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Merging strangeon stars

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Abstract The state of supranuclear matter in compact stars remains puzzling, and it is argued that pulsars could be strangeon stars. What would happen if binary strangeon stars merge? This kind of merger could result in the formation of a hyper-massive strangeon star, accompanied by bursts of gravitational waves and electromagnetic radiation (and even a strangeon kilonova explained in the paper). The tidal polarizability of binary strangeon stars is different from that of binary neutron stars, because a strangeon star is self-bound on the surface by the fundamental strong force while a neutron star by the gravity, and their equations of state are different. Our calculation shows that the tidal polarizability of merging binary strangeon stars is favored by GW170817. Three kinds of kilonovae (i.e., of neutron, quark and strangeon) are discussed, and the light curve of the kilonova AT 2017gfo following GW170817 could be explained by considering the decaying strangeon nuggets and remnant star spin-down. Additionally, the energy ejected to the fireball around the nascent remnant strangeon star, being manifested as a gamma-ray burst, is calculated. It is found that, after a prompt burst, an X-ray plateau could follow in a timescale of $10^2 - 10^3$ s. Certainly, the results could be tested also by further observational synergies between gravitational wave detectors (e.g., Advanced LIGO) and X-ray telescopes (e.g., the Chinese HXMT satellite and eXTP mission), and especially if the detected gravitational wave form is checked by peculiar equations of state provided by the numerical relativistical simulation.

Key words: stars: neutron — pulsars: general — X-rays: stars — gravitational waves

1 INTRODUCTION

The nature of pulsar-like compact stars is essentially a central question into the fundamental strong interaction (explained in quantum chromo-dynamics) at the low energy scale, the solution of which still remains a challenge though tremendous efforts have been tried. This kind of compact object could actually be strange *quark* stars instead of neutron stars, if strange quark matter in bulk may constitute the true ground state of strongly-interacting matter rather than ^{56}Fe (the so-called Witten's conjecture (Witten 1984)).

From astrophysical points of view, however, it is proposed that strange cluster matter could be absolutely stable and thus those compact stars could be strange *cluster* stars in fact. 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 strange cluster matter). A strange cluster with three-light-flavor symmetry is renamed a "strangeon," which is coined by combining "strange nucleon" for the sake of simplicity. A strangeon star can then be thought of 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. However, the most important issue is to find observational evidence to verify or disaffirm this proposal.

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 Lai & Xu 2017 and references therein). Since it could be possible that pulsar-like compact stars are actually strangeon stars, neutron star binaries could actually be strangeon star binaries. The coalescence of strangeon stars in a binary will release signals of gravitational waves as well as electromagnetic radiation, both of which would be detected. These signals, in addition to those from isolated stars, would provide additional useful ways to constrain the properties of pulsar-like compact stars. In this paper, we focus on the possible different electromagnetic behaviors of the merger strangeon stars, and the energy ejection to the fireball of a newborn remnant after the merge.

During the phase of tidal disruption of the stars as they approach each other before the final merger, a small fraction of the total mass of both stars should be released. Although strangeon stars could be in a solid state at low temperature ($\lesssim 1\,\mathrm{MeV}$), during the phase of tidal disruption and coalescence the temperature of both stars in the binary would rise so that the strangeon stars would be phase-converted to a liquid state. For a binary composed of two strangeon stars, both with the typical mass $\sim 1.4\,M_\odot$, the remnant could be a hyper-massive strangeon star with mass $\sim 2.6\,M_\odot$, which would still be in a liquid state until it cools down to $\sim 1\,\mathrm{MeV}$. In this case, strangeon stars in a binary just before merger and the remaining strangeon star at the early stage would behave more or less like conventional quark stars.

Hydrodynamical simulations of the coalescence of quark stars have been performed (Bauswein et al. 2010), under the equation of state (EOS) within the MIT bag model. Different from the case of a neutron star merger which forms dilute halo structures around the remnant, the merger of quark stars results in a clumpy strange matter disk. For a binary of two quark stars with equal mass $\sim 1.35\,M_\odot$, simulations show (Bauswein et al. 2010) that the mass of the disk around the remnant is about $0.1\,M_\odot$ and the mass of the ejecta is about $10^{-3}\,M_\odot$. The ejected small lumps of strange matter are called strangelets, and large lumps of strange matter are called strange nuggets, both of which would be present in cosmic rays (Madsen 2005). Interestingly, Geng et al. (2015) studied the coalescence of quark planets with quark stars and showed that it could be a new kind of gravitational wave sources. The merger of strangeon stars in a binary has not been calculated yet, but we could infer that the mass of ejecta could be larger than that in the case of binary quark stars, as the binding of strangeons in strangeon stars should be weaker than that of quarks in quark stars. Therefore, although strangeon stars in a binary just before merger and the remnant strangeon star at the early stage would behave like conventional quark stars, the masses of the ejecta and the disk around the remnant would be larger than those of a conventional quark star binary.

Some simulations of binary neutron star mergers, however, show that the released mass could be from $10^{-4}\,M_\odot$ to $10^{-2}\,M_\odot$ (Goriely et al. 2011; Piran et al. 2013), depending on parameters such as the stiffness of the EOS, the total mass of the binary and the production associated with the merge. After thermalization, the ejecta would play an important role in the afterglows, such as the radiation of optical and near infrared (Li & Paczyński 1998). If the total mass of ejecta is about $10^{-2}\,M_\odot$, the transient event is called a "kilonova" (Metzger et al. 2010). If a massive millisecond magnetar is formed after the merge, the transient event is called a "merger-nova" (Yu et al. 2013). However, if the compact star binaries are actually strangeon star binaries, the ejecta from tidally elongated strangeon stars and their merger could be relatively less than that from the merging of binary normal neutron stars, because a strangeon star is self-bound on the surface by the fundamental strong force but a neutron star is bound by gravity. Then what kind of electromagnetic radiation would be emitted after merging?

The gravitational event GW170817 and its multi-wavelength electromagnetic counterparts open a new era in which the nature of pulsar-like compact stars could be crucially tested. Unlike the neutron-rich ejecta in the case of merging neutron stars that will decay and radiate, the ejecta composed of strangeon nuggets would not lead to r-process nucleosynthesis. However, merging strangeon stars could also lead to a "kilonova" by decay of strangeon nuggets and the spindown of the remanent compact star. The observed "blue component" of kilonova AT 2017gfo following GW170817 could be powered by the decay of ejected strangeon nuggets, while the late "red component" could be powered by the spindown of the remnant strangeon star after merging. On the other hand, the clumpy strange matter disk instead of a dilute halo structure around the remnant would make it possible to detect the thermal radiation of the remnant shortly after the merger. In this paper, we also consider energy ejection via the cooling process of the remnant strangeon star, which could be tested by observations, e.g., by the Hard X-ray Modulation Telescope (HXMT) and the future enhanced X-ray Timing and Polarimetry mission (eXTP).

This paper is arranged as follows. In Section 2 we test the strangeon star model with constraints on tidal polarizability by GW170817. In Section 3 we introduce the "kilonova" by decay of strangeon nuggets, which is called a "strangeon kilonova." We derive the bolometric light curve of a strangeon kilonova, which shows that under reasonable parameters, the light curve of kilonova AT 2017gfo could be fitted by considering the decaying strangeon nuggets and remnant star spin-down. The thermal radiation of the remnant massive strangeon star is calculated in Section 4. Summary and discussions are provided in Section 5.

2 TIDAL POLARIZABILITY TESTED BY GW170817

Recently, a gravitational wave event with companion mass of $\sim 1.4\,M_\odot$ was discovered (Abbott et al. 2017). It was found that the tidal polarizability (see Eq.(3) below) of the individual companion star would not be larger than 10^3, and some relatively soft EOSs for normal neutron stars (e.g., SLy and APR4) could be favored (Read et al. 2009), with maximum masses of $M_{\rm max}\sim 2.05\,M_\odot$ for SLy and $M_{\rm max}\sim 2.21\,M_\odot$ for APR4 of $\{npe\mu\}$-matter, although the hyperon puzzle is unavoidable in nucleon star models (Bombaci 2017). Nevertheless, for a strangeon star with mass $\sim 1.4\,M_\odot$, the radius could be smaller than that of APR4, even though the EOS is still very stiff so that the maximum mass would reach $\sim 3\,M_\odot$. Clear evidence for a strangeon star could be obtained if a pulsar as massive as $\sim 2.3\,M_\odot$ is discovered by advanced instrumentation (e.g., the Chinese FAST facility).

Similar to binary neutron star mergers, the mass quadrupole moment will be induced in the late inspiral phase of a binary strangeon star merger, due to the tidal field of each companion on the other. This property can be characterized by the following relationship,

$$Q_{ij}=\lambda(m)\mathcal{E}_{ij}, \tag{1}$$

where the tensor $\mathcal{E}_{ij}$ is an external tidal field and Q_{ij} is the induced mass quadrupole moment. In this relationship, $\lambda(m)$ is a function of the stellar mass which also depends on internal structure of the star and is related to the so called $l=2$ tidal Love number k_2 by

$$k_2=\frac{3}{2}\lambda R^{-5}. \tag{2}$$

The induced mass quadrupole moment will accelerate the coalescence, and hence can be constrained by gravitational wave observations (Flanagan & Hinderer 2008).

In order to test the strangeon star model with constraints on tidal polarizability by GW170817 and future observations, we have calculated k_2 for a strangeon star EOS by introducing a static $l=2$ perturbation to the Tolman-Oppenheimer-Volkoff (TOV) solution (Hinderer 2008). Additionally, the finite surface energy density of the strangeon star requires a special treatment on the boundary condition to obtain the correct result (Postnikov et al. 2010). Once we have calculated k_2, it is straightforward to obtain the dimensionless tidal polarizability by

$$\Lambda=\lambda/M^5=\frac{2}{3}k_2(R/M)^5. \tag{3}$$

According to the observation of GW170817, the dimensionless tidal polarizability of a star with 1.4 $M_\odot$ (i.e., $\Lambda(1.4)$) is constrained with an upper limit of 800 for the low spin case and 1400 for the high spin case (Abbott et al. 2017). The corresponding value for strangeon star EOS is 381.9 in our calculation. This result indicates that although the strangeon star EOS is so stiff that the TOV maximum mass would reach $\sim 3\,M_\odot$, the tidal polarizability is actually similar to those soft EOS models such as APR4 and SLy which are favored by GW170817.

For a more systematic test, we have employed the 90% most probable fraction of component masses m_1 and m_2 for GW170817 to calculate Λ_1 and Λ_2 with a strangeon star EOS. The result is compared with the posterior distribution for Λ_1 and Λ_2 with post-Newtonian waveforms as well as three other neutron star EOSs obtained by Abbott et al. (2017). As shown in Figure 1, in both high spin and low spin cases, strangeon star EOS is favored by the constraints. Particularly, considering that the strangeon star will be in a solid state until the very late inspiral when the tidal heating might lead to a phase transition of the star to liquid state, the actual contribution from the mass quadrupole moment to the waveform will be even less significant. In this case, the strangeon star model is actually more favored by GW170817.

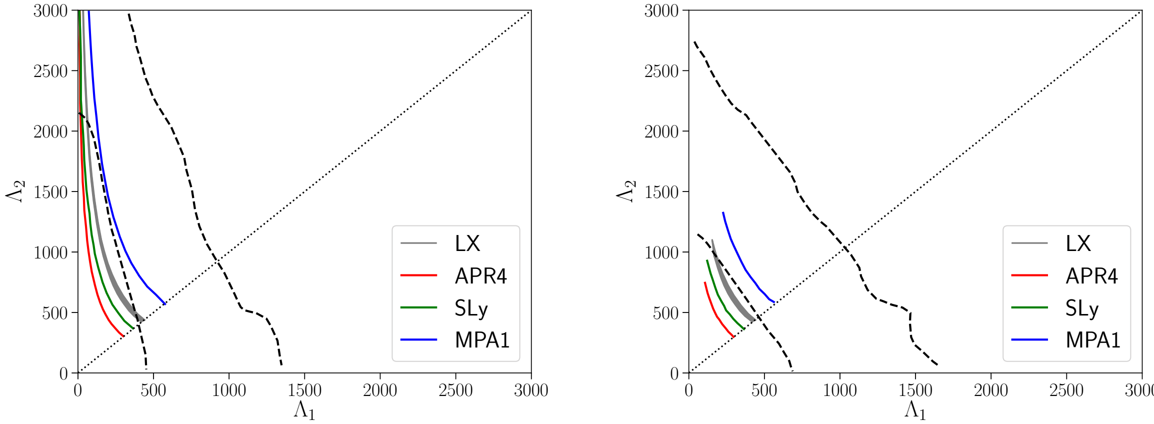

Fig. 1 Comparison of the tidal polarizability of the strangeon star model with the results obtained by Abbott et al. (2017). The *left panel* is for the higher spin prior (i.e., $|\chi| \le 0.89$) and the *right panel* is for the lower spin prior (i.e., $|\chi| \le 0.05$). The *dotted diagonal line* indicates the boundary of $\Lambda_1 = \Lambda_2$. The *dashed lines* are 50% (*the one to the bottom left corner*) and 90% posterior (*the one to the top right*) distribution contours for independent Λ_1 and Λ_2 priors with a post-Newtonian waveform (Abbott et al. 2017). As can be seen, the strangeon star EOS (labeled as 'LX') is favored as the other two soft EOSs (APR4 and SLy) in both cases.

3 STRANGEON MATTER KILONOVA

After discussing the tidal polarizability, we turn to the tidal destruction and head-on collision of merging compact stars. Certainly, the ejecta and radiation features depend on the composition of stellar material. For normal neutron stars in which neutron fluid is dominant, a neutron-rich environment forms, resulting in r-process nucleosynthesis as well as a Li-Paczyński nova (Li & Paczyński 1998), termed "*neutron matter*" kilonova afterwards (Metzger et al. 2010). However, it is also argued that Big Bang-like nucleosynthesis could occur for a strange quark star merger, reaching the Fe peak but not the lanthanides or gold (Paulucci et al. 2017). We may then call its observational consequence a "*quark matter*" kilonova. Will the tidal effects and collision of two strangeon stars behave similarly? Unfortunately, this process has never been studied extensively yet, but nonetheless there could be different physics from both scenarios above, except the note that r-process nucleosynthesis would also not occur during the coalescence of strangeon stars (Xu 2015). We are introducing these three kinds of kilonovae here, focusing on similarities and differences among them.

Neutron kilonova. Li & Paczyński (1998) put forth the idea that merging neutron stars could produce neutron-rich ejecta in which r-process nucleosynthesis will happen. The neutron-rich material can be ejected at a speed of about $0.1c$ (with c being the speed of light) due to the tidal polarization and probably maintains a low temperature, i.e., a large neutron fraction. Alternatively, the ejecta might also originate from the outflows of the accretion disk with a speed of $0.1 - 0.2c$ and could be proton rich (e.g., Barzilay & Levinson 2008). As the ejecta expands as an envelop, a rapid electromagnetic transient–the kilonova–powered by $\beta-$ decay and fission would occur. Metzger et al. (2010) further develop the model and find that the radioactive heating rate of the kilonova robustly peaks on a timescale $t_{\rm peak} \sim 1\,$day which results in a light curve with a similar $t_{\rm peak}$. This distinguishes a kilonova from a Type Ia supernova which has $t_{\rm peak} \sim$ weeks since the latter has a larger amount of ejecta and fuel (^{56}Ni) with a longer half-life. The r-process would also produce a significant amount of lanthanide elements that is optically thick in the ultraviolet (UV) bands due to the line blanketing effect and lead to a reddened spectrum. To a great extent, the optical follow-up of GW170817 confirms the prediction of the kilonova scenario.

Specifically, the early-time spectra reveal a relativistic expanding ($\sim 0.2c$, i.e., rapidly cooling) photosphere with a blackbody temperature of $10^4\,$K. As the transient fades out in subsequent days, the spectral peak moves redward to the infrared end (Shappee et al. 2017). However, a fast-fading blue component dominating the UV/optical bands in the early spectra is not expected from the model (e.g., Shappee et al. 2017; Drout et al. 2017; Cowperthwaite et al. 2017). This can be attributed to lanthanide-poor ejecta that originates from the squeezing of the neutron stars or the post-merger disk wind (e.g., Murguia-Berthier et al. 2017; Kasen et al. 2017), although alternatives are also proposed (e.g., Piro & Kollmeier 2017; Ioka & Nakamura 2017). Even by assuming two components of the ejecta with different masses, velocities and lanthanide fractions, the modeling of the long term spectral evolution is not completely satisfying (Kilpatrick et al. 2017; Chornock et al. 2017). Therefore, even if the kilonova is the true nature beneath the optical transient of GW170817, there is still a long way to go to figure out the nuclear-physical, dynamical and radiative details of the merger event.

Quark kilonova. It is shown by Paulucci & Horvath (2014) that no significant strangelet would survive in the ejecta after the merger and most of the ejecta would decay into protons and neutrons. Therefore, heavy elements would be built in a bottom-up manner in analogy to Big Bang nucleosynthesis. Assuming a subrelativistic free expansion speed of about $0.2c$, Paulucci et al. (2017) find that the proton-neutron equilibrium will freeze out on a millisecond timescale, resulting in a final neutron-to-proton ratio of about $0.7 - 0.8$, which is significantly higher than that from Big Bang nucleosynthesis but lower than that for r-process element synthesis. Consequently, nucleosynthesis stops at the Fe-peak elements and a total absence of lanthanides is expected. Nevertheless, many radioactive low-mass elements (with mass number < 70) being produced power a light curve peaking on a one-day timescale. The luminosity of this strange quark kilonova drops by 2 orders of magnitude in about a week, which is consistent with the optical/IR counterpart associated with GW170817 (Kilpatrick et al. 2017; Siebert et al. 2017). However, a detailed match of the spectral evolution is needed before drawing further conclusions.

Strangeon kilonova. Merging of strangeon stars has not been studied yet, but we could qualitatively describe some possible consequences which could be compared to observations. Being heated by the tidal process, two strangeon stars in a binary before coalescence would be phase-converted to a liquid state, so they would behave like conventional quark stars. Because the binding of strangeons in strangeon stars (which are bound by residual chromo interaction) should be weaker than that of quarks in quark stars (which are bound by the chromo interaction), we could infer that the mass of ejecta from binary strangeon stars could be larger than that from binary quark stars. Therefore, if the mass of ejecta from merging binary quark stars is about $10^{-3}\,M_\odot$ (Bauswein et al. 2010), then we could assume that the mass of ejecta from merging strangeon stars could be as high as $10^{-2}\,M_\odot$. Although strangeon matter in bulk could be more stable than nuclear matter, the ejected strangeon nuggets (small lumps of strangeon matter) could be unstable under the strong and weak interactions. We could put the lower limit of critical baryon number A_c of stable strangeon nuggets to be $10^9 - 10^{10}$, corresponding to strangeon nuggets with size comparable to the Compton wavelength of electrons (Lai & Xu 2017), and strangeon nuggets with baryon number $A < A_c$ are unstable and will decay to protons and neutrons. The luminosity of the decay is

$$L_{\rm strangeon\ kilonova} \sim 10^{42}\,{\rm erg\,s^{-1}} \left(\frac{M_{\rm unstable}}{10^{-4}\,M_\odot}\right) \times \left(\frac{\Delta\eta}{1\,{\rm MeV}}\right)\left(\frac{1\,{\rm d}}{\tau}\right), \tag{4}$$

where $M_{\rm unstable}$ is the mass of the ejected unstable strangeon nuggets (with $A < A_c$), $\Delta\eta$ is the energy released per baryon by the decay of unstable strangeon nuggets, and τ is the lifetime of the unstable strangeon nuggets. Therefore, if the ejected unstable strangeon nuggets constitute about 1% of the whole ejecta and have a lifetime of about one day, then the luminosity of the decay would be comparable to that of the observed peak of the blue component of the kilonova following GW170718 (Kasliwal et al. 2017).

The slowly fading red component could be explained by the spin-down power of the remnant strangeon star (Yu & Dai 2017). The spin-down power evolving with time depends on the initial spin-down power $L_{\rm sd}(0)$ and the spin-down timescale $t_{\rm sd}$. The radiation-transfer process depends on properties of the ejecta, such as the total mass $M_{\rm ej}$, the minimum and maximum velocities $v_{\rm min}$ and $v_{\rm max}$ respectively, the density distribution index δ and the opacity κ.

The bolometric light curve of a strangeon kilonova fitted to the data from Kasliwal et al. (2017) is presented in Figure 2, corresponding to the remnant strangeon star with $L_{\rm sd}(0) \simeq 7.59 \times 10^{41}\,{\rm erg\,s^{-1}}$ and $t_{\rm sd} = 2.51 \times 10^5\,{\rm s}$, and the ejecta with $M_{\rm ej} = 0.01\,M_\odot$, $v_{\rm min} = 0.1c$, $v_{\rm max} = 0.25c$, $\delta = 3.5$ and $\kappa = 0.2\,{\rm cm^2\,g^{-1}}$. A more detailed demonstration of parameters in the spin-down powered kilonova is given in Yu & Dai (2017).

In a word, more observational tests should be necessary though the neutron kilonova model is preferred and well tested by the single event of GW170817. Quark

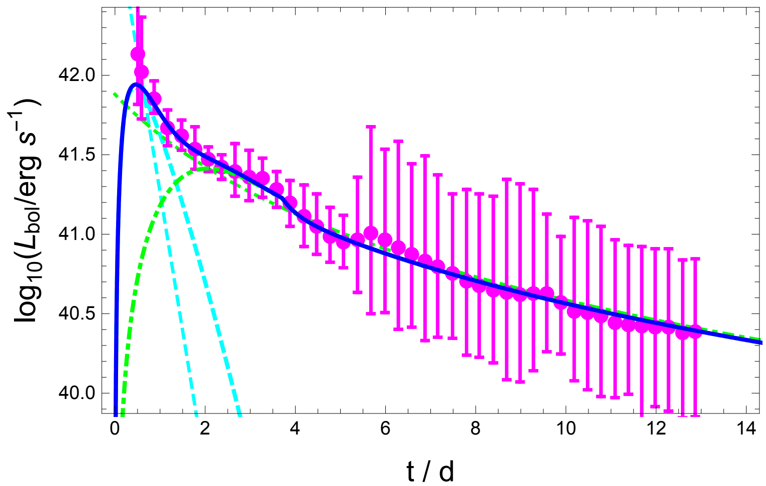

Fig. 2 Bolometric light curve of a strangeon kilonova including two energy sources, fitted to the data from Kasliwal et al. (2017). The *thin dashed* and *dash-dotted* lines represent the heating power of decaying strangeon nuggets and strangeon star spin-down, respectively. The *thick dashed* and *dash-dotted* lines are bolometric light curves powered by the corresponding single energy source. The *thick solid line* is the result of the combination of the two energy sources. The ejecta has mass $M_{\rm ej} = 0.01\,M_\odot$, minimal and maximum velocities $v_{\rm min} = 0.1c$ and $v_{\rm max} = 0.25c$ respectively, density distribution index $\delta = 3.5$ and opacity $\kappa = 0.2$ cm^2 g^{-1}. The remnant strangeon star has initial spin-down power of $L_{\rm sd}(0) = 7.59\times10^{41}$ erg s^{-1} and spin-down timescale $t_{\rm sd} = 2.51\times10^5$ s.

kilonovae as well as strangeon kilonovae models are two competing scenarios which might fit the diverse observations, but more detailed work is surely unavoidable.

4 ENERGY EJECTION FROM THERMAL RADIATION

We consider merging strangeon star binaries where the mass of both stars is $1.4\,M_\odot$, and the remnant strangeon star has mass $\sim 2.6\,M_\odot$.

After the tidal disruption and merging, the remnant strangeon star at the early stages is hot and in a liquid state. The newly formed hyper-massive strangeon star will release its internal energy by photons and neutrinos. During this cooling process a sharp drop of temperature would lead to a phase transition from the liquid to solid state. In the following we make a rough calculation about this cooling process, and the energy ejected to the fireball of a gamma-ray burst (GRB). Some of our calculations are based on Yuan et al. (2017) where the emission of supernova neutrinos is investigated in the strangeon star model.

In our calculation, we assume for simplicity that, inside the remnant strangeon star, the number density of strangeons is uniform with $n = 2.5n_0$, where n_0 is the saturated nuclear matter density. Although the number density of strangeons n decreases from the center to the surface, the variation could not be significant.

Figure 3 shows the values of n/n_0 as a function of distance from the center r, where the EOS is from Lai & Xu (2009), for three different values of strangeon star mass. In the calculations, the gravity-free density of strangeon matter (i.e., surface density) is assumed to be two times the nuclear density, for the sake of simplicity. It is evident that the density gradient would be comparably small due to the stiff state of strangeon matter. We can see that for the case of $M \simeq 2.6\,M_\odot$, n/n_0 only decreases from about 2.8 to 2, so we can make the approximation that the star has a uniform number density $n = 2.5n_0$.

The internal energy of a strangeon star includes contributions from both strangeons and electrons. The number density of electrons n_e is much smaller than that of strangeons n, with $n_e \sim 10^{-5}n$ (Alcock et al. 1986; Lai & Xu 2016). Before solidification, the energy of electrons could be ignored (Yuan et al. 2017) and we only consider the energy of strangeons. After the whole star becomes solid state, however, the contribution of electrons to the heat capacity will be significant. The results are shown below.

4.1 Cooling before Solidification

Before solidification, the energy of the strangeon system could be estimated as

$$U = \frac{3}{2}nk\cdot 4\pi\int_0^R r^2T(r)dr, \tag{5}$$

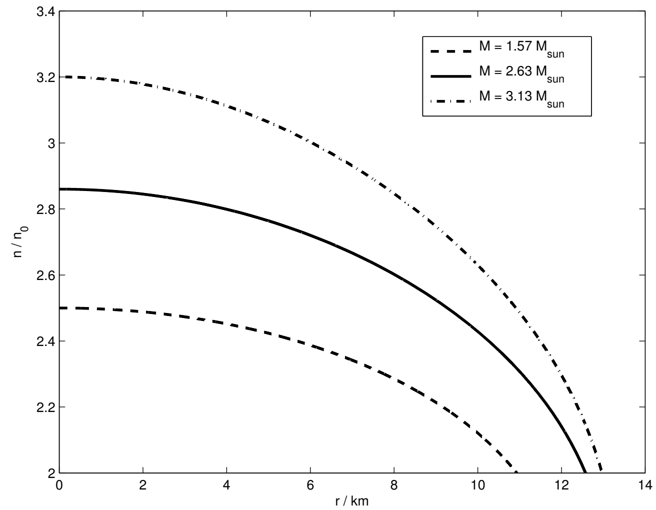

Fig. 3 Values of n/n_0 as a function of distance from the center r, where the EOS is from Lai & Xu (2009), for three different values of strangeon star mass with $M = 1.57\,M_{\odot}, 2.63\,M_{\odot}$ and $3.13\,M_{\odot}$. In the calculations, the gravity-free density of strangeon matter (i.e., surface density) is assumed to be two times the nuclear density, for the sake of simplicity. It is evident that the density gradient would be comparably small due to the stiff state of strangeon matter.

where $T(r)$ is the temperature inside the star with distance r from the center, and R is the radius of the star. The newly formed strangeon star is opaque to neutrinos, so it should be non-isothermal. Neutrinos collide with particles inside the star and the paths of neutrinos inside the star could follow the "random walking" process. The relation between internal temperature $T(r)$ and surface temperature $T_{\rm s}$ could then be estimated as $T(r) \sim T_{\rm s}(\frac{R-r}{l})^{1/4}$ (Yuan et al. 2017) where l is the mean free path of neutrinos.

The mean free path of neutrinos $l \simeq (n\sigma')^{-1}$, where the cross-section

$$\sigma' \simeq 0.5 \times 10^{-44}\,{\rm cm}^2\, A^2 (T/m_e c^2)^2$$

(Yuan et al. 2017), and A is the baryon number of each strangeon. For simplicity we take T as $T_{\rm s}$, and $A = 6$ which means that the number of quarks in each strangeon is 18. The internal energy of the strangeon star could then be derived as a function of $T_{\rm s}$.

The newly formed strangeon star decreases its internal energy by releasing photons and neutrinos, and the energy loss rate is

$$-\frac{dU}{dt} = L_\gamma + L_\nu, \tag{6}$$

where both L_γ and L_ν are luminosities of thermal radiation. The luminosity of photon radiation is $L_\gamma = 4\pi R^2 \sigma T_{\rm s}^4$, where σ is the Stefan-Boltzmann constant. The luminosity of neutrino radiation is $L_\gamma = 4\pi R^2 \sigma_\nu T_{\rm s}^4$, where $\sigma_\nu \sim 2.3\sigma$.

To derive the evolution of surface temperature $T_{\rm s}$ with time t, we should know the initial temperature T_0 at the time $t = 0$ when the remnant strangeon star is formed. Because strangeon stars in a binary just before merger and the remnant strangeon star at the early stages should be in a liquid state, they could behave like conventional quark stars. Simulations show that in the case of the quark star binary, the maximum temperature during the evolution is about 65 MeV if the mass of both quark stars is $1.35\,M_{\odot}$, so we assume that in our case the surface temperature of the newly formed massive strangeon stars is $\sim 50\,$MeV. After formation, the remnant massive strangeon star will release its internal energy by photons and neutrinos.

4.2 Cooling during and after Solidification

When the temperature drops below $\sim 1\,$MeV (the melting temperature) (Dai et al. 2011), the phase transition from liquid to solid state occurs. During this stage, the temperature will not decrease, and the latent heat E would be released through thermal emission,

$$E = (L_\gamma + L_\nu)\Delta t, \tag{7}$$

where Δt is the time interval at which the phase transition proceeds. The latent heat E could be estimated as

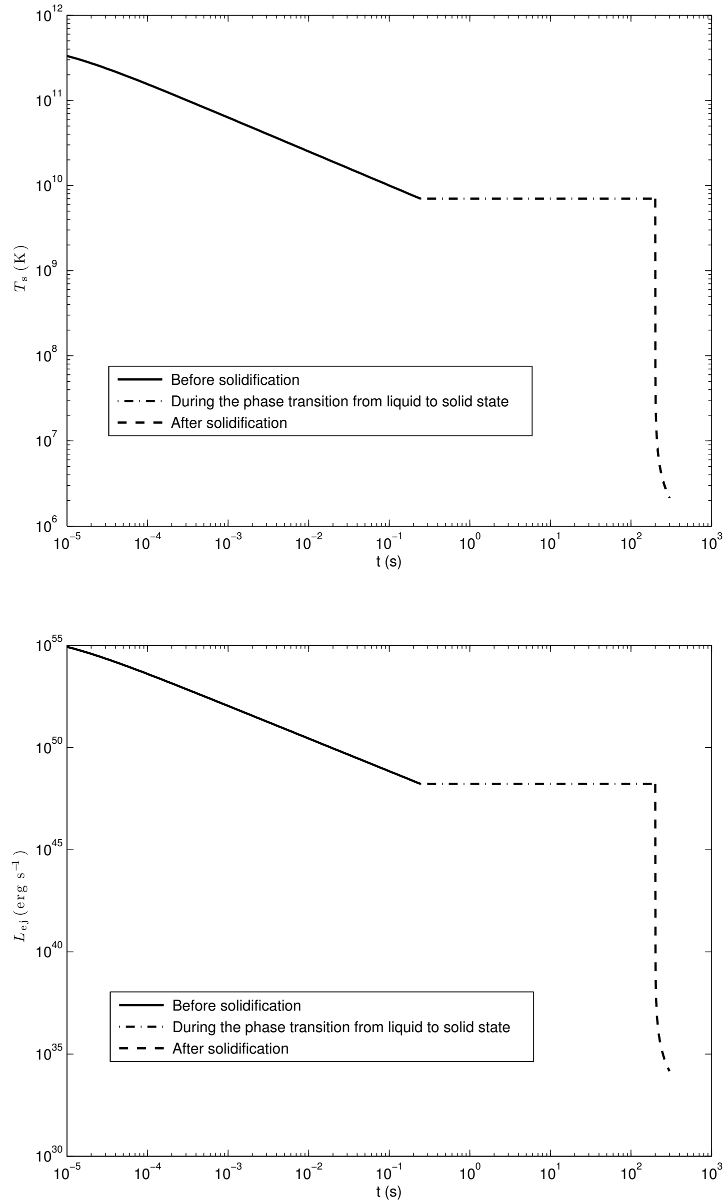

Fig. 4 Cooling curve (*the top panel*) and energy ejection from thermal radiation of the remnant strangeon star (*the bottom panel*), not considering heating by accretion or spin-down of the star. There are three stages: before solidification, during the phase transition from liquid to solid state and after solidification, with ϵ (the energy released by each strangeon during the phase transition) = 1 MeV. The time elapsed during the phase transition $\Delta t \simeq 200\,$s. If $\epsilon = 10\,$MeV, then $\Delta t \simeq 2000\,$s. The phase transition occurs when temperature drops to $\sim 1\,$MeV. This means that after a prompt burst, an X-ray plateau could follow in a timescale of $10^2 - 10^3$ s.

$E = \epsilon N$, where N is the number of strangeons and ϵ is the energy released by each strangeon during the phase transition.

As demonstrated before, the newborn strangeon star is non-isothermal. The phase transition from liquid to solid state starts at different times in different parts of the star, so the phase transition process is complicated. To make a rough estimation about the time elapsed during the phase transition Δt, we assume that $T_{\rm s} = 0.7\,$MeV when the internal temperature reaches 1 MeV. Choosing the ratio of inter-strangeon potential U_0 to the latent heat per strangeon ϵ to be $f = 0.01 - 0.1$, then for $U_0 = 100\,$MeV (Lai & Xu 2009), $\epsilon = 1{-}10\,$MeV. Due to the uncertainty about ϵ, we take it as a parameter and set $\epsilon = 1\,$MeV, leading to $\Delta t \simeq 200\,$s. Because $\Delta t \propto \epsilon$, we can see that if $\epsilon = 10\,$MeV, then $\Delta t \simeq 2000\,$s. Although the value of Δt depends on the value of ϵ and the melting temperature of strangeon stars, both of which are uncertain, we can see that Δt could have the order of 10^3 s, which means that the latent heat injected into the GRB fireball could explain the X-ray plateau observed in many GRBs (Dai et al. 2011; Hou et al. 2017).

When the phase transition completes, i.e., the whole star becomes solid, the internal energy of the star is then

$$U = \int C_v dt, \tag{8}$$

where C_v is the heat capacity of solid strangeon matter, including the contribution of strangeons and electrons, both of which depend on temperature.

In the Debye model (Yu & Xu 2011), C_v drops below 10^{35} erg K^{-1} when temperature drops below 1 MeV, so after solidification the temperature drops very quickly. Here we only consider cooling from the residual thermal energy at very early stage, and do not consider heating by accretion or spin-down of the star late after its birth, because the energy ejected from thermal radiation of the remnant strangeon star to the fireball around the star shortly after its birth could be manifested as a GRB after a prompt burst. If the heating proceeds such as the accretion heating or spin-down heating (Yu & Xu 2011), the temperature of the star could be sustained at $10^6 - 10^7$ K in the late stages.

The cooling curve is shown in the bottom panel of Figure 4, demonstrating three stages: before solidification, during the phase transition from the liquid to solid state and after solidification, with $\epsilon = 1$ MeV. Energy ejection in the form of thermal photons from the remnant strangeon star is shown in the top panel of Figure 4. The phase transition occurs when temperature drops to ~ 1 MeV, and the time elapsed during the phase transition $\Delta t \simeq 10^2 - 10^3$ s.

Figure 4 shows that luminosity of the energy ejection during the phase transition is about 10^{48} erg, indicating that after a prompt burst an X-ray plateau could follow in a timescale of $10^2 - 10^3$ s.

5 SUMMARY AND DISCUSSION

Pulsar-like compact stars could actually be so-called "strangeon stars." The merger of a strangeon star binary composed of two strangeon stars with mass $\sim 1.4\,M_\odot$ could result in the formation of a hyper-massive strangeon star with mass $\sim 2.6\,M_\odot$, accompanied by bursts of gravitational waves and electromagnetic radiation.

In this paper we discuss the corresponding electromagnetic behavior. From the constraints on tidal polarizability by GW170817, we find that the strangeon star model is more favored than the neutron star model. The "strangeon kilonova" scenario is introduced, which could be powered by the decay of ejected strangeon nuggets and the spin-down of the remnant strangeon star. The energy ejection from thermal radiation of the remnant strangeon star is also calculated, which shows that an X-ray plateau could follow in a timescale of $10^2 – 10^3$ s. Our result could be tested by observations, i.e., by HXMT and the future eXTP.

In the strangeon kilonova scenario, we show that the bolometric light curve of the kilonova following GW170817 could be explained by combining two energy sources including the decay of ejected strangeon nuggets and the spin-down of the remnant strangeon star. It is worth mentioning that there are two other possibilities. On one hand, the nucleosynthesis of protons and neutrons from the decaying strangeon nuggets could produce radioactive heavy elements whose decay could also contribute to the slowly fading red component in the kilonova following GW170817. On the other hand, if all the ejected strangeon nuggets are stable, only the spin-down of the remnant strangeon star could also power the bolometric light curve.

More observational tests should be necessary though the neutron kilonova model is preferred and well tested by the single event of GW170817. Quark kilonovae as well as strangeon kilonovae models are two competing scenarios which might fit the diverse observations, but more detailed work is surely unavoidable. Certainly, our results could be tested also by further observational synergies between gravitational wave detectors (e.g., Advanced LIGO) and X-ray telescopes (e.g., the Chinese HXMT satellite and eXTP mission), and especially if the detected gravitational wave form is checked by a peculiar EOS provided by the numerical relativistical simulation.

The coalescence of neutron stars in binaries is taken as the origin of the GRBs (Paczynski 1986). The fireballs in GRB associated supernovae could be explained if strangeon stars are formed in core-collapse supernovae (Chen et al. 2007), then it is possible that merging strangeon stars can give rise to short GRBs, although no calculation or simulation has been performed yet. Interestingly, strange nuggets in the torus (or disk) could behave like dust if each of them contains high enough baryon number ($\sim 10^{20} - 10^{30}$). These strange nuggets might absorb X-rays from the newly formed strangeon star and could reradiate in infrared wavelengths, which would be tested by observations.

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