The X-Ray Light Curve in GRB 170714A: Evidence for a Quark Star?

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Abstract

Two plateaus and a following bump in the X-ray light curve of GRB 170714A have been detected by the *Swift*/X-ray Telescope, which could be very significant for the central engine of gamma-ray bursts (GRBs), implying that the origin of this burst might be different from those of other ultra-long GRBs. We propose that merging two neutron stars into a hyper-massive quark star (QS) and then collapsing into a black hole (BH), with a delay time around 10^4 s, could be responsible for these X-ray components. The hyper-massive QS is initially in a fluid state, being turbulent and differentially rotating, but would solidify and release its latent heat, injecting it into the GRB fireball (lasting about 10^3 s during the liquid–solid phase transition). A magnetic field as high as $\sim 10^{15}$ G can be created by dynamo action of the newborn liquid QS, and a magnetar-like central engine (after solidification) supplies significant energy for the second plateau. More energy could be released during a fall-back accretion after the post-merger QS collapses to a BH, and the X-ray bump forms. This post-merger QS model could be tested by future observations, with either advanced gravitational wave detectors (e.g., advanced LIGO and VIRGO) or X-ray/optical telescopes.

Key words: dense matter – gamma-ray burst: individual (GRB 170714A) – magnetic fields – star: neutron

1. Introduction

Many aspects of gamma-ray bursts (GRBs) remain a mystery, including the central engine and the radiation mechanism (for reviews see, e.g., Zhang 2011; Kumar & Zhang 2015). According to the duration of the prompt emission, GRBs are classified into two categories: long- and short-duration GRBs (LGRBs and SGRBs). They are generally related to the collapsars (see the review by Woosley & Bloom 2006) and compact binary (neutron star (NS)–NS or NS–black hole (BH)) mergers (e.g., Eichler et al. 1989; Paczyński 1991; Narayan et al. 1992). However, some recent observations support the existence of new subclasses of GRBs: long-short GRBs (e.g., Gehrels et al. 2006; Zhang et al. 2007, 2009) and ultra-long GRBs (ULGRBs, see e.g., Gendre et al. 2013; Levan et al. 2014; Zhang et al. 2014; Greiner et al. 2015; Ioka et al. 2016).

The typical GRB X-ray light curve is generally divided into five distinct phases, i.e., steep decay, shallow decay, normal decay, late steep decay, and X-ray flares (e.g., Nousek et al. 2006; Zhang et al. 2006). The internal X-ray plateaus often appear in the X-ray afterglow of LGRBs and SGRBs (see e.g., Rowlinson et al. 2010; Lü & Zhang 2014; Lü et al. 2015; Gao et al. 2016b) and might be related to long-lasting activities of the central engines (e.g., Troja et al. 2007). The energy injection from a magnetar or quark star (QS) has been proposed to explain these phenomena (e.g., Dai & Lu 1998; Zhang & Mészáros 2001; Paczyński & Haensel 2005; Fan & Xu 2006; Staff et al. 2008; Lyons et al. 2010; Piro et al. 2014; Wu et al. 2014; Gao et al. 2016b; Li et al. 2016, 2017; Beniamini & Mochkovitch 2017).

It is worth noting that, after the binary NS merger, a new compact star is formed. It may not immediately collapse into a BH, depending on the equation of state (EoS) of the NS matter, due to rotation (see the review by Bartos et al. 2013). In fact, the EoS of dense matter at a few nuclear densities is a great challenge in physics and astronomy, and it is still a matter of debate whether the fundamental degree of freedom of supra-nuclear matter is either a hadron or a quark (Weber et al. 2013). Nevertheless, it is addressed, from an astrophysical point of view, that a pulsar-like compact star could be in a solid state of quark matter (Xu 2003), with a strangeon (former name: quark-cluster) as the constituent because of strong coupling, thereby enabling quarks to be localized there (Lai & Xu 2017). A hot strangeon star would be in a liquid state, but could be phase-converted to a solid state when its temperature is lower than ~ 1 MeV. It is proposed that the GRB X-ray plateau can be understood by considering the solidification of newborn strangeon stars with latent heat released as energy injection to the GRB afterglow (Dai et al. 2011). Note that the state equation of strangeon matter is so stiff that massive pulsars ($\gtrsim 2\,M_\odot$) can be naturally explained (Lai & Xu 2009, 2017). It is worth noting that the strangeon star model passes the dynamical test of tidal polarizablility, while mergers of two strangeon stars and accompanying electromagnetic radiation have been studied based on multi-band observations of GW170817 (Lai et al. 2018).

In ULGRB observations, the various profiles of the X-ray light curves appear. For example, the X-ray light curve of GRB 101225 can be fitted by two smooth exponential functions (e.g., Campana et al. 2011), the X-ray afterglow of GRB 111209A can be represented by three-segment functions with a supernova (SN)-like bump (e.g., Gendre et al. 2013; Stratta et al. 2013; Greiner et al. 2015; Gao et al. 2016a; Ioka et al. 2016; Liu et al. 2018), GRB 121027A has a large X-ray bump superimposed on the shallow decay (e.g., Wu et al. 2013; Hou et al. 2014a; Zhang et al. 2014), and GRB 130925A has many giant flares superimposed on the shallow decay (e.g., Hou et al. 2014b; Piro et al. 2014). The significant peculiarity of

these bursts might be related to certain processes or mechanisms of the GRB central engines. In their various guises, they arise from a single origin, i.e., BH hyperaccretion or a magnetar resulting from collapsars or compact binary mergers. Ioka et al. (2016) investigated three candidates for the ULGRB central engine, i.e., blue supergiant collapsars, newborn magnetars, and white dwarf tidal disruption, on GRB 111209A associated with SN 2011kl. They found that all three models can explain this burst, although the SN-like bump requires that the spin-down time of the magnetar be a hundred times longer than the timescale of the GRB. Liu et al. (2018) also tested the initial masses and metallicities of the progenitor stars of ULGRBs by using a BH hyperaccretion inflow–outflow model. Gao et al. (2016a) suggested that GRB 111209A/SN 2011kl may originate from the BH hyperaccretion process through the Blandford–Znajek (BZ; Blandford & Znajek 1977) and Blandford–Payne (Blandford & Payne 1982) mechanisms.

Recently, another ULGRB GRB 170714A was observed by the *Swift* telescope. Its X-ray light curve appears to be composed of two plateaus and one bump. This characteristic feature challenges all known models of the central engine. Therefore, we propose to interpret the three X-ray components of GRB 170714A using the phase transition of a QS, the QS spin-down process, and fall-back accretion into a BH, respectively. In Section 2, the data analysis is shown. We describe our model in Section 3. A summary is contained in Section 4.

2. Data

GRB 170714A was discovered at $T_0 = 12{:}25{:}32$ UT on 2017 July 14 by the Burst Alert Telescope (BAT) on board *Swift* (D'Ai et al. 2017) and accurately located by X-ray Telescope (XRT) at a position of $\alpha = 02^h17^m23^s.95$, $\delta = -1°59'24''.4$ (J2000), with an uncertainty of $5''.0$ (Evans et al. 2017). The redshift is $z = 0.793$ (de Ugarte Postigo et al. 2017). The mask-weighted light curve of prompt emission shows no obvious pulse and only continuous weak emission (Palmer et al. 2017). Then it is difficult to estimate T_{90}. The time integrated spectrum from $T_0 - 73$ s to $T_0 + 464.4$ s is best fitted by a simple power-law model and the fluence in the 15–150 keV energy band is $(2.8 \pm 0.3) \times 10^{-6}$ erg cm^{-2} (Palmer et al. 2017), yielding an isotropic gamma-ray energy release about $(1.58 \pm 0.08) \times 10^{52}$ erg.

The observation of XRT on this burst began at $T_0 + 392.7$ s (D'Avanzo et al. 2017). Figure 1 shows the XRT light curve in the 0.3–10 keV band (Evans et al. 2009). Unfortunately, due to the satellite motion, there is no data in 5 time gaps, i.e., from ~1700 s to ~5000 s, ~7300 s to ~10,700 s, ~13,100 s to ~16,500 s, ~18,650 s to ~22,240 s, and ~35,800 s to ~83,700 s. However, the contours of the light curve can still be inferred. The XRT light curve of GRB 170714A is unusual, two plateaus and one following bump being dominant.

Three smooth broken power-law functions are used to fit the data from ~400 s to ~83,786 s. The first plateau decays as a power law with the temporal index $\alpha_1 \sim 0.02$ and $\beta_1 \sim 20.83$ until the steep decay at $t_{b,1} \sim 1473$ s and lasts ~1700 s. The temporal indexes of the second plateau are $\alpha_2 \sim 0.11$ and $\beta_2 \sim 80.15$, respectively, and the break time is about $t_{b,2} \sim 17,223$ s. This plateau is obviously superimposed with some flares. Interestingly, the end of the second plateau has a deep dip, which implies that a giant bump is following. There still exist several flares. The values of α_3 and β_3 are about
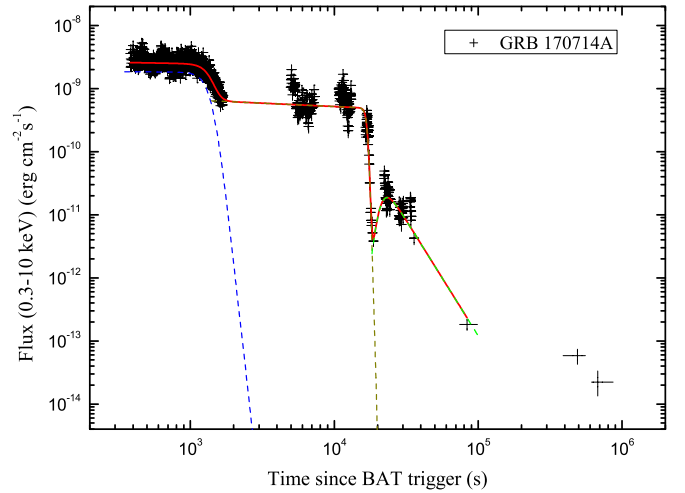

Figure 1. XRT (black) light curve of GRB 170714A. Three smooth broken power-law functions are used to fit the data from ~400 s to ~83,786 s. The solid line and the dashed line represent the total and each component fitting line. The parameters of these three parts (α, β, t_b) are (0.02, 20.83, 1473 s), (0.11, 80.15, 17,223 s), and (-23.25, 3.66, 20,288 s), respectively.

-23.25 and 3.66; the peak time is ~20,288 s. All the fitting results are reported in Table 1, including α, β, the X-ray flux F_0, the break time t_b, and the isotropic luminosity L_b of the three components. We can roughly estimate the energy of the three components as being about 3×10^{51} erg, 10^{52} erg, and 10^{51} erg, respectively.

3. The Model

Generally, a compact binary merger can release a large amount of energy to power the prompt emission of SGRBs. After merger, a new compact star is born, and can be either a massive magnetar, a QS, or a BH. For GRB 170714A, we assume that a two-NS merger occurs in the center, then a QS forms with mass of about $3\,M_\odot$. The massive and highly rotating QS may be in the liquid phase owing to the extreme conditions in the merger process. This phase is unstable. After an initial cooling stage due to neutrino and photon emission, the phase of matter inside the new QS will quickly change to the solid state. This process will be accompanied by an energetic release. As with a magnetar, the solidified QS can release its rotational energy via strong magnetic dipole radiation. When the QS spins down and the self-gravity cannot oppose, it will collapse into a BH.

According to the solid QS model, the depth of the potential U_0 usually takes 100 MeV (Dai et al. 2011) and the ratio of melting heat to the potential f is between 0.01 and 0.1. Then the released energy per baryon during the phase transition can be estimated as

$$E \sim fU_0 \approx 1 - 10\,\text{MeV}. \qquad (1)$$

Here the mass of a QS is assumed to be $3\,M_\odot$ ($\sim 6 \times 10^{33}$ g), then the number of baryons n is about 3×10^{57}. During the phase transition process, the total energy released by the QS, E_1, is roughly estimated as

$$E_1 = nE \sim nfU_0 \approx 5 \times 10^{51} - 5 \times 10^{52}\,\text{erg}. \qquad (2)$$

E_1 is in the magnitude of the energy required by the shallow decay phase of a GRB. Here we assume the blackbody

Table 1
Fitting Results of the X-ray Light Curves of GRB 170714A

	α	β	F_0 (erg cm^{-2} s^{-1})	t_b (s)	L_b (erg s^{-1})
1st plateau	0.02 ± 0.05	20.83 ± 1.85	$(1.81 \pm 0.09) \times 10^{-9}$	1473 ± 15	$(5.47 \pm 0.27) \times 10^{48}$
2nd plateau	0.11 ± 0.05	80.15 ± 5.16	$(4.91 \pm 0.21) \times 10^{-10}$	$17,223 \pm 37$	$(1.48 \pm 0.06) \times 10^{48}$
Bump	-23.25 ± 3.68	3.66 ± 0.22	$(4.14 \pm 0.32) \times 10^{-11}$	$20,288 \pm 343$	$(1.25 \pm 0.10) \times 10^{47}$

radiation luminosity L_1, which can be represented as

$$L_1 = \sigma T^4 4\pi R^2, \tag{3}$$

where σ is the Stefan–Boltzman constant, R is the radius of the newborn QS, and T is the temperature of the blackbody radiation. The radiation timescale t_1 can be express as E_1/L_1. If the temperature kT is 1 MeV, the timescale would be around thousands of seconds, which agrees well with the typical X-ray plateau of GRBs. More importantly, the luminosity L_1 can be roughly considered as a constant because the temperature remains almost unchanged. So the corresponding light curve would appear as a plateau. Of course, there must exist an efficiency from L_1 to the isotropic luminosity of the plateau. It should be emphasized that the released energy in the initial cooling stage and the phase transition process will be injected into the GRB jet and power the nonthermal radiation.

The spin-down of the magnetar is widely used to explain the plateaus in both LGRBs and SGRBs. We consider that the nature of the newborn QS is similar to that of the magnetar. Then the characteristic spin-down luminosity of QS, L_2, can be expressed as (e.g., Zhang & Mészáros 2001; Lü & Zhang 2014)

$$L_2 \approx 10^{49} B_{p,15}^2 P_{0,-3}^{-4} R_6^6 \text{ erg s}^{-1}, \tag{4}$$

and the characteristic spin-down timescale τ of the QS can be written as

$$\tau \approx 2 \times 10^4 I_{46} B_{p,15}^{-2} P_{0,-3}^2 R_6^{-6} \text{ s}, \tag{5}$$

where I_{46} is the dimensionless moment of inertia of a QS ($I \sim 10^{46} \text{ g cm}^2$ for massive QSs; see, e.g., Li et al. 2016, 2017), $B_{p,15}$ is the dimensionless magnetic field strength, $P_{0,-3}$ is the dimensionless initial period, and R_6 is the dimensionless QS radius. If the isotropic luminosity of a plateau is $L_{b,2}$, we obtain $L_{b,2} = \xi L_2$, where ξ is a coefficient by considering the radiation efficiency and the beaming factor in the range 0–1.

A massive QS should finally collapse into a BH if the centrifugal force fails to overcome gravity. Since the ejecta emerged from the merger events falls back, a BH hyperaccretion system forms.

Wu et al. (2013) proposed that a BH fall-back accretion with the BZ mechanism powering a jet can explain the giant X-ray bump of GRB 121027A in the collapsar scenario for LGRBs. Hou et al. (2014a) analyzed the variability of the giant X-ray bump in GRB 121027A and suggested that a jet precession in the BH hyperaccretion framework can explain this. Recently, similarly motivated, Chen et al. (2017) found that a small X-ray bump follows the plateau in GRB 070110, which can be interpreted as caused by a fall-back accretion onto a BH collapsing from a spin-down magnetar. They considered that the bump can be regarded as evidence of the magnetar powering the internal plateau.

We consider that the BZ mechanism dominates in this accretion process. The BZ luminosity L_{BZ} can be written as

(e.g., Lee et al. 2000a, 2000b; Liu et al. 2018)

$$L_{BZ} = f(a_*) c R_g^2 \frac{B_{in}^2}{8\pi}, \tag{6}$$

where a_* is the dimensionless BH spin parameter, $f(a_*)$ is a factor depending on the specific configuration of the magnetic field, $R_g = GM_{BH}/c^2$ is the Schwarzschild radius, M_{BH} is the BH mass, and B_{in} is the poloidal magnetic field strength near the BH horizon. If the isotropic luminosity of the bump is $L_{b,3}$, then $L_{b,3} = \zeta L_{BZ}$. The coefficient ζ also includes the radiation efficiency and the beaming factor in the range 0–1.

Furthermore, according to the balance between ram pressure of the innermost part of the disk P_{in} and the magnetic pressure on the BH horizon (e.g., Liu et al. 2017a, 2018), one has

$$\frac{B_{in}^2}{8\pi} = P_{in} \sim \rho_{in} c^2 \sim \frac{\dot{M}_{in} c}{4\pi R_H^2}, \tag{7}$$

where $R_H = (1 + \sqrt{1 - a_*^2}) R_g$ is the radius of the BH horizon, and $\dot{M}_{in}$ and ρ_{in} are the net accretion rate and density at the inner boundary of the disk, respectively. We can estimate the accreted mass, i.e., the lower limit of the mass of the ejecta from mergers, based on the above equation.

We consider that the gamma- and X-ray features of GRB 170714A can be well explained in the following scenario.

(a) *Prompt emission.* At the beginning, after the merger event of two NSs, the newborn QS should undergo the initial cooling stage. If we reasonably assume that the initial temperature (kT) is about 30–50 MeV, and only 10% energy has been injected into the fireball released by the photons, the gamma-ray energy of GRB 170714A is satisfied as to the cooling mechanism. The smooth cooling process just corresponds to the continuous weak gamma-ray emission.

(b) *First plateau.* The phase transition provides the energy to interpret the first X-ray plateau from ∼400 s to ∼1700 s. At this stage, the energy conversion efficiency is set as 0.1, then the energy of the first plateau is within the range of energy released by the phase transition. We assume that t_1 roughly equals $t_{b,1}/(1 + z)$ and R is taken to be 10 km; then the blackbody temperature can be estimated as $kT \sim 4$ MeV, which is within reasonable limits (e.g., Yuan et al. 2017).

(c) *Second plateau.* For the plateau from ∼1700 s to ∼13,000 s, when the coefficient ξ takes the value 0.1 and the characteristic spin-down timescale $\tau \sim t_{b,2}/(1 + z)$, the initial period P and the magnetic field strength B can be inferred to be ∼1.2 ms and ∼1.6 × 10^{15} G by Equations (4) and (5) which are all in the reasonable value range of massive newborn QSs (e.g., Li et al. 2016).

(d) *Bump.* For the bump from ∼19,000 s to ∼80,000 s, we can estimate B_{in} by Equation (6). If ζ, a_*, and $f(a_*)$ take values of 0.1, 0.9, and 1 (e.g., Liu et al. 2015), and from

observations L_{BZ} is about 1.25×10^{48} erg s^{-1}, then we obtain B_{in} to be about 3×10^{13} G, which accords with the QS spin-down process. Form Equation (7), we derive an accretion mass of $\sim 0.15\,M_{\odot}$, which is lower than the ejecta mass resulting from NS–NS merger simulations (e.g., Dietrich et al. 2015).

4. Summary

We have studied the X-ray features of GRB 170714A and discussed their possible origins. There are two plateaus and a bump superimposed on the X-ray afterglow, which is quite different from the normal X-ray afterglow. We proposed that the fast cooling stage of a newborn QS after merger corresponds to prompt emission, and the phase transition of a QS, spin-down of a QS, and BH fall-back hyperaccretion can be used to explain the three X-ray components in turn. We tested that this theoretical framework is reasonable and self-consistent. Then we considered that the X-ray multi-plateau phase of GRBs might be evidence of the existence of QSs.

As with a magnetar, if a QS exists in the center of a GRB, it will collapse into a BH or remain a stable magnetar after spin-down (e.g., Bartos et al. 2013; Lü & Zhang 2014; Lü et al. 2015; Chen et al. 2017). For GRB 170714A, the massive QS, $\sim 3\,M_{\odot}$, may indeed collapse into a BH; then the BH hyperaccretion process powers an X-ray bump.

It is generally believed that the mass of the ejecta from NS–NS mergers is larger than that from QS–QS mergers, so considering that parts of the ejecta are required in the BH fall-back accretion process to effectively reignite the central engine and provide the energy of the bump, we believe that an NS–NS merger might be the progenitor of GRB 170714A. Besides, other parts of the ejecta may power other potential electromagnetic counterparts like kilonovae (or mergernovae, see e.g., Li & Paczyński 1998; Metzger et al. 2010; Yu et al. 2013; Metzger 2017; Song et al. 2017), so the NS–NS merger is favorable for GRB 170714A.

Considering the requirements of the phase transition and the ejecta from mergers, the total mass of the progenitor of GRB 170714A may be greater than $3\,M_{\odot}$, which implies that similar events are definitely rare. Nonetheless, more samples of X-ray light curves of GRBs like GRB 170714A are expected to reveal the secret of these issues, especially with synergy observations of gravitational wave (GW) detectors, to constrain the EoS of NSs or QSs.

Liu et al. (2017b) compared GWs from the BH hyperaccretion processes and millisecond magnetar models as candidates for the GRB central engines. If we combine multi-band electromagnetic signals, we might shed light on the hidden GRB central engine. For high-energy explosions like GRB 170714A, we can expect that merging binary compact stars and collapsing QSs will produce GWs and X-ray multi-plateaus, which will be observed by either advanced GW detectors (e.g., LIGO and VIRGO) or X-ray/optical telescopes, thereby further verifying our model.

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