# Rotating Massive Strangeon Stars and X-Ray Plateau of Short GRBs (Postprint)

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**Date:** 2024-03-29T00:00:00+00:00

## Abstract

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## Full Text

## Preamble

Research in Astronomy and Astrophysics, 24:035005 (11pp), 2024 March © 2024. National Astronomical Observatories, CAS and IOP Publishing Ltd. Printed in China and the U.K. https://doi.org/10.1088/1674-4527/ad2127 ChinaXiv Rotating Massive Strangeon Stars and X-Ray Plateau of Short GRBs Xi-Yan Yang1,2, Xiao-Yu Lai2, Wei-Wei Tan2,3, and Ren-Xin Xu4,5

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Received 2023 September 4; revised 2023 December 31; accepted 2024 January 16; published 2024 February 21

## Abstract

Strangeon stars, which are proposed to describe the nature of pulsar-like compact stars, have passed various observational tests. The maximum mass of a non-rotating strangeon star could be high, which implies that the remnants of binary strangeon star mergers could even be long-lived massive strangeon stars. We study rigidly rotating strangeon stars in the slowly rotating approximation, using the Lennard-Jones model for the equation of state. Rotation can significantly increase the maximum mass of strangeon stars with unchanged baryon numbers, enlarging the mass-range of long-lived strangeon stars. During spin-down after merger, the decrease of radius of the remnant will lead to the release of gravitational energy. Taking into account the efficiency of converting the gravitational energy luminosity to the observed X-ray luminosity, we find that the gravitational energy could provide an alternative energy source for the plateau emission of X-ray afterglow. The fitting results of X-ray plateau emission of some short gamma-ray bursts suggest that the magnetic dipole field strength of the remnants can be much smaller than that of expected when the plateau emission is powered only by spin-down luminosity of magnetars.

Key words: dense matter -(stars:) pulsars: general -(stars:) gamma-ray burst: general

## 1. Introduction

Pulsar-like compact stars, among which the well-known ones are radio pulsars, are born in supernova explosions. Although abundant observational data of pulsars have been accumulated, their interior structure remains a controversial topic. The typical density of a pulsar is slightly larger than that of nuclear matter on average, so the equation of state (EoS) of pulsars essentially depends on the behavior of quantum chromodynamics (QCD) at low-energy scales, which remains challenging to understand. Some fundamental questions persist: Have quarks been deconfined there? Does strangeness play an essential role? Based on different viewpoints, a variety of models for pulsars have been speculated, such as neutron stars (NSs) and quark stars (QSs).

A strangeon star (SS) model was originally proposed by Xu (2003) and has been studied for twenty years from both observational and theoretical perspectives (see Lai et al. 2023a and references therein). Briefly speaking, at realistic densities inside pulsars, the energy scale is much higher than the mass difference between strange (s) and up/down (u/d) quarks, while additionally not being high enough to justify the validity of perturbative QCD. Net strangeness could emerge due to weak interactions, and u, d, and s quarks in the light-flavor sector would tend toward equal abundance symmetry. Simultaneously, the non-perturbative effects of QCD could be significant, similar to the case of the strong interaction in nuclei. It is then conjectured that strangeons, which can be understood as "nucleons with strangeness" or "strange nucleons," could be the building blocks of dense matter in pulsars (Xu 2003; Xu & Guo 2017).

Compact stars composed entirely of strangeons are called strangeon stars (SSs). SSs differ from both NSs and strange quark stars (SQSs). Unlike baryons inside NSs, strangeons are three-flavored, and the number of constituent quarks (Nq) of a strangeon can be larger than three. For instance, strangeons with Nq = 18 are similar to the so-called quark-alpha (Michel 1988), which are completely asymmetric in spin, flavor, and color space. Moreover, NSs are gravitationally bound and have crusts composed of normal nuclei, while SSs are self-bound and have almost the same composition from center to surface. SSs also differ from SQSs, with the main distinction being that SSs are self-bound by the residual interaction between strangeons, whereas SQSs are self-bound by bag-like confinement.

The SS model has passed various observational tests. It predicted high-mass pulsars (possibly even larger than 3M ) (Lai & Xu 2009a, 2009b) before the formal discovery of massive pulsars with $M > 2M$ . Additionally, the strangeon matter surface could naturally explain pulsar magnetospheric activity (Xu et al. 1999) as well as the subpulse-drifting of radio pulsars (Lu et al. 2019). Pulsar glitches (Zhou et al. 2004, 2014; Lai et al. 2018b) and glitch recovery (Lai et al. 2023b) can also be explained under the framework of starquakes in SSs. The plasma atmosphere of SSs 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 of merging binary SSs is consistent with the results of the gravitational wave event GW170817 (Lai et al. 2018a, 2019).

Rotation affects the structure of pulsars, and related astrophysical consequences are worth exploring to provide tests for EoS models. A perturbative approach describing distorted NSs with uniform and slow rotation to the second order of angular frequency $\Omega$ was developed by Hartle (1967) and Hartle & Thorne (1968), and extended to the third order of $\Omega$ by Hartle (1973) for calculating variations of moments of inertia. Slow rotation means that $\Omega$ of a star with mass M and radius R is much smaller than the Keplerian frequency, $\Omega$ √(GM/R$^3$), in which case the rotating configuration can be considered as a perturbation on a non-rotating one of the same central density. It has been shown that this perturbative approach can be applied with great accuracy for most observed

NSs, even for most millisecond pulsars (Berti & Stergioulas 2004; Benhar et al. 2005; Berti et al. 2005). Gao et al. (2022) have provided detailed calculations about the structure of slowly rotating SSs, using the EoS of the Lennard-Jones model, and derived the moments of inertia, quadrupole moments, eccentricities, changes in gravitational and baryonic masses, and universal relations between some of these quantities.

The effect of rotation on stability is crucial for the fate of the products of binary NS/SS mergers. The maximum mass of non-rotational NSs/SSs, denoted by MTOV, can be derived by solving the Tolman–Oppenheimer–Volkoff (TOV) equations (Oppenheimer & Volkoff 1939) for a given EoS. According to the widely used definition, the rotating NS/SS that is stabilized by differential rotation is hypermassive, the one stabilized by rigid rotation is supramassive, and the one stable without rotation is stable or long-lived. The maximum mass of rotating NSs/SSs, denoted by Mmax, will increase with angular frequency $\Omega$, which also depends on EoSs. Considering that EoSs should satisfy the constraints of both the existence of two-solar-mass pulsars and the tidal deformability of GW170817 (Abbott et al. 2017), we use the EoS of the Lennard-Jones model (Lai & Xu 2009b) (which has also been used by Gao et al. 2022) for SSs and the EoS of the AP4 model (Akmal & Pandharipande 1997) for NSs.

The fate of the product of a merger event should be determined at constant baryon number. We will explicitly show the increases of Mmax with $\Omega$ along lines of constant baryonic mass, with results indicating that the increases of Mmax are more pronounced for SSs than for NSs. Combined with the previous conclusion that MTOV of SSs can be larger than 2.5M across a wide parameter space (Lai & Xu 2009a, 2009b; Lai et al. 2013; Guo et al. 2014), we can infer that if pulsar-like compact stars are actually SSs, the remnants of binary strangeon star mergers are very likely to be long-lived massive SSs. The long-lived SSs as remnants of binary strangeon star mergers could have interesting observational consequences; for example, they could reproduce the light curves observed in kilonovae (Lai et al. 2018a, 2021). As will be demonstrated in this paper, the long-lived massive SSs could also provide sufficient gravitational energy to explain the X-ray afterglow of short gamma-ray bursts (GRBs).

Short gamma-ray bursts (SGRBs) are generally believed to originate from binary NS mergers (Eichler et al. 1989) or binary NS-BH (black hole) mergers (Paczynski 1991). Among them, those with an afterglow phase are often interpreted as originating from binary NS mergers, where the afterglow emission is widely accepted as being powered by millisecond magnetars (e.g., Dai & Lu 1998; Zhang & Mészáros 2001). The electromagnetic dipolar radiation of postmerger magnetars could explain the X-ray flares following SGRBs (Dai et al. 2006; Gao & Fan 2006), and the light curves produced by magnetar spindown winds could explain the X-ray plateaus at observed luminosities of SGRBs (Strang & Melatos 2019; Strang et al. 2021). The gravitational bursts due to magnetar wind dissipation of millisecond magnetars left behind by binary neutron star mergers (Zhang 2013) and the associated multi-wavelength afterglows (Gao et al. 2013) have been investigated. Moreover, some plateaus with long durations are suggested to be powered by nascent SQSs (Yu et al. 2009), which could be supported by observations of the break time of internal X-ray plateaus in SGRBs (Li et al. 2016).

The X-ray plateaus in the afterglow of GRBs observed by the Swift satellite have been explained by magnetar central engines, where a dipole field strength larger than $10^{15}$ G is required (Rowlinson et al. 2013; Stratta et al. 2018). In this paper, we investigate the gravitational energy released by long-lived massive SSs and its implications for the X-ray afterglow of SGRBs.

If pulsar-like compact stars are actually SSs instead of NSs—that is, if binary neutron star mergers are actually binary SS mergers—then SGRBs with plateaus in the X-ray afterglow phase originate from binary SS mergers. It is worth noting that a strong magnetic field may not be necessary for the SS scenario; for example, the elastic and gravitational energy released from SSs can explain AXPs/SGRs (anomalous X-ray pulsars/soft gamma repeaters) associated with glitches (Zhou et al. 2014) and the precursor emission of SGRBs (Zhou et al. 2023). The latent heat released in the solidification of the strangeon star was proposed as energy injection into the X-ray plateau of GRB afterglow (Dai et al. 2011), and this idea is supported by the X-ray light curve of GRB 170714A, whose two plateaus can be interpreted as being powered respectively by latent heat and the spin-down of a massive strangeon star that is the remnant of a binary star merger (Hou et al. 2018). For simplicity, it was assumed that the latent heat released in solidification was emitted as blackbody radiation to power the relativistic jet of GRBs; however, a more realistic and detailed mechanism should be taken into account.

If pulsars are actually SSs instead of NSs, it is worth exploring explicitly how the plateaus in the X-ray afterglows of SGRBs originate from binary SS mergers. In this paper, we consider the contribution of gravitational energy to the X-ray light curves of GRBs from binary star mergers. The remnants of binary SS mergers will undergo spin-down due to energy loss. The gravitational mass M and radius R will decrease as the angular velocity Ω reduces under the same baryonic mass Mb, so gravitational energy will be released as an isolated star spins down. Because the remnants of binary SS mergers would be long-lived massive SSs, we study the spin-down process of massive SSs and investigate whether the gravitational energy could provide energy injection to the X-ray plateau in the afterglow of SGRBs. As we will demonstrate, the shrinkage of the star would lead to oscillations and turbulence, which would convert gravitational energy into kinetic energy and finally inject it into the GRB fireball.

Assuming that spin-down is due to magnetic dipolar radiation, we can derive the luminosity of gravitational energy release, and the X-ray luminosity can be obtained by taking into account the efficiency of converting gravitational energy into observed X-ray luminosity. From Stratta et al. (2018), which interpreted GRBs presenting X-ray afterglow plateaus as having magnetar origins, we select some SGRBs with obvious plateaus in the Swift GRB sample and fit their X-ray afterglow data using the MCMC (Markov Chain Monte Carlo) method. Our fitting results will be compared with those in Stratta et al. (2018). The $^2$/d.o.f values in our scenario are not much larger (and in some cases are even smaller) than those in Stratta et al. (2018). Additionally, the results show that the magnetic dipole field strength of the remnants can be much smaller than expected when the plateau emission is powered only by spin-down luminosity of magnetars.

This paper is organized as follows. After introducing the Lennard-Jones model of SSs in Section 2.1, we demonstrate how to calculate the structure of slowly rotating SSs in the Hartle–Thorne approximation in Section 2.2, and show results for maximum mass and spherical stretching under rotation. Based on the luminosity of gravitational energy during spin-down derived in Section 3.1, we investigate in Section 3.2 whether gravitational energy release during spin-down could provide sufficient energy injection for the plateau emission of X-ray afterglow of SGRBs. Conclusions and discussions are presented in Section 4.

## 2.1. Static Strangeon Stars

We choose the Lennard-Jones model to describe the EoS of SSs (Lai & Xu 2009b) because it can well characterize the non-relativistic nature and strong-repulsive interactions at short distances, and the allowed parameter space to satisfy constraints from both the existence of two-solar-mass pulsars and the tidal deformability of GW170817 is large (Lai et al. 2019).

The potential between two strangeons is given by

$$U(r) = U_0 \left[ \left( \frac{r_0}{r} \right)^{12} - 2 \left( \frac{r_0}{r} \right)^{6} \right],$$

where $\mathrm{U}_0$ is the depth of the potential and $\mathrm{r}_0$ is the range of interaction. The total energy density includes the densities of potential energy, lattice vibration energy, and baryonic mass-energy. The lattice energy density is negligible compared to the other two energy densities, so the total energy density is

$$\varepsilon = nm + nU_0 \left[ \left( \frac{r_0}{r} \right)^{12} - \left( \frac{r_0}{r} \right)^{6} \right],$$

and the pressure is

$$p = nU_0 \left[ \left( \frac{r_0}{r} \right)^{12} - \left( \frac{r_0}{r} \right)^{6} \right],$$

where n is the number density of strangeons, m is the mass of each strangeon, and a simple-cubic lattice structure is assumed. If the number of quarks in each strangeon is Nq, then m   Nq · 300 MeV. The parameter $r_0$ is related to the baryon number density on the surface nb,s where the pressure vanishes.

As in Gao et al. (2022), we choose the EoS with parameters nb,s = 0.36 $\mathrm{fm}^{-3}$, $U_0$ = 30 MeV (denoted by LX3630), and Nq = 18, because it satisfies the constraint from the measurement of the moment of inertia of PSR J0737-3039A (Hu et al. 2020). Given the EoS, the structure of non-rotating SSs is governed by the TOV equations (Oppenheimer & Volkoff 1939). The gravitational mass is

$$M = \int_0^R 4\pi r^2 \varepsilon(r) dr,$$

the baryonic mass is

$$M_b = \int_0^R 4\pi r^2 \rho_b(r) e^{\lambda(r)/2} dr,$$

where  b = nm is the baryon density, and m is the gravitational mass enclosed in radius r.

## 2.2. Strangeon Stars under Slow Rotation

Given a central density  c and the EoS, the structure derived from the TOV equation serves as the static and spherical background, upon which the gravitational mass M, radius R at the equator, and baryonic mass Mb of a rigidly rotating star in the slow rotation approximation can be derived by adding corrections to second order in Ω. This procedure was first formulated by Hartle (1967) and Hartle & Thorne (1968) for rotating NSs, and the structure of rotating SSs was given in detail by Gao et al. (2022), including corrections induced by matching conditions on the surface. Here we adopt the same procedure as Gao et al. (2022) to show evolution along given values of Mb. The values of M, Mb, and R are calculated to spherical terms in second order of Ω, so only spherical deformations are considered. The moment of inertia I in Section 3.1 is calculated by taking into account corrections to third order in Ω for the angular momentum J.

The calculation proceeds as follows, with details found in Gao et al. (2022): (i) Choose a central density  c to calculate the structure of a non-rotating configuration. (ii) The gravitational mass M and radius R of a rotating SS with angular frequency Ω are derived by adding perturbations to a non-rotating configuration under the same  c, taking into account the matching condition at the surface. (iii) The values of M and R for a configuration with a different angular frequency Ω (< Ωc) and the same central density can be obtained by multiplying the perturbations by the rescaling factor $\Omega^2/\Omega c^2$. (iv) By connecting the same value of Mb on each M–R curve we obtain a constant-Mb line. Changing the values of  c gives the M–R curve. The M–R curve with another value of $\Omega$ ($<$ $\Omega$c) can be derived from the same procedure.

### 2.2.1. Evolution under Constant Baryonic Mass

An isolated star has unchanged baryonic mass during spin-down. For a given EoS, the stable configuration with M = MTOV has the baryonic mass Mb,max^{stable}, and the sequences with Mb > Mb,max^{stable} will evolve to stable configurations with unchanged baryonic mass as they spin down. We plot the gravitational mass and radius curves of strangeon stars in Figure 1 [Figure 1: see original paper], under EoS LX3630 with Nq = 18, where sequences of constant-Mb are denoted by red dotted lines with Mb = 4.4M , 2.4M , and 1.6M . For comparison, we also plot the result for NSs under EoS AP4 (Akmal & Pandharipande 1997), where sequences of constant-Mb are denoted by blue dotted lines with Mb = 2.7M , 2.4M , and 1.6M . Solid lines represent non-rotating configurations, and dashed lines represent rotating configurations with the critical angular frequency $\Omega$c.

Our results show that the increase in gravitational mass due to rotation is larger for larger mass, and the increases of Mmax by rigid rotation for SSs are more pronounced than for NSs. The Mmax value for SSs is roughly 9.3% higher than MTOV along constant baryonic mass lines, while for NSs the result is roughly 5.6%. If compared only with the maximum values of the M–R curves, both results are roughly 20% for SSs and NSs. However, although the increases in Mmax by rigid rotation of SSs are larger than for NSs, at values of M well below MTOV the advantage of SSs over NSs regarding the increase of gravitational mass M due to rotation is not significant.

In fact, the gravitational energy released by an NS during spin-down is usually larger than that of an SS, since the shrinkage of the NS is larger. Although this conclusion seems to favor NSs for providing gravitational energy to explain plateau emission, we still prefer SSs to NSs. The reason is that an NS as the remnant of binary neutron star mergers would not be long-lived. Although the AP4 model for NSs could pass both tests of massive pulsars and tidal deformability during mergers (Annala et al. 2018), MTOV   2.2M , which is well below the total mass of known binary neutron star systems inferred by Antoniadis et al. (2016).

### 2.2.2. Spherical Stretching Due to Rotation

From Figure 1 we can see that between $\Omega = \Omega$c and $\Omega = 0$, the change in radius of an NS will be greater than that of an SS. Spherical stretching due to rotation has been discussed in Gao et al. (2022), which was found to increase toward the surface of the star for NSs while being nearly unchanged throughout the star for SSs. To examine the change in density due to rotation, we show explicitly here the change in central baryon density. We plot curves showing the change of central baryon density  c,b with $\Omega$ under some given values of initial mass

$M_0 = M(\Omega = \Omega_0)$ in Figure 2 [Figure 2: see original paper], with initial angular frequency $\Omega_0 = 2\pi/(1 \text{ ms})$. The red solid and dashed curves represent results for SSs for Mb = 1.6M  (corresponding to initial mass $M_0$   1.36M ) and Mb = 2.7M  (corresponding to $M_0$   2.16M ), respectively. For comparison, results for NSs are shown by blue solid and dashed curves for Mb = 1.6M  (corresponding to $M_0$   1.44M ) and Mb = 2.7M  (corresponding to $M_0$   2.22M ), respectively.

From the change of  c,b with $\Omega$, we see that spherical stretching of an NS is more significant than that of an SS with the same baryonic mass and initial spin frequency, especially when the initial mass $M_0$ exceeds 2M . Conversely, during spin-down, the shrinkage of an NS is more significant than that of an SS, especially in the case of binary merger remnants. This may imply that a neutron star with $M_0$   2.2M  as the remnant of a binary NS merger, although being long-lived, would undergo phase transition during spin-down. It would be interesting to explore the implications of such phase transitions in massive or supramassive NSs; for example, energy released from phase transitions has been considered as an energy source related to GRB observations (Dai & Lu 1998; Sarin 2021). An SS, however, is close to incompressible matter and would not undergo phase transition during spin-down.

It is worth noting that if the AP4 model applies to NSs both before and after mergers, the increase in central density during merger is much more significant than during spin-down. The central density increases to almost twice that before merger, but only increases by about 10% during spin-down. Therefore, if an NS with $M_0$   2.2M  as the remnant of a binary NS merger would undergo phase transition during spin-down, the phase transition would be more likely to occur during merger instead of during spin-down.

Differential rotation may be a short-term process during the early stages of merger remnants and would no longer be important on longer timescales for the afterglow. In addition, we take the initial angular frequency $\Omega_0 = 2\pi/(1 \text{ ms})$, which satisfies the slow rotation condition $\Omega$   $\sqrt{}(GM/R^3)$. Therefore, we can use the slow rotation approximation in the case of rigid rotation to derive the change of gravitational energy with time.

## 3. Gravitational Energy Release of the Binary Merger Remnants

Because MTOV values are high for strangeon stars, remnants of binary strangeon star mergers would probably not immediately collapse into black holes and could even be long-lived. Being rapidly spinning initially, the remaining massive strangeon stars will undergo spin-down due to energy loss. As shown in Section 2.2, the radius of a strangeon star decreases as its angular frequency $\Omega$ decreases, so gravitational energy will be released during spin-down. We will show that although only a fraction of gravitational energy will be converted into X-ray emissions, it may play an important role in the X-ray afterglow of SGRBs.

### 3.1. Luminosity of Gravitational Energy

The gravitational energy of a relativistic star can be derived as

$$E_{\mathrm{grav}} = M_p c^2 - \int_0^R 4\pi r^2 \varepsilon(r) e^{\lambda(r)/2} dr,$$

where the proper mass Mp is defined as

$$M_p = \int_0^R 4\pi r^2 \rho_b(r) e^{\lambda(r)/2} dr,$$

and the kinetic spin energy Ekin is related to the angular momentum J by Ekin = JΩ/2. The change of Egrav with Ω for a given Mb can be derived by a procedure similar to that used in Section 2.2, where the proper mass Mp is calculated to second order in Ω by a procedure similar to that for deriving Mb. Using the slow rotation approximation to calculate Ekin, the angular momentum J is calculated to first order in Ω by considering the rotational dragging of inertial frames, so Ekin is also calculated to second order in Ω.

The luminosity of gravitational energy can be derived by

$$L_{\mathrm{grav}} = -\frac{dE_{\mathrm{grav}}}{dt}.$$

Assuming that spin-down is due to electromagnetic (EM) dipolar radiation and gravitational wave (GW) radiation, the change of Ω with time t is (Shapiro & Teukolsky 1983)

$$\frac{d\Omega}{dt} = -\frac{B_p^2 R^6 \Omega^3}{6Ic^3} - \frac{32GI\epsilon^2\Omega^5}{5c^5},$$

where Bp is the dipolar field strength at the poles, I is the moment of inertia, R and  are the radius and ellipticity of the star, respectively. Combining Equations (5) and (6), we can obtain the luminosity of gravitational energy Lgrav. It is worth noting that in calculating both Lgrav and the luminosity of magnetic dipole radiation, the changes of R and I with Ω are taken into account. R is calculated by adding spherical deformation to second order in Ω, as demonstrated in Section 2.2. The corrections to I = J/Ω are also to second order in Ω, since the corrections to angular momentum J for calculating I are derived to third order in Ω (Hartle 1973; Gao et al. 2022).

### 3.2. The Role of Lgrav in the X-Ray Afterglow of SGRBs

We investigate whether gravitational energy release during spin-down could provide sufficient energy injection for the afterglow of SGRBs. In a supernova explosion, most gravitational energy is carried away by neutrinos produced in phase transitions involving weak interactions. However, as shown in Section 2.2.2, the shrinkage of an SS during spin-down would not be large enough to cause a phase transition, so energy loss due to neutrinos would be unimportant. How then will the gravitational energy released due to SS shrinkage be injected into the GRB fireball?

Similar to the process of heating the solar corona and solar wind by high-frequency Alfvén waves (Tu & Marsch 1997; Kaghashvili 1999), gravitational energy could be converted into kinetic energy and finally injected into the GRB fireball by Alfvén waves. The oscillations and turbulence due to star shrinkage would lead to magnetic reconnection and generate Alfvén waves to carry away kinetic energy (which comes from gravitational energy), like oscillation-driven magnetospheric activity in pulsars (Lin et al. 2015). In this way, the conversion of gravitational energy into the fireball may involve processes similar to kinetic-energy-dominated shells (Zhang & Mészáros 2002) or Poynting-flux-dominated outflows (Mészáros & Rees 1997). Because the efficiency g for gravitational energy to be converted into X-ray emissions of GRB afterglow is unknown, all complexities are encapsulated in g.

In models interpreting X-ray afterglow plateau emission in GRBs as powered by electromagnetic dipolar emission from millisecond magnetars, the efficiency em of converting dipole spin-down luminosity to observed luminosity must be considered. However, em is derived by fitting observational data because its prior value is hard to calculate, and fitting results usually differ. Although some simulations suggest em = 0.4–1 (Gao et al. 2016), a more detailed study indicates that X-ray radiation efficiency strongly depends on the saturation Lorentz factor and the typical value is of order $10^{-2}$ (Xiao & Dai 2019). Similarly, efficiency g of converting gravitational energy luminosity to observed X-ray luminosity should also be considered, but determining g remains problematic. The data points for each SGRB we choose are insufficient to provide good fitting with more than three free parameters, so we can only choose either g or em as a free parameter. We find that fitting results with g = em do not differ significantly from those with em = 0, so to highlight the role of gravitational energy we set em = 0, except in two cases where we set g = em to avoid g > 1, as will be shown later. In addition, because spin-down due to GW radiation is not important in the afterglow phase (Zhang & Mészáros 2001), we neglect the second term of Equation (6).

To test the validity of our scenario, we select some SGRBs from Stratta et al. (2018), which fit a sample of GRB X-ray afterglows assuming plateau emission is powered by spin-down luminosity of millisecond magnetars. They derived $^{2}$/d.o.f values for fitting results that can be compared with ours. Because we do not use model or quantitative selection criteria to identify the plateau phase, we choose those with obvious plateaus and identify the flat part of the data as the plateau phase to begin our fitting. Among the ten SGRBs fitted in Stratta et al. (2018), we choose six–051221A, 060614, 061201, 070714B, 070809, and 090510–which have redshifts and obvious plateaus. Besides these, we choose two additional SGRBs from the Swift GRB sample with obvious plateaus: 130603B and 140903A.

For a given burst in Swift data (Evans et al. 2007, 2009), the source rest frame luminosity is derived from the flux F(t) at time t by

$$L(t) = 4\pi D_L^2(z)F(t),$$

where DL(z) is the luminosity distance at redshift z. For correction from 1 to $10^4$ keV in the burst rest frame to the observed band, the X-ray luminosity derived in our model is divided by factor kc. The redshifts of the eight SGRBs are from Table 1 of Kisaka et al. (2017) (and references therein). We adopt cosmological parameters from Komatsu et al. (2009) to obtain DL(z), and kc is derived by the method used in Bloom et al. (2001).

In MCMC fits of different SGRBs, we assume Mb   3.1M , which corresponds to $M_0$   2.36M  under the fitted values of initial spin period $P_0$. Certainly, the mass range for remnants in binary star mergers is unknown. The total mass of the binary system associated with GW170817, which is probably larger than 2.7M  (Abbott et al. 2017), and the masses of known binary neutron star systems (Antoniadis et al. 2016) suggest that an initial mass $M_0$   2.36M  for remnants in binary star mergers could be reasonable. We find that changing $M_0$ from 2.2M  to 2.5M  does not produce significant effects.

The afterglow component from interaction between the jet and interstellar medium should also be considered. We use the Python package "afterglowpy" (Ryan et al. 2020), which utilizes semianalytic approximations to jet evolution and synchrotron emission to calculate afterglow light curves with structured jets, taking into account relativistic beaming effects. In our calculations, the Gaussian jet model is used to calculate the contribution from jet-interstellar medium interaction, assuming fractions of post-shock energy in radiating electrons  e = 0.04 and magnetic fields  B = $10^{-4}$ (Ryan et al. 2020), jet half-opening angle  c   6.87° (Fong et al. 2015), and truncation angle  w = 5 c. The values of interstellar medium number density $n_0$ and electron power-law distribution index p are chosen from Fong et al. (2015) for each SGRB. The isotropic equivalent energy of the blast wave $E_0 = 10^{52 \cdot 2}$ erg (Cao et al. 2023), and the viewing angle  v can be derived from the photon index and peak flux for the Gaussian jet. After obtaining the flux at 3 keV under these parameters using "afterglowpy," the flux at 0.3–10 keV can be derived by the method of Gehrels et al. (2008). The results are shown by dashed lines in Figure 3 [Figure 3: see original paper], which indicate that compared with internal energy injection, the afterglow component from jet-interstellar medium interaction is not important.

We use the MCMC (Markov Chain Monte Carlo) method to fit three parameters: Bp, $P_0$, and g. The comparison of our fitting results with those of Stratta et al. (2018) for six SGRBs is shown in Table 1 . The X-ray light curves (1-$10^4$ keV) of eight SGRBs and histograms and contours for MCMC fits are shown in Figures 3 [Figure 3: see original paper] and 4 [Figure 4: see original paper], respectively.

Because we find that fitting results with g = em do not differ significantly from those with em = 0, we choose to fix em to avoid introducing an additional parameter. To highlight the role of gravitational energy we set em = 0 for 051221A, 060614, 061201, 070714B, and 070809. For 090510 and 140903A, we set g = em to avoid g > 1. From the fitting results, we see that for the six SGRBs from Stratta et al. (2018), the $^2$/d.o.f values in our scenario are not much larger than those in Stratta et al. (2018), indicating that our scenario is at least not inferior. Additionally, the Bp values are much smaller than those expected in Stratta et al. (2018).

## 4. Conclusions and Discussions

The effects of rotation on the structure of pulsar-like compact stars have interesting consequences and provide tests for EoS models. Under the hypothesis that pulsar-like compact stars are SSs, whose EoS is described by the Lennard-Jones model, we study rigidly rotating SSs in the slow rotation approximation. Although we only choose the EoS of LX3630 and Nq = 18 for our calculations, other forms of EoS under different parameters may not bring qualitative differences. We find that rotation can significantly increase the maximum mass of a stable SS. An SS with mass M larger than MTOV by approximately 9% can still be stable or long-lived during spin-down with unchanged baryonic mass Mb. Considering that MTOV of SSs can be much larger than 2.5M across a wide parameter space, it is very likely that remnants of binary SS mergers are long-lived massive SSs.

To explore the consequences of rotating massive SSs, we investigate whether their gravitational energy release during spin-down could provide sufficient energy injection for the afterglow of SGRBs. We derive the luminosity of gravitational energy release, where spin-down is due to magnetic dipolar radiation and changes of radius R and moment of inertia I with angular frequency Ω are taken into account. The X-ray light curves can be derived by assuming a fraction of gravitational energy release contributes to X-ray luminosity. By fitting X-ray afterglows of six SGRBs from Stratta et al. (2018) that have redshifts and obvious plateaus, we find that gravitational energy released by long-lived massive strangeon stars could provide an alternative energy source for plateau emission in X-ray afterglows. Our fitting results show that the magnetic dipole field strength of the remnants can be much smaller than expected in the magnetar scenario. The fitting results of our scenario appear not inferior compared to the magnetar scenario, which is much more sophisticated than ours.

We offer the following discussions. Although the plateau of X-ray afterglows of SGRBs is widely accepted as being powered by electromagnetic dipolar emission from millisecond magnetars, we demonstrate that gravitational energy could provide an alternative energy source. To avoid complexity in the details of the millisecond magnetar origin scenario, we choose to fix em to be either 0 or equal to g. It is expected that a reasonable way to combine both contributions to account for X-ray afterglow emission of SGRBs will be found by fitting a larger sample of SGRBs.

Certainly, we employ some simplifications and assumptions to obtain our results. The star is assumed to rotate rigidly, and the slow rotation approximation is used to calculate its structure. Moreover, how gravitational energy can be injected into the GRB fireball to power afterglow emission is unknown. Here we assume that a fraction of gravitational energy could be converted into kinetic energy and finally injected into the GRB fireball by Alfvén waves, which could be generated by oscillations and turbulence due to star shrinkage, and we encapsulate all uncertainties in the efficiency g. Similar to efficiency em in the magnetar scenario, g would not be constant and would depend on many factors, such as injected luminosity and injection process. An improved version of our scenario in the future by fitting a larger sample of SGRBs would be promising.

Further investigations of GRB afterglows are expected. We only consider in this paper the afterglows of SGRBs instead of long GRBs (LGRBs), which are generally believed to originate from supernova explosions whose remnants are pulsar-like compact stars or black holes. Millisecond magnetars, if the magnetic dipole field could be high enough, are generally accepted as the engine of X-ray afterglow plateaus for both LGRBs and SGRBs. However, for LGRBs whose remnants are stable compact stars with masses of about 1.4M , gravitational energy released during spin-down alone may not be large enough to account for X-ray afterglow plateaus, regardless of whether the remnants are SSs or NSs. The real process of energy injection into GRB afterglows would be complex, and gravitational energy would only be part of the available energy sources.

In addition, we only consider long-lived remnants of binary mergers and their implications for X-ray afterglow plateaus of SGRBs. Some X-ray afterglows of SGRBs show rapid decay after the plateau phase, in which case the plateau is interpreted as being powered by supramassive remnants and the rapid decay is thought to signal collapse into BHs. The study of the distribution of break time (i.e., collapse time) of X-ray plateaus in SGRBs could provide tests for EoS models of NSs and QSs (Li et al. 2016). For the SS model, the implication for break time of X-ray plateaus in SGRBs is worth exploring. On one hand, calculating break time requires knowledge of the mass distribution of binary neutron stars via population synthesis and more detailed observations of SGRBs, which currently have many uncertainties. On the other hand, sudden decreases in X-ray light curves may not imply collapse into black holes, since the decay of Lgrav could be rapid even for a long-lived massive SS. As a first attempt to explore these issues, in this paper we only consider the case of long-lived remnants and try to explain observed luminosities of X-ray plateaus. Further work on how to test different EoS models through GRB observations is expected.

## Acknowledgments

We would like to thank Dr. Yong Gao and Prof. Yun-Wei Yu for useful discussions, and the anonymous referee for comments. This work makes use of data supplied by the UK Swift Science Data Centre at the University of Leicester. This work is supported by the National SKA Program of China (Nos. 2020SKA0120300, 2020SKA0120100), the Outstanding Young and Middle-aged Science and Technology Innovation Teams from Hubei colleges and universities (No. T2021026), the Young Top-notch Talent Cultivation Program of Hubei Province, and the Key Laboratory Opening Fund (MOE) of China (grant No. QLPL2021P01).

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