RAA 2021 Vol. **21** No. **10**, 250(11pp) doi: 10.1088/1674-4527/21/10/250
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Research in Astronomy and Astrophysics

Merging strangeon stars II: the ejecta and light curves

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Received 2021 May 5; accepted 2021 June 24

Abstract The state of supranuclear matter in compact stars remains puzzling, and it is argued that pulsars could be strangeon stars. The consequences of merging double strangeon stars are worth exploring, especially in the new era of multi-messenger astronomy. To develop the "strangeon kilonova" scenario proposed in Paper I, we make a qualitative description about the evolution of ejecta and light curves for merging double strangeon stars. In the hot environment of the merger, the strangeon nuggets ejected by tidal disruption and hydrodynamical squeezing would suffer from evaporation, in which process particles, such as strangeons, neutrons and protons, are emitted. Taking into account both the evaporation of strangeon nuggets and the decay of strangeons, most of the strangeon nuggets would turn into neutrons and protons, within dozens of milliseconds after being ejected. The evaporation rates of different particles depend on temperature, and we find that the ejecta could end up with two components, with high and low opacity respectively. The high opacity component would be in the directions around the equatorial plane, and the low opacity component would be in a broad range of angular directions. The bolometric light curves show that the spin-down power of the long-lived remnant would account for the whole emission of kilonova AT2017gfo associated with GW170817, if the total ejected mass $\sim 10^{-3}\,M_\odot$. The detailed picture of merging double strangeon stars is expected to be tested by future numerical simulations.

Key words: dense matter — equation of state — pulsars: general

1 INTRODUCTION

Matter in our Universe takes on various forms, although the fundamental particles making up matter are just three generations of Fermions in the Standard Model of particle physics. The state of matter at extremely high densities created by the gravitational collapse of massive stars is still far from certain, which is yet essential for us to explore the nature of pulsar-like compact stars. It is still under debate if the main constitution of pulsar-like compact stars is two-flavored or three-flavored matter. The gravity-compressed matter produced after a core-collapse supernova of an evolved massive star is currently speculated be either neutron matter or strange matter, and a historical roadmap to these ideas is introduced briefly by Xu et al. (2021).

For bulk matter, at densities around the saturated nuclear matter density ρ_0, the weak equilibrium among u, d and s quarks is possible, instead of simply that between u and d quarks. Rational thinking about stable strangeness dates back to the 1970s. A bulk strange object, composed of nearly equal numbers of u, d and s quarks, is speculated to be the absolutely stable ground state of strongly-interacting matter, which is known as Witten's conjecture (Witten 1984). It should be also noted that, due to the non-perturbative effect of strong interaction, quarks inside pulsar-like compact stars may be grouped into clusters, similar to the case that u and d quarks are grouped into nucleons. Although Witten's conjecture was proposed based on *strange quark matter* that is composed of almost free quarks, we can make an extension that it still reasonably holds no matter whether quarks are free or localized.

At densities in compact stars, which are around the saturated nuclear matter density, the coupling between quarks would be so strong that quarks are hard to maintain itinerant. Initiated by the thoughts that the quark-clusters are the main constituents of compact stars in Xu (2003) and Lai & Xu (2009a), where the three-flavored quark-clusters are afterward called "strangeons" by combining "strange nucleons", this model has been developed based on more advanced observations (see a review by Lai & Xu (2017) and references therein).

The strangeon star model had been found to be helpful to understand different manifestations of pulsar-like compact stars. The strangeon star model predicts high mass pulsars (Lai & Xu 2009a,b) before the discovery of pulsars with $M > 2\,M_\odot$ (Demorest et al. 2010). A strangeon matter surface could naturally explain the pulsar magnetospheric activity (Xu et al. 1999) as well as the subpulse-drifting of radio pulsars (Lu et al. 2019). Starquakes of solid strangeon stars could induce glitches (Zhou et al. 2004, 2014; Lai et al. 2018b), and the relation between the recovery coefficients and glitch sizes was found to be consistent with observations (Lai et al. 2018b). The glitch activity of normal radio pulsars (Lyne et al. 2000; Espinoza et al. 2011; Fuentes et al. 2017) can also be explained under the framework of a starquake in the solid strangeon star model (Wang et al. 2020). The plasma atmosphere of strangeon stars can reproduce the Optical/UV excess observed in X-ray dim isolated neutron stars (Kaplan et al. 2011; Wang et al. 2017). The tidal deformability (Lai et al. 2019) as well as the light curve (Lai et al. 2018a, hereafter Paper I) of merging binary strangeon stars has been derived, and these are consistent with the results of gravitational wave (GW) event GW170817 (Abbott et al. 2017). The details will be explained later.

The inner structure of pulsar-like compact stars as well as the equation of state (EOS) of supranuclear dense matter is challenging in both physics and astronomy. The significant non-perturbative effect makes it difficult to derive the properties of dense matter inside pulsar-like compact stars from first principles. The theoretical models (including neutron star model as the mainstream, quark star model and strangeon star model) need to be tested by astrophysical observations.

Strangeon matter, similar to *strange quark matter*, is composed of nearly equal numbers of u, d and s quarks at the level of quarks; however, different from that in *strange quark matter*, quarks in *strangeon matter* are localized inside strangeons due to the strong coupling between quarks. There are differences and similarities between strangeon stars and neutron/quark stars. On the one hand, quarks are thought to be localized in strangeons in strangeon stars, like neutrons in neutron stars, but a strangeon has three flavors and may contain more than three valence quarks. On the other hand, the matter at the surface of strangeon stars is still strangeon matter, i.e., strangeon stars are self-bonded by the strong force, like quark stars.

The detections of GW event GW170817 (Abbott et al. 2017) and its multiwavelength electromagnetic counterparts (e.g., Kasliwal et al. 2017; Kasen et al. 2017) opened a new era in which the nature of pulsar-like compact stars could be crucially tested. In a conventional neutron star merger, the neutron-rich ejecta undergoes rapid neutron capture (r-process) nucleosynthesis. The radioactive decay of these unstable nuclei powers a rapidly evolving and supernova-like transient named as AT2017gfo, which was predicted to be associated with neutron star mergers and in literatures was called "kilonova" (Li & Paczynski 1998), "macronova" (Kulkarni 2005) or "mergernova" (Yu et al. 2013; Gao et al. 2015). The observed multi-band light curves can be understood by such a radioactivity-powered transient (e.g., Cowperthwaite et al. 2017; Smartt et al. 2017; Villar et al. 2017), containing a low-opacity ($\kappa \sim 10^{-1}$ cm^2 g^{-1}) component ("blue" component) whose luminosity peaks at $\sim 10^{42}$ erg s^{-1} at the time of about one day, and a high-opacity ($\kappa \sim 10 - 100\,\mathrm{cm^2\,g^{-1}}$) component ("red" component) whose luminosity peaks at the time of about one week.

Combining the constraint by GW170817 with the existence of high mass pulsars puts a dramatic reduction in the family of allowed EOSs of neutron stars (Annala et al. 2018). As more massive pulsars are being found (Demorest et al. 2010; Antoniadis et al. 2013; Cromartie et al. 2019), the lower limit of the maximum mass increases, which will put a more stringent constraint on neutron star models. Due to the lack of information on the post-merger remnant, the observation of a GW alone cannot exclude other possibilities on the origin of GW170817. For binary quark stars, the tidal deformability of GW170817 can be used to constrain parameters in the equation of state, which imply the maximum mass of quark stars to be $\sim 2.18\ M_\odot$ within the MIT bag model (Zhou et al. 2018) and $\sim 2.32\ M_\odot$ with color-flavor-locked superfluity (Li et al. 2020).

Differently, for equation of state of strangeon stars, the constraint by combining the tidal deformability and high maximum mass seems not severe at all[1]. For the strangeon matter proposed in Lai & Xu (2009b), in a large parameter space the equation of state of a strangeon star is compatible with the constraint by GW170817 even if the maximum mass of pulsars is higher than 2.8 $M_\odot$ (Lai et al. 2019). For the linked bag model of strangeon matter (Miao et al. 2020) which can be adopted for strong condensed matter

[1] The strangeon star model is neither in the "twin-stars" scenario (Most et al. 2018) nor in the "two-families" scenario (De Pietri et al. 2019).

in both 2-flavored (nucleons) and 3-flavored (hyperons and strangeons) scenarios, it is also found that in a large parameter space the maximum mass and tidal deformability of strangeon stars are consistent with the current astrophysical constraints.

It is interesting to note that, some studies showed that, when introducing realistic current quark masses, the strange quark becomes disfavored because of its large dynamical mass, and three flavored strange quark matter would not be absolutely stable (Buballa & Oertel 1999). Under such consideration, quark matter with only u and d quarks (udQM) has also gained some attentions. By some phenomenological models for interacting quarks, udQM was shown to be more stable than nuclear matter and strange quark matter (Holdom et al. 2018). The maximum mass of quark stars with udQM could be larger than $2.7\ M_\odot$ (Cao et al. 2020), and the obtained values of the tidal deformability are in good compatibility with the experimental constraints of GW170817 (Zhang 2020). Therefore, it remains an interesting and unsolved problem whether quark matter is 2- or 3-flavored. Strangeon matter that we focus on in this paper is also the result of significant interaction between quarks.

Besides determining the tidal deformability, the equation of state of compact stars also determines the properties of the post-merger remnant, which would affect the electromagnetic transient after merger. The allowed equations of state of neutron stars and strange quark stars are hard to sustain a mass higher than $2.5\ M_\odot$ (Annala et al. 2018; Zhou et al. 2018), so the remnant of merger for GW170817 is more likely to be short-lived and will collapse into a black hole within 100 ms (Ruiz et al. 2018). The lanthanide-bearing ejecta is important for the "red" component of the post merger light curves, but most of the ejecta is lanthanide-free ($Y_e \gtrsim 0.3$) if the neutron star survives longer than about 300 ms (Kasen et al. 2015). However, a long-lived neutron star is favored for a consistent picture to account for the opacity and ejected mass of AT2017gfo (Yu et al. 2018; Li et al. 2018).

The observed electromagnetic counterparts, on the other hand, are still difficult to utilize to directly probe the nature of pulsar-like compact stars. The production of heavy elements has an impact on the opacity and will consequently affect the time and magnitude of peak luminosity. Neutron star mergers could not be the only complement to supernovae that produce elements around or heavier than the iron peak. The merger of double quark stars would eject fragments of strange quark matter, which are called strangelets. For mergers of double quark stars, under the multi-fragmentation model (Paulucci & Horvath 2014) of quark matter, all the ejected strangelets would decay into nuclear matter, and the nucleosynthesis of quark star mergers would only reach the iron peak (Paulucci et al. 2017). Bucciantini et al. (2019) calculate the evaporation process of ejected strangelets, and find that almost all of the ejected strangelets will evaporate into nucleons (most of them are neutrons). Although the evaporation of strangelets into nucleons could produce neutron-rich condition and then could lead to high opacity, there is a lack of explanation about the observed low opacity component.

The consequences of merging double strangeon stars are worth exploring. The "strangeon kilonova" scenario has been discussed in Paper I, in which the peak of the light curve at about one day after merger is powered by the decay of ejected unstable strangeon nuggets, and the slowly fading component of the light curve is powered by the spin-down of the remnant strangeon star[2]. To match the observations, the lifetime of unstable strangeon nuggets is assumed to be one day. However, detailed descriptions about the evolution of ejected strangeon nuggets as well as the properties of the decay products are needed.

To present a whole picture of merging double strangeon stars and the astrophysical consequences, there is still a long way to go. The full analysis about the ejection process of strangeon nuggets, including the total mass and the size-distribution of nuggets, relies on numerical simulations. In addition, the evolution of ejected strangeon nuggets is difficult to trace due to our ignorance of their properties. However, as will be shown in this paper, the ejection and evolution of strangeon nuggets happened and terminated at a very early stage of merger, so these processes could not have much impact on the later processes such as the strangeon kilonova. As a first stage in exploring the astrophysical consequences of merging double strangeon stars, a qualitative description about the evolution of ejecta and light curve of kilonova is necessary, which is focused on in this paper.

Beginning with a rough picture for ejection of strangeon nuggets during merger of double strangeon stars in Section 2, we discuss the evaporation of ejected strangeon nuggets in Section 3. It is found that, except the ones that have initial baryon numbers near the maximum value, almost all the ejected nuggets turn into strangeons within several milliseconds, and turn into neutrons and proton within tens of milliseconds. Because strangeons would instantly decay which leads to more protons than neutrons, the high and low opacity components could be naturally created. If the total ejected mass is about $10^{-3}\ M_\odot$, the light curve would be powered by the spin-down of the remaining long-lived strangeon star, which can

[2] Such a hybrid energy source model was firstly suggested by Yu et al. (2018) for explaining AT 2017gfo with a long-lived normal neutron star.

fit the bolometric light curve of AT2017gfo, as described in Section 4. Conclusions and discussions are provided in Section 5.

2 EJECTION OF STRANGEON NUGGETS

The electromagnetic counterparts of GWs in merging binary compact stars are essentially determined by the amount and composition of the ejecta. Similar to quark stars, strangeon stars are self-bound on the surface. It is known that modeling the large discontinuities at the surface of quark stars faces numerical challenges, and only a few works have explored the dynamics of binary quark stars. The hydrodynamical simulations of the coalescence of quark stars (Bauswein et al. 2010) indicate that the small lumps of quark matter form around the remnant, and the total ejected mass is $\sim 0.004\, M_\odot$. Recently, fully general-relativistic simulations of binary quark stars have been presented (Zhu & Rezzolla 2021), which show that the dynamical mass loss is about $0.003\, M_\odot$.

The clumpy ejecta and the low ejected mass are due to the fact that quark stars are self-bound by the strong interaction, which is also a characteristic of strangeon stars. We may expect that the ejected mass of merging binary strangeon stars is more or less the same as that of merging quark stars, although the full numerical simulations of binary strangeon stars remain to be done. In the following, we assume that there are two main ejection processes in the merger of double strangeon stars, similar to the merger of quark stars. The first process is the tidal disruptions during the merger, ejecting matter in the equatorial plane. The second process is the hydrodynamical squeeze from the contact interface between the merging stars, expelling matter in a broad range of angular directions. We further assume that the ejected matter in both processes has mass as low as $\sim 10^{-3}\, M_\odot$.

Due to the self-binding of strangeon stars, both tidal disruption and hydrodynamical processes eject strangeon nuggets, instead of ejecting individual strangeons. The ejected strangeon nuggets could be like the water drops splashed out of a pool of water, and they should have various sizes, i.e., various baryon numbers A. Here we can estimate the maximum and minimum sizes of strangeon nuggets.

The maximum size could be estimated by the balance between tidal force $GMmr/R^3$ and surface tension force σr, where σ is the surface tension, M and R are the stellar mass and radius, m and r are the nugget's mass and radius respectively ($m \sim \rho r^3$, ρ is the density for both strangeon stars and strangeon nuggets, $\rho \sim 2\rho_0$). For $\sigma = 10$ MeV fm^{-2}, we can get the maximum radius of nuggets $r_{\rm max} \sim 1$ cm, corresponding to maximum baryon number $A_{\rm max} \sim 10^{39}$.

From the method applied in Bucciantini et al. (2019), the minimum size could be estimated by evaluating the Weber number, defined by $W = \rho v^2 r/\sigma$, where v is the turbulent velocity. The ejection of strangeon nuggets can be treated as the turbulent fragmentation on the surface of merging stars, where the turbulent velocity v is the ejection velocity. The ejection takes place as long as $W \geq 1$, then if $v = 0.1c$ (c is the speed of light) we can get the minimum radius of nuggets $r_{\rm min} \sim 1$ fm, corresponding to minimum baryon number $A_{\rm min} \sim 1$.

Actually, the strangeon nuggets which are stable at zero temperature should have a critical size, smaller than which the energy per baryon of strangeon matter would be higher than that of two-flavor ordinary matter[3]. In a qualitative estimation (Lai & Xu 2017) the critical size could be set to be the Compton wavelength of electrons, $\lambda_{\rm e} \sim 10^3$ fm, corresponding to the critical baryon number $A_{\rm c} \sim 10^9$. Then the primary strangeon nuggets that are ejected during merger would have baryon numbers from 10^9 to 10^{39}.

The lack of numerical simulations about the merging processes of binary strangeon stars makes it hard to derive exactly the distribution of sizes and the total amount of ejecta. In fact, the size-distribution of strangeon nuggets would not have much impact on the electromagnetic radiation. After being ejected, strangeon nuggets will suffer evaporation, as will be demonstrated in Section 3, and the the final components in the ejecta which have observational effects (e.g., the power of the kilonova) would depend weakly on the initial conditions.

3 EVAPORATION OF STRANGEON NUGGETS

During merger, the temperature could reach up to tens of MeV (e.g., Bauswein et al. 2010), especially when the shock heating is taken into account (De Pietri et al. 2019), so naturally the strangeon nuggets would suffer from losing particles from the surface. Strangeon nuggets themselves would behave like dark matter because of their extremely low charge to mass ratio (Lai & Xu 2010), but the particles emitted from their surface would lead to significant consequences. In the high temperature environment of the merger, the ejected strangeon nuggets would suffer from emission of particles from the surface,

[3] Note the difference between strangeon nuggets and strangeons. The former are composed of the latter. A strangeon nugget would be stable against decaying to two flavor matter if its baryon number is higher than the critical value (a strangeon star is a huge "nugget" with baryon number $\sim 10^{57}$). A strangeon has baryon number $\lesssim 10$ and is extremely unstable in a vacuum (their decay would lead to interesting consequences, discussed in Sect. 4.1).

i.e., evaporation, including neutrons, protons, strangeons and so on.

In this section, we calculate the evaporation rate of strangeon nuggets, which depends on temperature. It will be found that the components in the ejecta after tens of milliseconds from the merger would be similar to that in merging double neutron stars.

3.1 Widths of Particle Emissions

The width Γ_β for the emission of particles can be obtained with a statistical model (Shen 2005), i.e.,

$$\Gamma_\beta(\varepsilon^*) = \frac{g_\beta m_\beta}{\pi^2} \int_0^{\varepsilon^* - s_\beta} \frac{\rho(\varepsilon^* - s_\beta - \varepsilon)}{\rho(\varepsilon^*)} \varepsilon \sigma_\beta(\varepsilon) \mathrm{d}\varepsilon, \quad (1)$$

where g_β, m_β and s_β are the degeneracy factor, mass and separation energy of the particle respectively. Here $\rho(E^*)$ represents the level density of the a strangeon nugget with an excitation energy ε^*, and $\sigma_\beta(\varepsilon)$ the absorption cross section of particle β with an incident energy ε. For electrically neutral particles such as strangeons or neutrons, we take the cross section as $\sigma_{q,n}(\varepsilon) = \pi r^2$, while for charged particles one has to take into account the Coulomb interaction (Wong 1973), i.e.,

$$\sigma_\beta(\varepsilon) = \frac{r^2 \omega_0}{2\varepsilon} \ln\left\{1 + \exp\left[\frac{2\pi(\varepsilon - \varepsilon_\mathrm{C})}{\omega_0}\right]\right\}, \quad (2)$$

where the transmission probability of Coulomb barrier is obtained based on the Hill-Wheeler formula (Hill & Wheeler 1953) assuming a typical barrier width $\omega_0 = 4$ MeV. For the Coulomb barrier, we simply take $\varepsilon_\mathrm{C} = q_\beta \varphi(r)$.

Note that for the emission of nucleons and α particles, one needs to take into account the transition probability from strangeons into nucleons. If strangeon matter is usually more stable than nuclear matter and the transition is a weak reaction process, we expect a vanishing transition probability. If we assume the transition probability from strangeons into nucleons is f_N, the transition probability from strangeons into α particles is approximately f_N^4. Thus the cross sections become

$$\sigma_{p,n} \to f_N \sigma_{p,n} \text{ and } \sigma_\alpha \to f_N^4 \sigma_\alpha. \quad (3)$$

At this moment, the exact form of f_N is unclear. According to the reaction rate of $s + u \to u + d$ in quark matter given in Madsen (1993), we suppose $f_N = 3 \times 10^{-12}$.

When the temperature of strangeon matter exceeds a certain value (~ 1 MeV), the solid state is turned into a liquid. In such cases, we expect the statistical properties of strangeon nuggets are similar to those of finite nuclei, thus for strangeon nuggets we adopt the level density of nuclei typically calculated from the Fermi-gas model,

$$\rho = \frac{\mathrm{e}^{2\sqrt{a\varepsilon^*}}}{\sqrt{48}\varepsilon^*}, \quad (4)$$

where the temperature is given by $T = \sqrt{\varepsilon^*/a}$. The level density parameter is taken as $a = A/12A_q$ MeV^{-1} since the effective degree of freedom is strangeon instead of nucleon, where A is the total baryon number of a strangeon nugget, and A_q is the baryon number of each strangeon. If the number of valence quarks in each strangeon is N_q, then the strangeon baryon number $A_q = N_q/3$. In this work we take $N_q = 18$, i.e., $A_q = 6$, in which case a strangeon is an 18-quark cluster (called quark-α) (Michel 1988).

At large excitation energies ($\varepsilon^* \gg s_\beta + \varepsilon$), the ratio of level densities in Equation (1) can be simplified and gives

$$\frac{\rho(\varepsilon^* - s_\beta - \varepsilon)}{\rho(\varepsilon^*)} = \exp\left(-\frac{s_\beta + \varepsilon}{T}\right). \quad (5)$$

3.2 Evaporation Rate of Strangeon Nuggets

Here we consider four evaporation channels, i.e., the emission of strangeons ($\beta = q$), neutrons ($\beta = n$), protons ($\beta = p$) and α particles ($\beta = \alpha$). The separation energy is then obtained with $s_q = m_q - A_q\mu_n$, $s_n = m_n - \mu_n$, $s_p = m_p - \mu_p$ and $s_\alpha = m_\alpha - 2\mu_n - 2\mu_p$, where m_q, m_n, m_p and m_α are the masses of strangeons, neutrons, protons and α particles, respectively. Here the neutron and proton chemical potentials are obtained with $\mu_n = \frac{\partial M}{\partial A}$ and $\mu_p = \frac{\partial M}{\partial Z}$, where M is the mass of a strangeon nugget with baryon number A and charge number Z.

The emission rates $W_\beta = \Gamma_\beta/\hbar \approx 1.52 \times 10^{21}\Gamma_\beta$ (in s^{-1}) for various evaporation channels can be derived, where the widths Γ_β are obtained with Equation (1). In principle, the surface tension σ determining the dynamic stability of the strangeon-vacuum interface would affect the emission rate. However, for larger strangeon nuggets (radius $r > 10^5$ fm, or baryon number $A > 10^{15}$), the finite size effect becomes insignificant and the emission rate is proportional to the surface area of strangeon nuggets. As will be shown in Section 3.3, the strangeon nuggets with initial baryon number $A_0 \leq 10^{36}$ will almost disappear within ~ 1 ms as the result of evaporation. For simplicity we only consider large strangeon nuggets and neglect the surface tension, since larger strangeon nuggets would emit more particles.

In Figure 1 we present the emission rates per surface area for various evaporation channels $\mathcal{R}_\beta$, including strangeons ($\beta = q$), neutrons ($\beta = n$), protons ($\beta = p$) and α ($\beta = \alpha$). The evaporation channels are dominated by strangeons at temperature $T > 10$ MeV, and dominated by neutrons at $T < 10$ MeV. This result gives the emission rates for any strangeon nuggets with radius $r \gtrsim 10^5$ fm via multiplying it by the surface area $S = 4\pi r^2$.

The dependence of evaporation channels on temperature could be understood. Strangeons are heavier than neutrons and protons, so they are easier to be emitted at

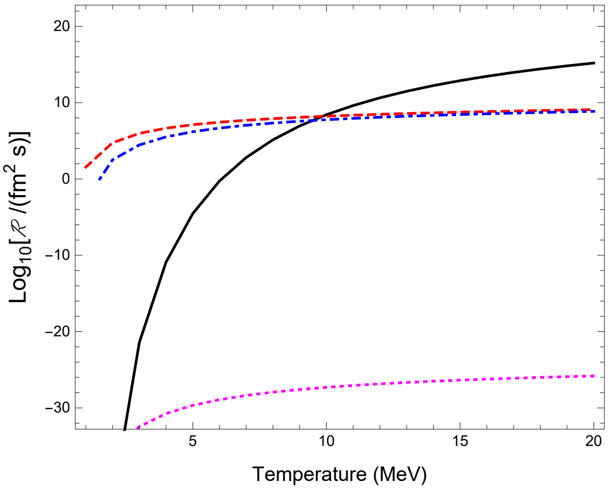

Fig. 1 Emission rates per surface area for evaporation channels $\mathcal{R}_\beta$ to strangeons (*solid black line*), neutrons (*long-dashed red line*), protons (*dash-dotted blue line*) and α particles (*short-dashed magenta line*).

high temperature. If temperature is not high enough, it is energetically favored for strangeons to decay into neutrons and protons before being emitted. The emission of protons is suppressed due to the Coulomb barrier.

3.3 The Fate of Strangeon Nuggets

By simplifying the expanding envelope surrounding the remnant to be adiabatic (Li & Paczynski 1998), the temperature deceases with time, $T \propto t^{-1}$. As indicated in Figure 1, the production rate of strangeons, neutrons and protons depends on the temperature. If the initial temperature is ~ 10 MeV at the initial time ~ 1 ms, then in ~ 10 ms the temperature decreases to 1 MeV, when the evaporation nearly ceases. Therefore, evaporation only happens at the very early stage of expansion.

The calculations in Section 3.2 affirm that at different temperatures, the dominant evaporation products are different. When the temperature $T \simeq 20$ MeV, the main evaporation products are strangeons, with the rate (per unit surface area) $\mathcal{R} = \mathcal{R}_q \simeq 1.5 \times 10^{15}\,\mathrm{s}^{-1}\,\mathrm{fm}^{-2}$. When the temperature is between 5 and 10 MeV, the main evaporation products are neutrons, with the rate (per unit surface area) $\mathcal{R} = \mathcal{R}_n \sim 10^8\,\mathrm{s}^{-1}\,\mathrm{fm}^{-2}$. Then we can estimate the upper limit of initial baryon number A of strange nuggets which would almost disappear as the result of evaporation.

Assuming each strangeon nugget is a sphere with radius r and baryon number density n, when suffering evaporation, the rate of losing baryons from the surface is

$$\frac{dA}{dt} = -\mathcal{R} \cdot 4\pi r^2 \,, \qquad (6)$$

where

$$A = \frac{4\pi}{3} r^3 n \,, \qquad (7)$$

$$A \simeq \left(A_0^{1/3} - \frac{\mathcal{R}}{\mathrm{fm}^{-2}} \cdot t \right)^3 . \qquad (8)$$

When $t = 1$ ms the temperature is about 20 MeV and $\mathcal{R} = \mathcal{R}_q \simeq 1.5 \times 10^{15}\ \mathrm{s}^{-1}\ \mathrm{fm}^{-2}$, then the strangeon nuggets with initial baryon number $A_0 \leq 10^{36}$ will almost disappear as the result of evaporation, via emitting strangeons. Because the initial baryon numbers of ejected strangeon nuggets are between 1 and 10^{39}, we can infer that if the initial temperature is about 20 MeV, then almost all of the ejected nuggets turn into strangeons within several milliseconds.

In the spiral arms from tidal interactions during the merger, however, the temperature would not be so high. Below 10 MeV, the emissions of neutrons and protons will be dominant instead of strangeons, which would happen in the spiral arms in the equatorial plane. Equation (8) indicates that, if the time duration from $T \sim 10$ MeV to 5 MeV is about 10 ms, when $\mathcal{R} = \mathcal{R}_n \simeq 10^{10}\,\mathrm{s}^{-1}\,\mathrm{fm}^{-2}$, then the strangeon nuggets with initial baryon number $A_0 \leq 10^{24}$ will almost disappear within tens of milliseconds as the result of evaporation, via emitting neutrons and protons.

4 STRANGEON KILONOVA

The scenario of a strangeon kilonova was proposed in Paper I, where the light curves are powered by the decay of ejected strangeon nuggets and the spin-down of the remnant strangeon star. To be consistent with observations of the kilonova AT 2017gfo following GW170817 (Kasliwal et al. 2017), the lifetime of the strangeon nuggets was assumed to be 1 day. Here we propose a more reasonable scenario of a strangeon kilonova based on a more detailed analysis of ejected strangeon nuggets and their evolutions.

In Section 3 we discuss a possible ejection process of merging double strangeon stars. The merger ejects strangeon nuggets directly, which would suffer from evaporation of particles, mainly strangeons, neutrons and protons. The tidal disruption during the merger ejects strangeon nuggets in the equatorial plane, which turn into neutrons and protons within dozens of milliseconds. The hydrodynamical squeeze from the contact interface between the merging stars ejects strangeon nuggets in a broad range of angular directions, which turn into strangeons within several milliseconds.

4.1 Electron Fraction

Strangeons are unstable and will decay instantly. Although we do not know the exact microscopic properties of a strangeon, we can infer its decay channels by analogy with hyperons. Taking Λ hyperon as an example, its lifetime is $\sim 10^{-10}$ s and the decay channels are (Tanabashi et al. 2018)

$$\Lambda \longrightarrow p + \pi^- \quad (63.9\%)\,, \tag{9}$$
$$\Lambda \longrightarrow n + \pi^0 \quad (35.8\%)\,. \tag{10}$$

The produced π^- and π^0 are still short-lived with lifetimes $\sim 10^{-8}$ s and $\sim 10^{-17}$ s respectively, and will decay via (Tanabashi et al. 2018)

$$\pi^- \longrightarrow \mu^- + \nu_\mu\,, \tag{11}$$
$$\mu^- \longrightarrow e^- + \nu_\mu + \bar{\nu_e}\,, \tag{12}$$

and

$$\pi^0 \longrightarrow 2\gamma\,(98.82\%)\,, \tag{13}$$
$$\pi^0 \longrightarrow e^+ + e^- + \gamma\,(1.17\%)\,. \tag{14}$$

Therefore, we infer that the main decay products of strangeons would also be protons, neutrons, e$^-$, $\bar{\nu_e}$, ν_μ and photons.

It is interesting to note that, in evaporation of strangeon nuggets and decay of strangeons, the ratio of production rate of neutrons to that of protons is different. In the evaporation products of strangeon nuggets, the neutrons dominate over protons, since the emission of protons is suppressed due to the Coulomb barrier. However, in the decay products of strangeons, there are more protons than neutrons, since protons are lighter than neutrons. This difference basically initiates different levels of neutron-richness in the ejecta that will be discussed later.

In summary, the strangeon nuggets ejected directly from the merger would emit particles from the surface, which are dominated by strangeons at $T > 10$ MeV and neutrons at 1 MeV $< T <$ 10 MeV. Strangeons are extremely unstable and will instantly decay into proton-rich matter, so electron fraction Y_e of the ejecta depends on temperature. Taking into account both the emission rates derived in Section 3.1 and the decay of strangeons, we can get the dependence of Y_e on temperature, as displayed in Figure 2. We can see that Y_e is higher than 0.5 at $T >$ 10 MeV and is well below 0.1 at 1 MeV $< T <$ 10 MeV.

4.2 Two-component Ejecta

The ejection processes of strangeon nuggets involve the tidal disruption that ejects matter in the equatorial plane, as well as the hydrodynamical squeezing from the contact interface between the merging stars that expels matter in a broad range of angular directions. Therefore, as the temperature would be different in different processes, the neutron-rich matter would be ejected from the directions around the equatorial plane, and the proton-rich matter would be ejected in a broad range of angular directions. All of the above processes happen within tens of milliseconds.

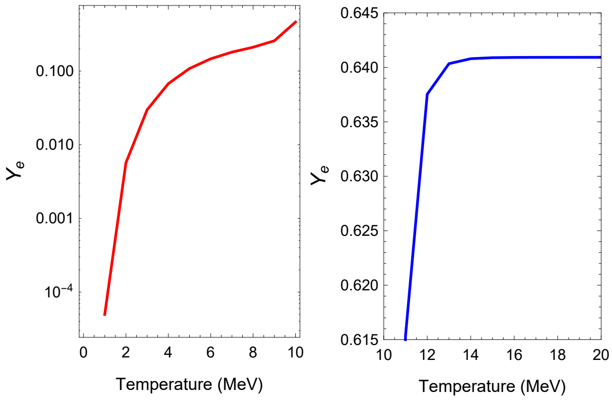

Fig. 2 The dependence of electron fraction Y_e on temperature T in the ejecta, taking into account both the evaporation of strangeon nuggets and the decay of strangeons.

Consequently, we may infer that the end products of the complex interactions within tens of milliseconds from the merger of double strangeon stars could be similar to those ejected in the merger of double neutron stars. In other words, after about dozens of milliseconds from the coalescence, the ejecta of merging double strangeon stars could be similar to that of merging double neutron stars, both of which would power the kilonova-like transient.

The neutron-abundance of ejecta depends on the viewing angles. Besides the emitted neutrons from strangeon nuggets that make the equatorial plane neutron-rich, the strangeons emitted from strangeon nuggets could also contribute to the neutron-richness. In the high density region of the disk, the produced $\bar{\nu_e}$ in decay (12) would transform protons into neutrons, via $p + \bar{\nu_e} \longrightarrow n + e^+$. Anyway, the matter ejected from around the equatorial plane could be neutron-rich. Moreover, even if the remnant is a long-lived stable star, the radiation from the star would be insufficient to increase Y_e significantly, since most of the ejecta in the equatorial plane can have very low Y_e, as indicated in Figure 2.

The components of ejecta are illustrated in Figure 3. The tidal disruption ejects matter in the equatorial plane, where the temperature is relatively low. The hydrodynamical squeeze from the contact interface expels matter in a broad range of angular directions, where the temperature is relatively high. Therefore, taking into account both the evaporation of strangeon nuggets and the decay of strangeons, the matter with high opacity would

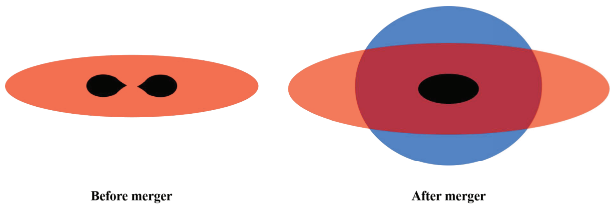

Fig. 3 Illustration of blue and red components of ejecta. The matter with high opacity would be ejected from the directions around the equatorial plane, and the matter with low opacity would be ejected in a broad range of angular directions.

be ejected from the directions around the equatorial plane, and the matter with low opacity would be ejected in a broad range of angular directions.

4.3 Light Curves

To derive the light curve, the radiation-transfer process is the necessary input. As demonstrated before, the ejecta after tens of milliseconds after merger could be similar to that ejected in the merger of double neutron stars. The neutron-rich matter (i.e., the red component) would be ejected from the directions around the equatorial plane, and the proton-rich matter (i.e., the blue component) would be ejected in a broad range of angular directions. The r-process nuclei can be produced in the neutron-rich environment, leading to high opacity and heat the ejecta by radioactive decay. Therefore, the radiation-transfer process would be similar to that of merging double neutron stars. Moreover, there would be not much differences between the amount of heavy nuclei produced in merging strangeon stars and that in merging neutron stars, since the total ejected masses are about the same (Zhu & Rezzolla 2021).

The maximum mass of strangeon stars would be as high as $2.3\,M_\odot$ or even higher, so the merger of double strangeon stars triggering GW170817 would probably leave a long-lived stable strangeon star. As indicated in Li et al. (2018), the emission of AT2017gfo associated with GW170817 can be explained by energy injection from a long-lived and spinning-down neutrons star. The spin-down power is independent of the interior structure of the remnant, so we can take the spin-down power as the energy source of the kilonova-like transients.

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. Here we choose typical values for such parameters. For both blue and red components, $M_{\rm ej} = 10^{-3}\,M_\odot$, $v_{\rm min} = 0.1\,c$, $v_{\rm max} = 0.3\,c$ (c is the speed of light) and the density distribution index $\delta = 1.5$. The opacity $\kappa = 0.1\,{\rm cm^2\,g^{-1}}$ for the blue component, and $\kappa = 3\,{\rm cm^2\,g^{-1}}$ for the red component. In order to significantly spin down the remnant, efficient secular GW spin-down is needed. The timescale of spin-down is $t_{\rm sd} = 3\times10^3\,{\rm s}$, and the initial spin-down luminosity is $1\times10^{43}\,{\rm erg}$, which are typical values for spinning down neutron stars.

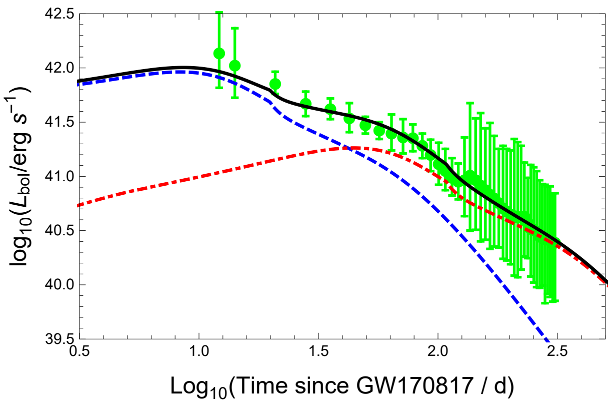

Fig. 4 Bolometric light curve of a strangeon kilonova including two-component ejecta, fitted to the data from Kasliwal et al. (2017). The *dashed* and *dash-dotted lines* represent light curves of the blue and red components, respectively. The *solid line* is the result of the combination of the two components. For both the blue and red component, the ejected mass $M_{\rm ej(red/blue)} = 10^{-3}\,M_\odot$, the minimum and maximum velocities $v_{\rm min} = 0.1\,c$ and $v_{\rm max} = 0.3\,c$ (c is the speed of light) respectively, and the density distribution index $\delta = 1.5$. The timescale of spin-down is $t_{\rm sd} = 3\times10^3\,{\rm s}$, and the initial spin-down luminosity is $1\times10^{43}\,{\rm erg\,s^{-1}}$. The opacity $\kappa = 0.1\,{\rm cm^2\,g^{-1}}$ and $3\,{\rm cm^2\,g^{-1}}$ for the blue and red components, respectively. The details of the ejecta model are given in Yu et al. (2018).

The bolometric light curve of a strangeon kilonova including two-component ejecta, fitted to the data from Kasliwal et al. (2017), is depicted in Figure 4. The dashed and dash-dotted lines represent the light curves of blue and red components, respectively. The solid line is the result of the combination of the two components.

Therefore, although the very initial components in ejecta of merging strangeon stars are different from those of merging neutron stars, the “strangeon kilonova” could have a light curve similar to that of a neutron kilonova. Under reasonable values of parameters, the bolometric light curve can fit the data of AT2017gfo.

5 CONCLUSIONS AND DISCUSSIONS

Strangeon matter in bulk is conjectured to be more stable than nuclear matter, and strangeon stars are conjectured to be actually pulsar-like compact stars. Besides the strangeon stars that are born in supernova explosions and undergo sufficient cooling, the astrophysical consequences in the hot environment created by merging double strangeon stars are worth exploring, especially in the new era of multi-messenger astronomy. To develop the "strangeon kilonova" scenario proposed in Paper I, we provide a qualitative description about the evolution of ejecta and light curves of a strangeon kilonova.

Due to the self-bonding of strangeon stars, the merger directly ejects strangeon nuggets instead of individual strangeons. The tidal disruption ejects strangeon nuggets in the equatorial plane, and the hydrodynamical squeeze from the contact interface expels strangeon nuggets in a broad range of angular directions. In the high temperature environment of the merger, the ejected strangeon nuggets would suffer from evaporation into strangeons, neutrons, protons and so on. The emission of strangeons dominates at temperature above $\sim$ 10 MeV, and the emission of neutrons dominates at temperature below $\sim$ 10 MeV.

The temperature of the matter expelled by hydrodynamical squeeze from the contact interface could be higher than 10 MeV, so the evaporation productions are dominated by strangeons, and almost all of the ejected nuggets turn into strangeons within several milliseconds. Strangeons in free space are extremely unstable and would immediately ($\sim 10^{-10}$ s) decay, and the decay products would contain more protons than neutrons. Besides, the temperature in the spiral arms from tidal interactions would be around or below 10 MeV, but would last for a relatively longer timescale of tens of milliseconds, which still leads to sufficient evaporation, and the evaporation productions are dominated by neutrons.

Taking into account both the evaporation of strangeon nuggets and the decay of strangeons, we find that the neutron-rich matter would be ejected from the directions around the equatorial plane, and the proton-rich matter would be ejected in a broad range of angular directions. The r-process nuclei can be produced in the neutron-rich environment, leading to high opacity and heat the ejecta by radioactive decay. Therefore, the radiation-transfer process would be similar to that of merging double neutron stars.

We find similarities between the consequences of merging strangeon stars and those of merging neutron stars, although the very initial components in ejecta of the former are different from those of the latter. Light curves are then for both low and high opacity components, under a typical model of ejecta to include the radiation-transfer process. Under reasonable values of parameters, the bolometric light curves can fit the data of AT2017gfo, by the energy injection from a long-lived and spinning-down strangeon star, if the total ejected mass is about $0.002\,M_\odot$. Although the rotational energy released by the remnant during its spin-down will be transferred into the gamma-ray burst (GRB) jet (Margalit & Metzger 2017), the radiation of the fast rotating remnant would be compatible with the observed GRB if the magnetic field of the remnant is not higher than 10^{12} Gauss (Yu et al. 2018).

This paper is the first qualitative description about the evolution of ejecta of merging strangeon stars. Despite our lack of numerical simulations, our conclusions are qualitatively acceptable, for the following reason. Most of the ejected strangeon nuggets would almost disappear and evaporate into strangeons, neutrons and protons, then strangeons instantly decay into protons and neutrons. The ejection, evaporation and decay happen at a very early stage of merger and terminate at a time of about tens of milliseconds when the temperature drops below $\sim$ 1 MeV, so that the ejecta would end up with neutrons and protons within tens of milliseconds. Consequently, the early processes could not have much impact on the later processes such as the r-process nucleosynthesis and strangeon kilonova. Future numerical simulations are necessary to explore the full processes and consequences of merging double strangeon stars.

How to distinguish strangeon stars and neutron stars by the observational consequences is crucial to test the strangeon star model. We find that, even if the remnant is a long-lived stable star, the radiation from the star would be insufficient to increase Y_e significantly, since most of the ejecta in the equatorial plane can have Y_e well below 0.1 (lanthanide-bearing). As found in our previous work, the merger of double strangeon stars triggering GW170817 would probably leave a long-lived stable strangeon star. Therefore, the merging strangeon stars scenario seems to be helpful to include both a long-lived remnant and sufficient lanthanide-bearing ejecta. Conversely, for merging double neutron stars, most of the ejecta would have $Y_e \gtrsim 0.3$ (lanthanide-free) if the remnant survives longer than about 300 ms (Kasen et al. 2015). More information about the post-merger remnant of GW170817 in the future will undoubtedly provide a stricter test for both neutron star and strangeon star models.

The above statements are based on the hypothesis that the emission of neutrinos of newly born strangeon stars is the same as that of newly born neutron stars, in which case the luminosity of ν_e is larger than that of $\bar{\nu}_e$. The emission of neutrinos of newly born strangeon stars is still unknown, so the consequences of neutrino radiation from the hot strangeon stars on the ejecta and torus remain to be answered. It is interesting to see that neutrinos could be a probe to distinguish strangeon stars and neutron stars, if the decay of strangeons is similar to that of hyperons. As indicated in Section 4.1, the decay of strangeons would produce a large amount of ν_μ, which would not be produced as much in neutron star mergers. This may be tested by neutrino detections, e.g., the Super-Kamioka Neutrino Detection Experiment.

The critical baryon number A_c of stable strangeon nuggets, smaller than which the strangeon matter will decay to ud matter, should be determined by both the weak and strong interactions. The value 10^9 for A_c adopted in Section 2, by setting the critical size to be the Compton wavelength of electrons, is actually determined by the weak interaction only. If the strong interaction dominates, A_c could be much smaller, e.g., the calculations under a liquid drop model indicate that A_c could be as low as $\sim 10^3$ (Wang et al. 2018). Consequently, the actual value of A_c might be in the range from 10^3 to 10^9. Certainly, the exact value of A_c would not affect the physical picture concerned in this paper.

It is worth noting that the consequence of surviving nuggets would also be interesting. In calculating the evaporation rate of strangeon nuggets, we neglect the surface tension, since larger nuggets would emit more particles and we only care about the emitted particles that affect the subsequent transient, then we find that a small amount of large size nuggets, with initial baryon number $A_0 > 10^{24}$ produced by tidal forces and $A_0 > 10^{36}$ produced by hydrodynamical squeeze, can survive evaporation. However, when the radius of a nugget decreases to $\sim 10^5$ fm (with baryon number $\sim 10^{15}$), the surface tension would become significant, which would lower the emission rate and make it easier to survive. Moreover, although most of the baryons are lost during evaporation, the absorption of energy and decrease of temperature due to evaporation may prevent further evaporation, then the strangeon nuggets with smaller A_0 may be left as microscopic strangeon nuggets with $A \gtrsim A_c$. The surviving strangeon nuggets would perform like the ultra-high energy cosmic rays, and their density in galaxies and impact on the evolution of stars are worth exploring in the future.

Acknowledgements We would like to thank Dr. Shuang Du (PKU) for useful suggestions. This work is supported by the National SKA Program of China (Grant No. 2020SKA0120300), the National Key R&D Program of China (Grant No. 2017YFA0402602), the National Natural Science Foundation of China (Grant Nos. U1831104, 11673002, U1531243, 11705163, 11822302 and 11803007), the Strategic Priority Research Program of CAS (Grant No. XDB23010200) and Ningbo Natural Science Foundation (Grant No. 2019A610066). The support provided by China Scholarship Council during a visit by C.-J. X to JAEA is acknowledged.

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