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Strangeons constitute bulk strong matter: 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 bulk strong matter. From an observational point of view, it is proposed that bulk strong matter could be composed of strangeons, *i.e.* quark-clusters with three-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_{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 GW 170817. The future GW detections for smaller values of Λ and mass measurement for larger values of M_{TOV} will help find a better constraint on the strangeon star model.

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 (with sizes \sim fm). In normal matter, nuclei are far away 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 bulk strong matter is macroscopic and the surface effect is negligible¹. The lower limit of A for bulk strange/strangeon matter, however, is in fact not matter since we are concerned about the three-flavor symmetric system. The three-flavor symmetry would be restored in the strong matter with size approximating to or even

larger than the Compton wavelength of electrons [4], corresponding to baryon number $A > 10^9$. Therefore, the surface effect can be safely ignored for strong matter with three-flavor symmetry, which is actually the bulk strong matter.

Bulk strong matter 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 bulk strong matter, which could manifest in the form of a pulsar-like compact object.

Nevertheless, the true nature of bulk strong matter is still uncertain, which is essentially related to the ignorance about the behavior of strong interaction at the low energy scales. The neutron star and quark star are two models that have attracted most attention. The former originates from the concept of “gigantic nucleus” initiated by Landau [5], and the latter compares the whole star to a gigantic hadron composed of deconfined quarks, based on the conjecture of Witten [6]. From astrophysical points of view, however, it is proposed that “strangeons”, which were formerly named as quark-clusters with strangeness, could constitute bulk strong matter, and the pulsar-like compact stars could actually be “strangeon stars” composed totally of strangeons. The observational consequences of strangeon stars show that different manifes-

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¹ Similar to the case of strange quark matter, the surface energy ($\propto R^2$) will become unimportant compared to the bulk energy ($\propto R^3$) when the baryon number A is large enough. The “bulk approximation” is generally good for $A > 10^2$ for strange quark matter [2,3].

tations of pulsar-like compact stars could be understood in the regime of strangeon stars (see the review [4] and references therein). More observational pieces of evidence to verify or disaffirm this proposal are needed.

The gravitational wave event GW 170817 [7] and its multiwavelength electromagnetic counterparts (*e.g.*, [8]) 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 GW 170817 and the bolometric radiation could be understood if the signals come from the merge of two strangeon stars in a binary [9], where the tidal deformability is derived from the EOS in [10]. 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 sect. 2 we briefly introduce the concept of strangons constituting the bulk strong matter, and the EOS of strangeon stars in a Lennard-Jones model. In sect. 3 we derive the dependence of tidal deformability of merging strangeon stars on the parameters in the Lennard-Jones model [10], and the constraint by GW 170817. Conclusions and discussions are made in sect. 4.

2 The bulk strong matter

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 $e^- + p \rightarrow n + \nu_e$ 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 (~ 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 [6], 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 [11] and the color-superconductivity state model [12], realistic stellar densities cannot be high enough to justify the use of perturbative QCD which most of compact star models rely on.

The bulk strong matter whose density is higher than the nuclear matter density is proposed to be strangeon matter. This can be understood in two approaches. In the approach from free quark state (a top-down scenario), the strong coupling between quarks may naturally render quarks grouped in quark-clusters [13,4]; and in the approach from hadronic state (a bottom-up scenario), it is the *strangeonization* to convert nucleons into strangeons, instead of the *neutronization* that convert protons to neutrons, during compressing normal baryonic matter of core-collapse supernova. 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.

Bulk strangeon matter may constitutes the true ground state of strong-interacting matter rather than nuclear matter [14]. This proposal could be regarded as a *general Witten's conjecture*: bulk strange matter 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 [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 [15], the clean fireball for core-collapse supernovae and cosmic gamma-ray bursts (GRBs) [16], the neutrino burst during SN 1987A [17], the spectra of XDINSs from optical to X-ray bands [18], the high-mass pulsars [10,14,19], the radiation of anomalous X-ray pulsars (AXPs) and soft gamma-ray repeaters (SGRs) [20,21], and the glitch behavior of pulsars [22]. It is also worth noting that, although the the EOS is very stiff, the causality condition is still satisfied for strangeon matter [23].

Moreover, the recently observed gravitational waves GW 170817 [7] as well as the electromagnetic radiation (*e.g.*, [8]) could be understood if the signals come from

the merge of two strangeon stars in a binary [9]. The tidal deformability is derived in the Lennard-Jones model [10], where the interaction between strangeons is 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. Similar to a nucleon, a strangeon is composed of constituent quarks, but there are two differences: the strangeon is of 3-flavored, and the number of constituent quarks could be large than three. Although we have proposed that *H*-dibaryons (with structure *uuddss*) could be a possible kind of strangeons [14], what could be the realistic strangeons inside compact stars is uncertain due to the difficulties in QCD calculations.

As shown by Wilczek [24], the interaction between nucleons is characterized by the long-range attraction and short-range repulsion. Although the Lennard-Jones potential originally describes the interaction between inert gas molecules, it also has the character of long-range attraction and short-range repulsion. In this paper, we use a more general and phenomenological model, the Lennard-Jones model [10], to describe the EOS of strangeon stars and to find out the constraints from the tidal deformability of GW 170817.

In the Lennard-Jones model, the interaction between strangeons is assumed to be similar to that between molecules of inert gas, since strangeons are colorless as in the case of chargeless atoms². The dependence of the potential u on the distance between strangeons r is

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

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 [10].

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 [25] 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 [10] to the EOS.

² It is worth noting that nucleon (2-flavored) and strangeon (3-flavored) are two kinds of the colorless strong units, like the atom of chargeless electric unit, and it would not be surprising that both nucleon/strangeon and atom could share a common nature of 6-12 potential.

The energy density is then

$$\epsilon = 2U_0 (A_{12}r_0^{12}n^5 - A_6r_0^6n^3) + nmc^2, \quad (2)$$

and the pressure is

$$P = 4U_0 (2A_{12}r_0^{12}n^5 - A_6r_0^6n^3), \quad (3)$$

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.

At the late stage of coalescence of binary strangeon stars, the stars would melt by the tidal heating, but we still adopt $A_{12} = 6.2$ and $A_6 = 8.4$ for simplicity as in the case of the simple-cubic structure, since other choices would not bring significant changes. The Lennard-Jones model reflects an important feature of strangeon matter, *i.e.* the long-range attraction and short-range repulsion between strangeons, no matter the strangeon matter is in the solid or liquid state. The short-range repulsion plays the crucial role in stiffening the EOS and raising the maximum mass. The form of EOS will not change significantly when the matter changes from the solid to liquid state, although the specific values of A_{12} and A_6 should change since they are determined by the micro-structure.

Moreover, although the values of A_{12} and A_6 will also affect the tidal deformability of strangeon stars, the quantitative results remain unchanged when we choose some different values of A_{12} and A_6 (but not different by the order of magnitude) for liquid stars. Other choices of A_{12} and A_6 would not change the result that the tidal deformability of (liquid) strangeon stars are very different from that of neutron stars, and the allowed parameter space is quite large for the Lennard-Jones EOS models to satisfy the tidal deformability constraint by GW 170817.

It is also worth mentioning that, as discussed in sect. 4, there would be a sudden increase in the tidal deformability resulting from the phase transition. Qualitatively, this change is due to the differences in breaking strain and shear modulus between solid and liquid states, regardless of what specific values of parameters we choose.

Besides the different compositions, there is another difference between neutron stars and strangeon stars, *i.e.* the surface densities, which also affect the global structure of the stars. Neutron stars are gravity-bound, while strangeon stars are self-bound (similar to strange quark stars, and the self-bound nature of strangeon stars is helpful to understand the drifting sub-pulses). Consequently, neutron stars have negligible surface density, while strangeon stars have the surface density that is higher than nuclear matter density. Although it seems that the hadronic matter can also be described by the Lennard-Jones model and has the corresponding form of EOS, the global structures of neutron stars and strangeon stars are still different.

The parameters U_0 and r_0 included in the EOS characterize the inter-strangeon potential. The potential in

Wilczek's paper [24] has a well with a depth of about 100 MeV, so in the calculation of sect. 3, we choose the range of U_0 to be from 20 MeV to 100 MeV. The surface number density of strangeons n_s determines r_0 by the fact that the pressure vanishes at the surface. When translating n_s into the rest-mass density of strangeon matter on the surface $\rho_s = mn_s$, we can constrain U_0 and ρ_s by the EOS-dependent observable properties. The constraints by the mass-radius curves are discussed in [10], and the TOV maximum mass could be higher than $3M_\odot$.

The majority of pulsar-like compact stars are produced in core-collapse supernovae, which usually have masses around $\sim 1.5M_\odot$. More massive ones with masses approaching or beyond $2M_\odot$ are produced in binary star mergers and binary systems with high accretion rates (*e.g.* some Ultra-Luminous X-ray sources), so the birth rate is much lower. Therefore, although the theoretical TOV maximum mass of pulsar-like compacts in strangeon star model could be above $3M_\odot$, the most detected ones are below $2M_\odot$. In the era of multi-messenger astronomy, gravitational wave events from binary star mergers, like GW 170817, could give better constraints of the maximum mass and test various models.

In the next section we will show the constraints by both the maximum mass of a static compact star (M_{TOV}) and the tidal deformability of GW 170817.

3 Strangeon star merger tested by GW 170817

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 GW 170817 and possible future observations.

The most robust constraint that the binary strangeon star merger scenario has to confront is the tidal deformability constraint of GW 170817. Mass quadrupole moment will be induced by the external tidal field of the companion during the late inspiral stage, accelerating the coalescence, hence detectable by GW observations [26]. 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 the strangeon star model, we have calculated k_2 for a set of strangeon star EOSs with various choices of U_0 and ρ_s . We have followed the procedure as in [27] to calculate k_2 , namely, introducing a static $l = 2$ perturbation to the TOV equation and solving it with the strangeon star EOSs. It is worth noting that due to the finite surface density of strangeon star model, a boundary treatment has to be done to ensure correct results [28]. In this study, we have explored parameter spaces with U_0 ranging from 20 MeV to 100 MeV and ρ_s from 1.5 times to 2 times the nuclear density ($2.67 \times 10^{14} \text{ g/cm}^3$). The TOV maximum mass

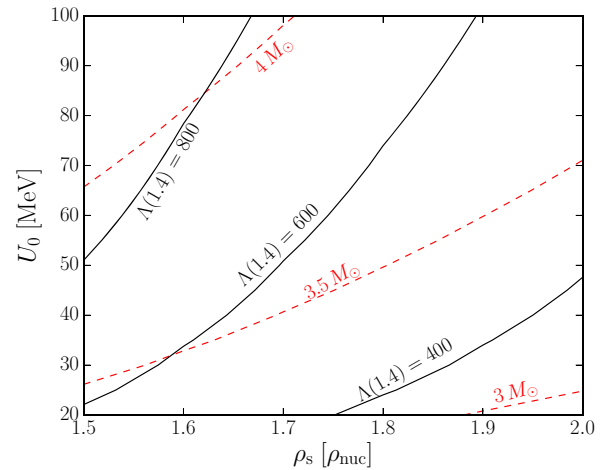


Fig. 1. Constraints on the equation of state parameters: U_0 and ρ_s (in unit of nuclear density with $\rho_{\text{nuc}} = 2.67 \times 10^{14} \text{ g/cm}^3$). Contours of the tidal deformability of a $1.4M_\odot$ star ($\Lambda(1.4)$) are plotted in solid lines. According to the constraint of GW 170817, any parameter choices below the top left solid contour is reasonable. Contours for the TOV maximum mass are 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 [29,30] in the parameter space we consider.

with each EOS model is also calculated, as it is tightly related to the post-merger evolution of the binary merger events.

Assuming both stars in the binary have low spins, the GW 170817 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_{TOV} increases. Consequently, the upper limit of $\Lambda(1.4)$ will rule out NS EOSs with M_{TOV} larger than 2.8 solar mass very robustly. According to our calculation in the strangeon star model, the relationship between $\Lambda(1.4)$ and M_{TOV} still holds qualitatively. However, the quantitative results change a lot. The largest possible M_{TOV} for the strangeon star EoSs preserving the $\Lambda(1.4) < 800$ constraint is larger than $4M_\odot$. This quite large difference results 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 GW 170817. We also show the contour lines for M_{TOV} in fig. 1 to indicate the relation between $\Lambda(1.4)$ and M_{TOV} . As can be seen, both M_{TOV} and $\Lambda(1.4)$ decrease as the surface density increases, which is similar to the case of conventional quark stars described by MIT bag model [32], whereas a larger U_0 makes the EoS stiffer, resulting in

a larger M_{TOV} and $\Lambda(1.4)$. For all the models we have considered, the minimum $\Lambda(1.4)$ is 287 (see footnote³) with M_{TOV} equal to $2.9 M_{\odot}$ (for the model with $U_0 = 20$ MeV and $\rho_s = 2\rho_{\text{nuc}}$), which is still far beyond the 2 solar mass constraint [29,30]. This sharp difference of M_{TOV} has a clear consequence to the study of GRBs, as the post-merger should not be a black hole and would power significantly both the GW 170817-fireballs of GRB and kilonova in strangeon star model.

4 Conclusions and discussions

Bulk strong matter could be composed of strangeons, *i.e.* quark-clusters with three-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 ρ_s are constrained by both the tidal deformability Λ of GW 170817 and M_{TOV} . We find that the available parameter space is quite large as most of the EOS models satisfy the tidal deformability constraint by GW 170817.

Different from neutron stars, strangeon stars are self-bound rather than gravity-bound. The finite surface density leads to a correction to calculate the tidal deformability. As a result, they can reach a much higher maximum mass under the same tidal deformability constraint. By contrast, it is not so easy for neutron star models to pass all the tests. For example, according to [31], neutron stars cannot reach higher than $2.8 M_{\odot}$ in order to satisfy the constraint of tidal deformability.

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 the low energy scales. From the constraints by both GWs ($\Lambda \leq 800$) and the mass measurement ($M_{\text{TOV}} \geq 2 M_{\odot}$), the allowed region of parameters is still very large. We may expect $U_0 < 60$ MeV and $\rho_s > 1.5$ times of nuclear density since the detected masses of stellar black holes are usually larger than $4 M_{\odot}$ at least [35,36]. 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 $2 M_{\odot}$, 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-lived remnant could be helpful to understand the GW 170817 associated kilonova observation AT2017 gfo [9,37,38]. 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

³ 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 $M_{\text{TOV}} = 2.2 M_{\odot}$.

hinted that there might be an X-ray flare related to the central engine after more than 100 days of the merger [39], 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, an 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 than or even negligible with respect to the values estimated with the 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 [28].

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

in which λ is the tidal deformability resuming the dimensional units and $Q_{22\text{max}}$ is the maximum quadrupole moment that should be induced in the solid star before it is melt, which can be estimated as [40]

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

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. This should be studied in more details in future work.

The state of supranuclear matter in compact stars essentially relates to the fundamental strong interaction at the low energy scales, 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 will tell us more about the strangeon stars and the bulk strong matter.

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