Merging strangeon stars II: the ejecta and light curves

Xiao-Yu Lai\textsuperscript{1,2}, Cheng-Jun Xia\textsuperscript{3}, Yun-Wei Yu\textsuperscript{4}, Ren-Xin Xu\textsuperscript{5,6}

\textsuperscript{1} Department of Physics and Astronomy, Hubei University of Education, Wuhan 430205, China; laixy@hue.edu.cn
\textsuperscript{2} Research Center for Astronomy, Hubei University of Education, Wuhan 430205, China
\textsuperscript{3} School of Information Science and Engineering, NingboTech University, Ningbo 315100, China
\textsuperscript{4} Institute of Astrophysics, Central China Normal University, Wuhan 430079, China
\textsuperscript{5} School of Physics, Peking University, Beijing 100871, China
\textsuperscript{6} Kavli Institute for Astronomy and Astrophysics, Peking University, Beijing 100871, China

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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. 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 even if the total ejected mass would be as low as $\sim 10^{-4} M_\odot$, the spin-down power of the long-lived remnant would account for the whole emission of kilonova AT2017gfo associated with GW 170817. 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 certainty, 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 $\rho_0$, 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 1970s. Bulk strange object, composed of nearly equal numbers of u, d and s
as Witten’s conjecture \cite{witten1984}. 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 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 being the main constituents of compact stars in \cite{xu2003} and \cite{lai2009a}, where the three-flavored quark-clusters are afterward called “strangeons” by combining “strange nucleons”, this model has been developed based on more advanced observations \cite{reviewlai2017} and references therein.

The strangeon star model had been found to be helpful to understand different manifestations of pulsar-like compact stars. Strangeon star model predicts high mass pulsars \cite{lai2009a} before the discovery of pulsars with $M > 2M_\odot$ \cite{demorest2010}. The strangeon matter surface could naturally explain the pulsar magnetospheric activity \cite{xu1999} as well as the subpulse-drifting of radio pulsars \cite{lu2019}. Starquakes of solid strangeon stars could induce glitches \cite{zhou2004, Zhou2014, lai2018a}, and the relation between the recovery coefficients and glitch sizes was found to be consistent with observations \cite{lai2018a}. The glitch activity of normal radio pulsars \cite{lyne2008, espinoza2011, fuentes2017} can also be explained under the framework of starquake of solid strangeon star model \cite{wang2020}. The plasma atmosphere of strangeon stars can reproduce the Optical/UV excess observed in X-ray dim isolated neutron stars \cite{kaplan2011, wang2017}. The tidal deformability \cite{lai2019} as well as the light curve \cite{lai2018a, paperI} of merging binary strangeon stars have been derived, which are consistent with the results of gravitational wave event GW170817 \cite{abbott2017}, and 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 are 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 the first principle. The theoretical models (including neutron star model as the mainstream, quark star model and strangeon star model) need to be tested by the astrophysical observations.

Strangeon matter, similar to strange quark matter, are 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 3 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-bond by strong force, like quark stars.

The detections of gravitational wave event GW170817 \cite{abbott2017} and its multiwavelength electromagnetic counterparts \cite{kasianwal2017, kasen2017} open a new era in which the nature of pulsar-like compact stars could be crucially tested. In the 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” \cite{li1998}, “macronova” \cite{kulkarni2005}, or “mergernova” \cite{yu2013, gao2015}. The observed multi-band light curves can be understood by such radioactivity-powered transient \cite{cowperthwaite2017, smartt2017, villar2017}, containing a low-opacity ($\kappa \sim 10^{-1} \text{ cm}^2 \text{g}^{-1}$) component (“blue” component) whose luminosity peaks at $\sim 10^{42} \text{ erg s}^{-1}$ at the time about one day, and a high-opacity ($\kappa \sim 10 - 100 \text{ cm}^2 \text{g}^{-1}$) component (“red” component) whose luminosity peaks at the time about one week.

Combining the constraint by GW170817 with the existence of high mass pulsars puts a dramatic reduction in the family of allowed equation of states of neutron stars \cite{annala2018}. As more massive pulsars are being found \cite{demorest2010, antoniadis2013, cromartie2019}, the lower limit of the maximum mass increases, which will put more stringent constraint on neutron star model. Due to the lack of information on the post-merger remnant, the observation gravitational wave alone cannot
GW170817 can be used to constrain parameters in the equation of state, which imply the maximum mass of quark stars to be \(~ 2.18M_\odot\) within the MIT bag model \cite{Zhou2018} and \(~ 2.32M_\odot\) with color-flavor-locked superfluidity \cite{Li2020a}.

Differently, for equation of state of strangeon stars, the constraint by combining the tidal deformability and high maximum mass seems not severe at all.\footnote{The strangeon star model is neither in the “twin-stars” scenario \cite{Most2018} nor in the “two-families” scenario \cite{dePierri2019}.} For the strangeon matter proposed in \cite{Lai2009b}, in a large parameter space the equation of state of strangeon star is compatible with the constraint by GW170817 even if the maximum mass of pulsars is higher than \(2.8M_\odot\).\footnote{Such a hybrid energy source model was firstly suggested by \cite{Yu2018} for explaining AT2017gfo with a long-lived normal neutron star.} For the linked bag model of strangeon matter \cite{Miao2020a} which can be adopted for strong condensed matter in both 2-flavoured (nucleons) and 3-flavoured (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 the three flavored strange quark matter would not be absolutely stable \cite{Buballa2002}. 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 \cite{Holdom2018}. The maximum mass of quark stars with udQM could be larger than \(2.7M_\odot\) \cite{Cao2020a}, and the obtained values of the tidal deformability are in good compatibility with the experimental constraints of GW170817 \cite{Zhang2020}. Therefore, it remains an interesting and unsolved problem that whether the 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 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 \(2.5M_\odot\) \cite{Annala2018, Zhou2018}, so the remnant of merger for GW170817 is more likely to be short-lived and will be collapse into a black hole within 100 ms \cite{Ruiz2018b}. The lanthanide-bearing ejecta is important for the “red” component of the post merger light curves, but most of the ejecta is lanthanide-free (\(Y_e > 0.3\)) if the neutron star survives longer than about 300 ms \cite{Kasen2015}. However, a long-lived neutron star is favored for a consistent picture to account for the opacity and ejected mass of AT2017gfo \cite{Yu2018, Li2018}.

The observed electromagnetic counterparts, on the other hand, are still difficult to directly probe the nature of pulsar-like compact stars. The production of heavy elements has 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 iron peak. 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 \cite{Paulucci2014} of quark matter, all the ejected strangelets would decay into nuclear matter, and the nucleosynthesis of quark star mergers would reach the iron peak only \cite{Paulucci2017, Bucciantini2019}. The lifetime of the unstable strangeon nuggets is assumed to be one day.\footnote{To match the observations, the lifetime of the unstable strangeon nuggets is assumed to be one day. However, the detailed descriptions about the evolution of ejected strangeon nuggets as well as the properties of the decay products is 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 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 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 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 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 at within several milliseconds, and turn into neutrons and proton within tens of milliseconds. Because strangeons would instantly decay that leads to more protons than neutrons, the high and low opacity components could be naturally created. Although the total ejected mass of would be as low as $\sim 10^{-4}$, the light curve would be powered by the spin-down of the remaining long-lived strangeon star, which can fit the bolometric light curve of AT2017gfo, as shown in Section 4. Conclusions and discussions are made 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 modelling 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] show that the small lumps of quark matter form around the remnant, and the total ejected mass is $\sim 0.004M_\odot$. Recently, the fully general-relativistic simulations of binary quark stars have been presented [Zhu & Rezzolla, 2021], which show that the dynamical mass loss is significantly suppressed to be about $\sim 10^{-4}M_\odot$.

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 the character of strangeon stars. We may expect that the ejected mass of merging binary strangeon stars is more or less the same as that merging quark stars, although the full numerical simulations of binary strangeon stars remains to be done. In the following, we assume that there are two main ejection process 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 $\sim 10^{-4}M_\odot$.

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 $Gm_rM/R^3$ and surface tension force $\sigma r$, where $\sigma$ is the surface tension, $M$ and $R$ are the stellar mass and radius, $m$ and $r$ are the nugget’s mass and radius ($m \sim r^3$, $\rho$ 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 $r_{\text{max}} \sim 1$ cm, corresponding to maximum baryon number $A_{\text{max}} \sim 10^{39}$.

From the method used in Bauswein 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 $r_{\text{min}} \sim 1$ fm, corresponding to minimum baryon number $A_{\text{min}} \sim 1$.

Actually, the strangeon nuggets 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.

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3 Note the difference between strangeon nuggets and strangeons. The former are composed of the latter. A strangeon nuggets 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 $\leq 10$ and is extremely unstable in vacuum (their decay would lead to...
In a qualitative estimation (Lai & Xu, 2017) the critical size could be set to be the Compton wavelength of electrons, \( \lambda_e \sim 10^3 \) fm, corresponding to the critical baryon number \( A_c \sim 10^9 \). Then the primary strangeon nuggets that 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 shown in Sec 3, and 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, 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 \( \Gamma_\beta \) for the emission of particles can be obtained with a statistical model (Shen, 2005), i.e.,

\[
\Gamma_\beta(\varepsilon^*) = \frac{g_\beta m_\beta}{\pi^2} \int_0^{\varepsilon^*-s_\beta} \frac{\rho(\varepsilon^* - s_\beta - \varepsilon)}{\rho(\varepsilon^*)} \varepsilon \sigma_\beta(\varepsilon) d\varepsilon,
\]

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

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

where the transmission probability of Coulomb barrier is obtained based the Hill-Wheeler formula (Hill & Wheeler, 1953) assuming a typical barrier width \( \omega_0 = 4 \) MeV. For the Coulomb barrier, we simply take \( \varepsilon_C = q_\beta \phi(r) \).

Note that for the emission of nucleons and \( \alpha \) 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 \( \alpha \) particles is approximately \( f_\alpha N \). Thus the cross sections become

\[
\sigma_{p,n} \rightarrow f_N \sigma_{p,n} \text{ and } \sigma_\alpha \rightarrow f_\alpha N \sigma_\alpha.
\]

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

When the temperature of strangeon matter exceeds certain value (\( \sim 1 \) MeV), the solid state is turned into liquid. In such cases, we expect the statistical properties of strangeon nuggets are similar to finite nuclei,
model,
\[ \rho = \frac{e^{2\sqrt{2}m\varepsilon}}{\sqrt{48\varepsilon}} \tag{4} \]
where the temperature is given by \( T = \sqrt{\varepsilon^2/\alpha} \). The level density parameter is taken as \( \alpha = A/12A_q \, \text{MeV}^{-1} \) 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-\( \alpha \)) (Michel, 1988).

At large excitation energies (\( \varepsilon^* \gg s_\beta + \varepsilon \)), the ratio of level densities in Eq. (1) can be simplified and gives
\[ \frac{\rho(\varepsilon^*-s_\beta-\varepsilon)}{\rho(\varepsilon^*)} = \exp\left(-\frac{s_\beta+\varepsilon}{T}\right). \tag{5} \]

### 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 \( \alpha \) particles (\( \beta = \alpha \)). The separation energy is then obtained with \( s_\beta = m_q - A_q\mu_n \), \( s_n = m_n - \mu_n \), \( s_p = m_p - \mu_p \), and \( s_\alpha = m_\alpha - 2\mu_n - 2\mu_p \), where \( m_q, m_n, m_p \) and \( m_\alpha \) are the masses of strangeons, neutrons, protons and \( \alpha \) particles, respectively. Here the neutron and proton chemical potentials are obtained with \( \mu_n = \frac{\partial M}{\partial Z} \) 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 \( \Gamma_\beta \) are obtained with Eq. (1). In principle, the surface tension \( \sigma \) determining the dynamic stability of the strangeon-vacuum interface would affect the emission rate. However, for larger strangeon nuggets (radius \( r > 10^5 \, \text{fm} \), 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 Sec.3.3, the strangeon nuggets with initial baryon number \( A_0 \leq 10^{36} \) will almost disappear within \( < 1 \, \text{ms} \) 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 Fig.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 \( \alpha \) (\( \beta = \alpha \)). The evaporation channels are dominated by strangeons at temperature \( T > 10 \, \text{MeV} \), and dominated by neutrons at \( T < 10 \, \text{MeV} \). This result gives the emission rates for any strangeon nuggets with radius \( r \geq 10^5 \, \text{fm} \) 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 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 of adiabatic (Li & Paczynski, 1998), the temperature decreases as time, \( T \propto t^{-1} \). As indicated in Fig.1, the production rate of strangeons, neutrons and protons depends on the temperature. If the initial temperature is \( \sim 10 \, \text{MeV} \) at the initial time \( \sim 1 \, \text{ms} \), then in \( \sim 10 \, \text{ms} \) the temperature decreases to 1 MeV, when the evaporation nearly ceases. Therefore, evaporation only happens at very early stage of expansion.

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

\[
\frac{dA}{dt} = -R \cdot 4\pi r^2, \tag{6}
\]

where

\[
A = \frac{4\pi}{3} r^3 n \tag{7}
\]

\[
A \simeq \left( \frac{A_0^{1/3} - \frac{R}{\text{ fm}^{-2}} \cdot t}{1} \right)^3 \tag{8}
\]

When \( t = 1 \) ms the temperature is about 20 MeV and \( R = R_q \approx 1.5 \times 10^{15} \text{ s}^{-1} \text{ fm}^{-2} \), 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 to \( 10^{39} \), 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. Eq.\( 8 \) indicates that, if the time duration from \( T \sim 10 \) MeV to 5 MeV is about 10 ms, when \( R = R_n \approx 10^{10} \text{ s}^{-1} \text{ fm}^{-2} \), 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 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 \cite{kasliwal2017}, the lifetime of the strangeon nuggets was assumed to be 1 day. Here we propose a more reasonable scenario of 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
interface between the merging stars ejects strangon 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 could 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)

$$Λ \rightarrow p + π^- \ (63.9\%)$$
$$Λ \rightarrow n + π^0 \ (35.8\%)$$

(9) (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)

$$π^- \rightarrow μ^- + ν_μ$$
$$μ^- \rightarrow e^- + ν_μ + \bar{ν}_e$$

(11) (12)

and

$$π^0 \rightarrow 2γ \ (98.82\%)$$
$$π^0 \rightarrow e^+ + e^- + γ \ (1.17\%)$$

(13) (14)

Therefore, we infer that the main decay products of strangeons would also be protons, neutrons, $e^-$, $\bar{ν}_e$, $ν_μ$, 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 are different. In the evaporation products of strangeon nuggets, the neutrons dominant 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 Sec. 3.1 and the decay of strangeons, we can get the dependence of $Y_e$ on temperature, as shown in Fig. 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.

![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.](image-url)
4.2 Two-component ejecta

The ejection processes of strangeon nuggets involves the tidal disruption that ejects matter in the equatorial plane, and 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.

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 that 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 $p + \bar{\nu}_e \rightarrow n + e^+$. 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 $Y_e$, indicated in Fig.2.

The components of ejecta are illustrated in Fig.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 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. The difference is that, the amount of heavy nuclei produced in merging strangeon stars would be much smaller than that in merging neutron stars, since the total ejected mass of the former would be much smaller than that of the latter.

The maximum mass of strangeon stars would be as high as $2.3M_\odot$ or even higher, so the merger of double strangeon stars triggering GW170817 would probably left a long-lived stable strangeon star. As indicated in [Li et al.] (2018), the emission of AT2017gfo associated with GW170817 can be explained by...
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 \(M_{\text{ej}}\), the minimum and maximum velocities \(v_{\text{min}}\) and \(v_{\text{max}}\), the density distribution index \(\delta\) and the opacity \(\kappa\). Here we choose typical values for such parameters. For both blue and red component, \(M_{\text{ej}} = 10^{-4} M_\odot\), \(v_{\text{min}} = 0.1c\), \(v_{\text{max}} = 0.3c\) (\(c\) is the speed of light), and the density distribution index \(\delta = 1.5\). The opacity \(\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}\) for blue component, and \(\kappa = 20 \text{ cm}^2 \text{ g}^{-1}\) for red component, respectively. In order to significantly spin down the remnant, efficient secular GW spin-down is needed. The timescale of spin-down is \(t_{\text{sd}} = 3 \times 10^3\) s, and the initial spin-down luminosity is \(1.5 \times 10^{43}\) erg, which are typical values for spinning down neutron stars.

Bolometric light curve of a strangeon kilonova including two-component ejecta, fitted to the data from Kasliwal et al. (2017) are shown in Fig.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. For both blue and red component, the ejected mass \(M_{\text{ej}} = 10^{-4} M_\odot\), the minimum and maximum velocities \(v_{\text{min}} = 0.1c\) and \(v_{\text{max}} = 0.3c\) (\(c\) is the speed of light), the density distribution index \(\delta = 1.5\). The timescale of spin-down is \(t_{\text{sd}} = 3 \times 10^3\) s, and the initial spin-down luminosity is \(1.5 \times 10^{43}\) erg s\(^{-1}\). The opacity \(\kappa = 0.1 \text{ cm}^2 \text{ g}^{-1}\) and \(20 \text{ cm}^2 \text{ g}^{-1}\) for blue and red components, respectively. The details of the ejecta model are given in Yu et al. (2018).

Therefore, although the very initial components in ejecta of merging strangeon stars are different from that of merging neutron stars, the “strangeon kilonova” could have light curves similar to that of 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 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 make a qualitative description about the evolution of ejecta and light curves of 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 hydrody-
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 relatively longer timescale of tens of milliseconds, which still lead 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 that of merging neutron stars, although the very initial components in ejecta of the former are different from that of the latter. Light curves are then for both low and high opacity components, under typical model of ejecta to include the radiation-transfer process. Under reasonable values of parameters, even if the ejected mass is only $\sim 10^{-4} M_\odot$, the bolometric light curves can fit the data of AT2017gfo, by the energy injection from a long-lived and spinning-down strangeon star. Although the rotational energy released by the remnant during its spin-down will be transferred into the 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 are instantly decay into protons and neutrons. The ejection, evaporation and decay happen at very early stage of merger and terminated at time about tens of milliseconds when temperature dropped 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 left a long-lived stable strangeon star. Therefore, the merging strangeon stars scenario seems to be helpful to include both 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 more sever test for both neutron star and strangeon star models.

The above statements are based on the hypothesis that, the the emission of neutrinos of newly born strangeon stars are the same as that of newly born neutron stars, in which case the luminosity of $\nu_e$ 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 [41] the decay of strangeons would produce a large amount of $\nu_\mu$, 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 $A_e$ of stable strangeon nuggets, smaller than which the strangeon matter
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 show 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 survived 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 decrease 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 left to be microscopic strangeon nuggets with $A \gtrsim A_c$. The survived 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.

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