 300$ MeV, where $N_q = 18$ in the following calculations. In addition, A_{12} and A_6 are coefficients. relating to the micro-structure of strangeon matter. Although we are considering the process where the stars should not be in the solid state, for simplicity we adopt $A_{12} = 6.2$ and $A_6 = 8.4$ as in the case of the simple-cubic structure, since other choices would not bring significant changes.

The parameters U_0 and r_0 included in the EOS characterize the inter-strangeon potential. The surface number density of strangeons $n_{\rm s}$ determines r_0 by the fact that the pressure vanishes at the surface. When translating $n_{\rm s}$ into the rest-mass density of strangeon matter on the surface $\rho_{\rm s} = mn_{\rm s}$, we can constrain U_0 and $\rho_{\rm s}$ from the EOS-dependent observable properties. The constraints by the mass-radius curves are discussed in [8], and in the next section we will show the constraints by both the maximum mass of a static compact star ($M_{\rm TOV}$) and the tidal deformability of GW 170817.

3 Strangeon star merger tested by GW170817

In the scenario that the pulsar-like compact stars could actually be strangeon stars, the merging binary compact stars that triggers gravitational wave events as GW 170817 could then actually be binary strangeon stars. In this section we will show the study on the parameter space of strangeon star model according to the observation of GW170817 and possible future observations.

The most robust constraint that the binary strangeon star merger scenario has to confront, is the tidal deformability constraint of GW170817. Mass quadrupole moment will be induced by the external tidal filed of the companion during the late inspiral stage, accelerating the coalescence, hence detectable by GW observations [28]. This property of the compact star can be characterized by the dimensionless tidal deformability $\Lambda = (2/3)k_2/(GM/c^2R)^5$, where k_2 is the second tidal love number.

In order to study the parameter space of strangeon star model, we have calculated k_2 for a set of strangeon star EOSs with various choices of U_0 and $\rho_{\rm s}$. We have followed the procedure as in [29] to calculate k_2, namely, introducing a static $l = 2$ perturbation to the TOV equation and solving it with the strangeon star EOSs. It's worth noting that due to finite surface density of strangeon star model, a boundary treatment has to be done to ensure correct results [30]. In this study, we have explored parameter spaces with U_0 ranging from 20 MeV to 100 MeV and $\rho_{\rm s}$ from 1.5 times to 2 times the nuclear density ($2.67 \times 10^{14}\,{\rm g/cm^3}$). The TOV maximum mass with each EOS model is also calculated, as it's tightly related to the post-merger evolution of the binary merger events.

Assuming both stars in the binary have low spins, the GW170817 observation translates into an upper limit on the tidal deformability for a 1.4 solar mass star (labeled as $\Lambda(1.4)$) of 800. Various studies on neutron star EOS models have been carried out based on this constraint, for example, a systematic study in [31]. According to their results for neutron stars, the tidal deformability increases as the $M_{\rm TOV}$ increases. Consequently, the upper limit of $\Lambda(1.4)$ will rule out NS EOSs with $M_{\rm TOV}$ larger than 2.8 solar mass very robustly. According to our calculation in strangeon star model, the relationship between $\Lambda(1.4)$ and $M_{\rm TOV}$ still holds qualitatively. However, the quantitative results change a lot. The largest possible $M_{\rm TOV}$ for the strangeon star EoSs preserving the $\Lambda(1.4) < 800$ constraint is larger than $4\,M_\odot$. This quite large difference is resulted from the finite surface density of strangeon stars. Therefore, for conventional quark star models which have a similar property, this quantitative difference is also found in previous studies [32,33].

The details of our calculation result are shown in Fig.1. The available parameter space is quite large as most of the EoS models satisfy the tidal deformability constraint by GW170817. We also show in the contour lines for $M_{\rm TOV}$ in Fig.1 to indicate the relation between $\Lambda(1.4)$ and $M_{\rm TOV}$. As can be seen, both $M_{\rm TOV}$ and $\Lambda(1.4)$ decrease as the surface density increase, which is similar to the case of conventional quark stars described by MIT bad model [32]. Whereas a larger U_0 makes the EoS stiffer, resulting in a larger $M_{\rm TOV}$ and $\Lambda(1.4)$. For all the models we have considered, the minimum $\Lambda(1.4)$ is 287[1] with $M_{\rm TOV}$ is $2.9\,M_\odot$ (for the model with $U_0 = 20\,{\rm MeV}$ and $\rho_{\rm s} = 2\rho_{\rm nuc}$), which is still far beyond the 2 solar mass constraint [24,25]. This sharp difference of $M_{\rm TOV}$ has clear consequence to the study of GRBs, as the post-merger should not be a black hole and would power significantly both the GW170817-fireballs of GRB and kilonova in strangeon star model.

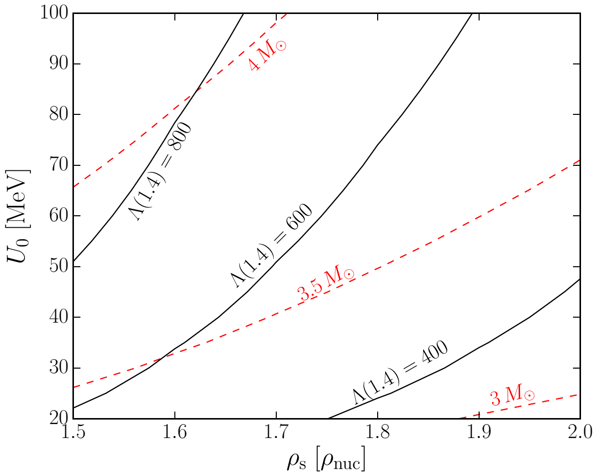

Fig. 1. Constraints on the equation of state parameters: U_0 and $\rho_{\rm s}$ (in unit of nuclear density with $\rho_{\rm nuc} = 2.67 \times 10^{14}\,{\rm g/cm^3}$). Contours of the tidal deformability of a $1.4\,M_\odot$ star ($\Lambda(1.4)$) are plotted in solid lines. According to the constraint of GW170817, any parameter choices below the top left solid contour is reasonable. Contours for the TOV maximum mass is also shown in dashed lines, although the strangeon star model is generally quite stiff. Hence the parameter choices will not be confronted by the observation of 2 solar mass pulsars [24,25] in the parameter space we consider.

4 Conclusions and discussions

Strong matter in bulk could be composed of strangeons, i.e. quark-clusters with there-light-flavor symmetry of quarks, and pulsar-like compact stars could actually be strangeon stars. The EOS of strangeon stars is described in the Lennard-Jones model, and the parameters U_0 and $\rho_{\rm s}$ are constrained by both the tidal deformability Λ of GW 170817 and $M_{\rm TOV}$. We find that the available parameter space is quite large as most of the EOS models satisfy the tidal deformability constraint by GW170817.

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[1] As a comparison, for NS models, $\Lambda(1.4)$ is 256 for the very soft EoS of APR4 (consists of n, p, e, and μ[34]), with $M_{\rm TOV} = 2.2M_\odot$.

The parameters U_0 and ρ_s, which characterize the inter-strangeon potential and determine the EOS of strangeon stars, should have implications on the properties of strong interaction at low energy scales. From the constraints by both GWs ($\Lambda \leq 800$) and the mass measurement ($M_\mathrm{TOV} \geq 2M_\odot$), the allowed region of parameters is still very large. We may expect $U_0 < 60\,\mathrm{MeV}$ and $\rho_\mathrm{s} > 1.5$ times of nuclear density since the detected masses of stellar black holes are usually lager than $4M_\odot$ at least. Future GW detections for smaller values of Λ along with larger values of M_TOV will be helpful to make better constraints on the strangeon star model.

All EOSs we choose here lead to values of M_TOV far beyond $2M_\odot$, indicating that all of the known pulsar-like compact stars are far below the maximum mass. High maximum mass also indicates quite a different scenario for the post-merger phase. A much longer lived strangeon star as the merger remnant should be expected. This long-live remnant could be helpful to understand the GW 170817 associated kilonova observation AT 2017gfo [7,26,27]. The continuous energy injection from the spin down power of the merger remnant is a natural energy source for the extended emission of AT2017 gfo, without requiring larger opacity and larger amount of ejecta mass compared with numerical simulation of binary mergers. Particularly, it is hinted that there might be an X-ray flare related to the central engine after more than 100 days of the merger [36], which highly favors the possibility that the remnant has not collapsed to a black hole yet. The strangeon star model will allow for such a long lifetime for the merger remnant even for the model with the smallest M_TOV.

Additionally, as mentioned above, isolate strangeon star, or binary strangeon stars in the early inspiral stage when they are separated far enough, could be in solid state, for which the tidal deformability could be much smaller or even negligible than the values estimated with perfect fluid energy momentum tensor. Depending on the breaking strain (σ) and shear modulus (μ) of the solid structure, the tidal heating effect might melt the solid star at a certain breaking frequency [30].

$$\begin{aligned} f_\mathrm{br} &= (\frac{2}{3})^{1/4}\frac{1}{\pi}(\frac{Q_{22\mathrm{max}}}{\lambda}) \\ &= 20 \times (\frac{Q_{22\mathrm{max}}}{10^{40}\,\mathrm{g\,cm^2}})^{1/2}(\frac{\lambda}{2\times 10^{36}\mathrm{g\,cm^2 s^2}})^{-1/2}\,\mathrm{Hz} \end{aligned} \quad (4)$$

in which λ is the tidal deformability resuming the dimensional units and $Q_{22\mathrm{max}}$ is the maximum quadrupole moment that should be induced in the solid star before it is melt, which can be estimated as [35]

$$\begin{aligned} &Q_{22\mathrm{max}} = 2.8\times 10^{41} \\ &\frac{\mu}{4\times 10^{32}\mathrm{erg\,cm^{-3}}}(\frac{R}{10\,\mathrm{km}})^6(\frac{M}{1.4\,M_\odot})^{-1}\frac{\sigma_\mathrm{max}}{0.01}\,\mathrm{g\,cm^2}. \end{aligned} \quad (5)$$

As a result, if indeed isolated strangeon stars are in solid state, we might be able to observe a sudden change in the tidal deformability at a certain gravitational wave frequency in future observations. The breaking frequency itself will also provide important information about the properties of the solid star.

The state of supranuclear matter in compact stars essentially relates to the fundamental strong interaction at low energy scale, which still remains a challenge. The strangeon star model perceives a pulsar-like compact star as a gigantic strange nucleus whose building blocks are strangeons. Up to now, the strangeon star model has passed all of the observational tests, and we expect that the more advanced GW observations in the future would tell us more about the strangeon stars and the strong matter in bulk.

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