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The plateau of gamma-ray burst: hint for the solidification of quark matter?

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The origin of the shallow decay segment in γ-ray bursts' (GRB) early light curves remains a mystery, especially those cases with a long-lived plateau followed by an abrupt falloff. In this paper, we propose to understand the origins of the long-lived plateau by considering the solidification of newborn quark stars with latent heat released as energy injection to the GRB afterglow, and we suggest that an abrupt falloff would naturally appear after the plateau due to the energy injection cutoff. We estimated the total latent heat released during the phase transition of quark stars from liquid to solid states to be on the order of $\sim 10^{51}$ ergs, which is comparable to the emission energy in the shallow decay segment. We also estimated the time scale of radiating the latent heat through thermal photon emission, and found that the time scale agrees with the observations. Based on our estimation, we analyzed the process of energy injection to GRB afterglow. We will show that the steady latent heat of quark star phase transition will continuously inject into the GRB afterglow in a form similar to that of a Poynting-flux-dominated outflow and naturally produce the shallow decay phase and the abrupt falloff after the plateau. We conclude that the latent heat of quark star phase transition is an important contribution to the shallow decay radiation in some GRB afterglows, and explains the long-lived plateau followed by an abrupt falloff, if pulsar-like stars are really (solid) quark stars.

γ-rays: bursts, X-rays, neutron stars, elementary particles

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1 Introduction

NASA's broadband (gamma-ray, X-ray, UV & optical) Swift satellite's [1] successful launch and operation opened a brand new era in the observation of the gamma-ray burst (GRB) phenomenon and has revolutionized our understanding of GRBs in many aspects [2,3]. The prompt slewing capability of Swift allows us to swiftly catch those very early signals following the GRB prompt emission, and the precise localizations make it possible for ground-based follow up observations of most bursts. A large number of well-sampled X-ray light curves from tens of seconds to days past the GRB triggers [4,5] have been accumulated through Swift's observations, which provide us a good chance to investigate early afterglows and study the GRB systematically.

A canonical light curve of X-ray afterglows as revealed by Swift [6–8] is composed of five parts: a prompt gamma-ray phase with a tail, a shallow decay phase, a normal decay phase, a jetlike decay phase, and erratic X-ray flares. The physical origins of these segments have been widely discussed in refs. [5–7,9]. In this paper, we mainly focus on the shallow decay phase and the subsequent phase. On the one hand, the physical origin of the shallow decay phase is still a mystery. Different models, such as the energy injection models [6,7,10,11], a combination of the GRB tail with delayed onset of the afterglow emission [12], off-beam jets [13,14], precursor activity [15], two-component jets [16,17], two-component emission model [18], varying microphysical parameters [15,16,19–21] and so on, are hard to differentiate among each other from the X-ray observations [3]. On the other hand, some puzzling facts related to the shallow decay phase are revealed by Swift's observations, which can not be explained by the current models. The two interesting facts are that the break between the shallow and the normal decay seg-

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ments in the X-ray light curve for some GRBs is chromatic [19,20] and that the light curve of GRBs like GRB 070110 shows a long-lived plateau followed by an abrupt falloff (the decay slope is about −9, with time zero at the trigger) [5]. The former fact suggests that the optical and X-ray emission in the shallow decay phase may not be the same component, and the latter fact indicates an internal origin of the X-ray plateaus and continuous operation of a long-term central engine. Systematic analysis of the Swift X-Ray Telescope data suggests that the physical origins of the shallow decay phase are diverse [5] and we expect to get more information from it, including the physics of dense materials and possible gravitational waves [22].

We note that the GRB central engines may relate to the physics of cold matter at supra-nuclear densities, which is now one of the daunting challenges in particle physics. Cold quark matter is conjectured to be in a solid state at the realistic baryon densities of compact stars [23], we are then considering the latent heat of quark star phase transition from liquid to solid as energy injection to the GRB afterglow in order to understand the features of plateaus followed by an abrupt falloff in some GRB's light curves. Quark stars, as a possible nature of pulsars, are likely to form in GRBs, no matter in the process of high-mass star collapses or merge of binary neutron stars. In the solid quark star model, which is successfully used to understand a variety of pulsars' observational features [24], it is likely that as the temperature of a quark star drops after a GRB, a phase transition from liquid to solid will occur [25]. Since a quark star in phase transition would emit energy with constant temperature and a solid quark star would cool very fast due to its low heat capacity [26], the latent heat of this quark star phase transition not only provides a long-term steady central engine, but also shows an abrupt cutoff of energy injection when the phase transition ends, which would then lead to the falloff in the light curve after the plateau. In this paper, we show that not only the energy released during the phase transition and the time scale of radiating latent heat agree with the observations, but the process of energy injection to the GRB afterglow is also reasonable. Thus the latent heat of quark star phase transition as energy injection to the GRB afterglow would be a prospective model to understand the physical origins of the shallow decay phase of the GRB light curve, especially for the feature of abrupt falloff after the plateau.

In sect. 2, we estimate the latent heat of the quark star phase transition in the solid quark star model. Sect. 3 discusses the process of energy injection. We summarize the conclusions in sect. 4.

2 Latent heat of quark star phase transition

To estimate the latent heat of the quark star phase transition from liquid to solid, we need to know the state of cold quark matter and the interaction between quarks. However, due to the non-perturbative effects of the strong interactions between quarks at a low energy scale and the many-body problem of vast assemblies of interacting particles, we can not describe the state of cold quark matter from first principles up to now. Yet, it is phenomenologically conjectured that astrophysical cold quark matter could be in a solid state, and a variety of observational features, which may challenge us in the hadron star model, can be naturally understood in the solid quark star model [24]. Recent results from relativistic heavy ion collision experiments also show that the interaction between quarks is very strong in hot quark-gluon plasma [27]. Then it is reasonable to conjecture that the interaction between quarks should be stronger in cold quark matter. The strong interaction may then make quarks group in clusters, and if the residual interaction between quark clusters is stronger than their kinetic energy, each quark cluster could be trapped in the potential well and cold quark matter will be in a solid state [23].

Considering that a single quark cluster inside a quark star is assumed to be colorless, just like each molecule in a bulk of inert gas is electrically neutral, Lai and Xu [28] in their recent work used the Lennard-Jones potential to describe the interaction between quark clusters in quark stars and got the equation of state of quark stars. The interaction is expressed as

$$u(r) = 4U_0\left[\left(\frac{r_0}{r}\right)^{12} - \left(\frac{r_0}{r}\right)^{6}\right], \tag{1}$$

where U_0 is the depth of the potential and r_0 can be considered as the range of interaction.

Based on this solid quark star model, we can then estimate the latent heat of quark star phase transition from liquid to solid. Rather than performing difficult molecular dynamics simulations of crystallization, we would prefer estimating the latent heat in order of magnitude by analogy with inert gas and common substances, since the quark clusters are non-relativistic and the interaction is similar to common substances. In Table 1 below, we list the melting heat, heat of vaporization, potential and ratio of melting heat to potential of inert gas and some common substances. The melting heat corresponds to the latent heat, and for substances with known heat of sublimation, we equal the potential to heat of sublimation, otherwise we equal the potential to the sum of melting heat and heat of vaporization.

From the data, we can see that for most substances the ratio of melting heat to potential is between 0.1 and 0.01. Considering that the interaction between quark clusters is similar to an inert gas and is relatively strong, we chose the ratio of potential to melting heat to be $f \approx 0.1 - 0.01$ for estimation. Then based on the solid quark star model proposed by Lai, choosing $U_0 = 100$ MeV [29], we can estimate the energy released by each quark cluster in the liquid to solid phase transition as

$$E_{\rm cluster} \sim fU_0 \approx 1 - 10\ {\rm MeV}. \tag{2}$$

For a quark star of one solar mass, $M_\odot \approx 2 \times 10^{33}$ g, the number of baryon is $n = 10^{57}$, then the total energy released

Table 1 The melting heat, heat of vaporization, potential and ratio of melting heat to potential of inert gas and some common substances [28]

	Melting heat (kcal/mol)	Heat of vaporization (kcal/mol)	Potential (kcal/mol)	Melting heat/potential
He	0.0033	0.0194	2.2944	0.0014
Ne	0.0801	0.422	9.1776	0.0087
Xe	0.5495	3.02	12.6192	0.0436
Rn	0.69	4.01	19.5024	0.0354
Al	2.56	69.5	78	0.0328
Cs	0.499	16.198	18.3	0.0272
Cu	3.17	72.74	81	0.0391
Fe	3.63	83.68	99.5	0.0365
Hg	0.5486	14.13	14.65	0.0375
Na	0.622	23.285	25.75	0.0242
Si	12	85.8	107.7	0.1114
C	25		171.29	0.1460
CO	0.2	1.444	1.644	0.1217
CO_2	1.99		6.03	0.3300
H_2O	1.436	9.717	11.153	0.1287
H_2O_2	2.987	10.53	12.34	0.2421
$CaCl_2$	6.8	56.2	77.5	0.0877

during the phase transition can be estimated as

$$E = E_{\rm cluster}n \approx 10^{51} - 10^{52}\ \text{ergs}. \tag{3}$$

This order of magnitude agrees with the typical energy released in the shallow decay phase of a GRB; that is to say, the latent heat of quark star phase transition from liquid to solid is sufficient to produce the plateau.

On the other hand, according to the Lindemann law that a solid melts when the root-mean-square amplitude of atomic vibrations exceeds a certain fraction of the equilibrium nearest-neighbor distance, we can estimate the temperature of the quark star phase transition and furthermore the time scale of radiating latent heat. In Mohazzabi and Behroozi's work in 1987, they obtained the expression for the ratio of the root-mean-square amplitude of atomic vibrations to the equilibrium nearest neighbor distance for an inert gas, and found the Lindemann law to be very consistent with experiments [30]. As for our estimation, we consulted the ratio of potential to heat, $\Gamma = U_0/kT$, for common substances, and then got the temperature of the quark star phase transition by analogy. For one-component plasma, $\Gamma \approx 175$ [31], for multi-component plasma, $\Gamma \approx 233$ [32]. So choosing $\Gamma \approx 200$, $U_0 = 100$ MeV, the temperature of the quark star phase transition is around 0.5 MeV.

During the liquid to solid phase transition, the temperature of a quark star would remain constant, and the latent heat would be released through thermal emission. Then the time scale of radiation can be estimated as

$$t = \frac{E}{\sigma T^4 4\pi R^2}, \tag{4}$$

where $E = 10^{51}$ ergs, σ is the Stefan-Boltzman constant, $R = 10$ km is the radius of quark star, and $T \approx 0.5$ MeV. We find that the time scale of radiation is $t \approx 1000$ s, which agrees with observations of the GRB afterglow plateau.

In Figure 1, a schematic cooling curve of a quark star is presented, which consists of three stages. The first stage is an initial fast cooling stage possibly due to the emission of neutrinos and photons at the very beginning of a quark star, when its initial temperature T_0 could be much higher than 10 MeV. When the temperature of a quark star drops to the melting point T_p, it could come to the second stage, the liquid to solid phase transition, which lasts from t_i to t_f. At this stage, the temperature of a quark star would remain constant and the latent heat would be released steadily which could provide a long-lived steady central engine. After the phase transition, the newly-born solid quark star would rapidly release its residual inner energy due to its low heat capacity, thus a steep falloff appears in the cooling curve corresponding to the abrupt falloff after the shallow decay segment.

According to our estimations above, we can briefly explain the scenario. Under the external shock wave model, we have a simple normal decay light curve. But if a phase transition

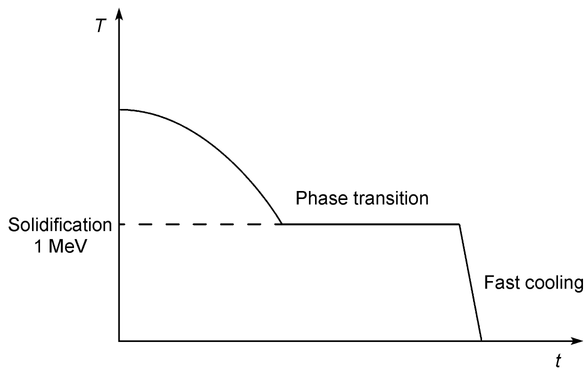

Figure 1 A schematic cooling behavior of a new-born quark star. Three stages are shown: an initial cooling stage due to the emission of neutrinos and photons at the very beginning of a quark star with initial temperature T_0, a liquid to solid phase transition stage from time t_i to t_f with constant temperature T_p, and, after solidification, a fast cooling stage because of solid quark star's low heat capacity. We focus on the duration from t_i to t_f in this paper.

of a quark star occurred, latent heat would be steadily injected to the afterglow, and a long-lived plateau would appear. After solidification, since the heat capacity of solid quark stars is very low [26], the central quark star would cool rapidly. The residual inner energy would be released almost immediately. Thus an abrupt cutoff of energy injection to the afterglow would appear. This would naturally result in a falloff of the light curve from the plateau to the normal decay predicted by the external shock wave model.

3 The standard fireball revisited?

In the standard GRB fireball model, it is assumed that a large amount of energy is instantly released through some explosive process. The energy drives some material to expand with an ultra-relativistic speed, which requires that the *fireball* outflow is low-baryon-loaded so that the total rest mass of the fireball is sufficiently small. The standard fireball is assumed to be highly non-uniform and in the extreme case is composed of many distinct shells. Collisions of different shells produce internal shock waves, which are thought to be responsible for the observed prompt emissions. Collisions of shells with the surrounding intermediate stellar material produce external shock waves, which are thought to be responsible for the observed GRB afterglow emissions. For the afterglow flares, they are usually thought to be produced by later injections of energy through internal shocks.

After having estimated the energy released by quark star phase transitions and the time scale of radiation, it is necessary for us to qualitatively discuss the process of energy injection to the GRB afterglow. Generally speaking, the energy injection into the afterglow could consist of some kinetic-energy (i.e., baryons) dominated shells or a Poynting-flux-dominated wind [33, 34]. In the case of afterglow, we always consider an impulsive shell that is already heated during the shell-ISM interaction and that is collecting material from the ISM, and in the meantime also receives a large enough injection of energy from a continuous Poynting-flux-dominated wind or a kinetic-energy dominated shell. As discussed in refs. [35,36], for the Poynting-flux-dominated wind case in which pure energy with negligible baryon loading is injected into the fireball, no reverse shock is expected, and the injection signature is produced only by the forward shock emission. For the kinetic-energy-dominated matter-shells case, depending on whether the collision between the injected and the impulsive shell is mild or violent, the injection process is quite different. If the relative velocity between the colliding shells does not exceed a critical value defined by their energy ratio, the collision is mild, and the injection may be analogous to the Poynting-flux injection case. Otherwise, the injection is violent, and an additional pair of strong shocks will form at the discontinuity between two colliding shells which will greatly influence the injection signature.

As for our energy injection model, the latent heat released during the quark star phase transition would produce a radiation-dominated fireball, whose luminosity is about $L \approx 10^{48}$ ergs/s according to our estimates. The optical depth can then be estimated as

$$\tau_{\gamma\gamma} = \frac{f_p \sigma_T F D^2}{R^2 m_e c^2}$$

$$= 10^{13} f_p \left(\frac{D}{3000\ \mathrm{Mpc}}\right)^2 \left(\frac{F}{10^{-11}\ \mathrm{ergs/cm^2}}\right) \left(\frac{R}{10\ \mathrm{km}}\right)^{-2}, \quad (5)$$

where, $R = 10$ km is the radius of a quark star. The optical depth is very large, so the energy flux from the central quark star would form a pure radiation fireball consisting of radiation and electron-positron pairs, which is similar to the fireballs of prompt emissions, but is continuous instead. We expect that this pure radiation fireball would expand and finally inject energy to the afterglow in the form of Poynting flux. If we consider possible baryons in the space swept by the fireball, we can estimate the velocity the matter shell could reach, assuming that all of the energy is converted to the kinetic energy of the baryons. Since in this late injection phase the baryon loading could be in principle much lower, we assume that the density of baryons is 10% of the original density in space. Then we can estimate that:

$$\gamma = E/Mc^2. \quad (6)$$

For $E \approx 10^{51}$ ergs, we get $\gamma \approx 100$. According to Zhang and Mészáros' work in 2002 [36], for such kinetic-energy-dominated matter-shells with $\gamma \approx 100$ and $L \approx 10^{48}$ ergs/s, the collision between the injected and the impulsive shell is mild, and the injection may be analogous to the Poynting-flux injection case.

4 Conclusions

A possible physical origin of the long-lived plateau of some GRB light curves is proposed in the solid quark star model. We suggest that quark stars may be born in GRB, and as the temperature of the quark star drops, a phase transition from liquid to solid may occur in the quark star. The latent heat of the phase transition would provide a long-lived steady energy injection to the GRB afterglow, since the temperature of the central star would remain constant during the phase transition. When the phase transition ends, an abrupt falloff after the plateau in the light curve would naturally appear which is hard to understand by other central engine models.

We estimate the latent heat of the quark star phase transition from liquid to solid based on the solid quark star model whose interaction between quark clusters is described by the Lennard-Jones potential. The energy of $\sim 10^{51}$ ergs and the radiation time scale of $\sim 10^3$ s agree with observations of the shallow decay phase. We also qualitatively discuss the process of energy injection into the afterglow, and show that the energy injection in the phase transition would be in a form similar to that of the Poynting-flux-dominated outflow. Both the estimation and the injection process suggest that the idea of considering the latent heat of the quark star phase transition as energy injection into the GRB afterglow is rational.

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1 Gehrels N, Chincarini G, Giommi P, et al. The Swift gamma-ray burst mission. Astrophys J, 2004, 611: 1005–1020
2 Mészáros P. Gamma-ray bursts. Rep Prog Phys, 2006, 69(8): 2259–2321
3 Zhang B. Gamma-ray bursts in the Swift era. Chin J Astron Astrophys, 2007, 7(1): 1–50
4 Burrows D N. The Swift X-ray telescope. Proc SPIE, 2004, 5165: 201–216
5 Liang E W, Zhang B B, Zhang B. A comprehensive analysis of Swift XRT data. II. Diverse physical origins of the shallow decay segment. Astrophys J, 2007, 670(1): 565–583
6 Zhang B, Fan Y Z, Dyks J, et al. Physical processes shaping gamma-ray burst X-ray afterglow light curves: Theoretical implications from the Swift X-ray telescope observations. Astrophys J, 2006, 642(1): 354–370
7 Nousek J A, Kouveliotou C, Grupe D, et al. Evidence for a canonical gamma-ray burst afterglow light curve in the Swift XRT data. Astrophys J, 2006, 642(1): 389–400
8 O'Brien P T, Willingale R, Osborne J, et al. The early X-ray emission from GRBs. Astrophys J, 2006, 647(2): 1213–1237
9 Dai Z G, Wang X Y, Wu X F, et al. X-ray flares from postmerger millisecond pulsars. Science, 2006, 311(5764): 1127–1129
10 Dai Z G, Lu T. Gamma-ray burst afterglows and evolution of postburst fireballs with energy injection from strongly magnetic millisecond pulsars. Astron Astrophys, 1998, 333: 87–90
11 Panaitescu A, Mészáros P, Gehrels N, et al. Analysis of the X-ray emission of nine Swift afterglows. Mon Not Roy Astron Soc, 2006, 366(4): 1357–1366
12 Kobayashi S, Zhang B. The onset of gamma-ray burst afterglow. Astrophys J, 2007, 655(2): 973–979
13 Toma K, Ioka K, Yamazaki R, et al. Shallow decay of early X-ray afterglows from inhomogeneous gamma-ray burst jets. Astrophys J, 2006, 640(2): 139–142
14 Eichler D, Granot J. The case for anisotropic afterglow efficiency within gamma-ray burst jets. Astrophys J, 2006, 641:(1): 5–8
15 Ioka K, Toma K, Yamazaki R, et al. Efficiency crisis of swift gamma-ray bursts with shallow X-ray afterglows: prior activity or time-dependent microphysics? Astron Astrophys, 2006, 458(1): 7–12
16 Granot J, Königl A, Piran T. Implications of the early X-ray afterglow light curves of Swift gamma-ray bursts. Mon Not Roy Astron Soc, 2006, 370(4): 1946–1960
17 Jin Z P, Yan T, Fan Y Z, et al. A two-component jet model for the X-ray afterglow flat segment in the short gamma-ray burst GRB 051221A. Astrophys J, 2007, 656(2): 57–60
18 Yamazaki R. Prior emission model for X-ray plateau phase of gamma-ray burst afterglows. Astrophys J, 2009, 690(2): 118–121
19 Panaitescu A, Mészáros P, Burrows, D, et al. Evidence for chromatic X-ray light-curve breaks in Swift gamma-ray burst afterglows and their theoretical implications. Mon Not Roy Astron Soc, 2006, 369(4): 2059–2064
20 Fan Y, Piran T. Gamma-ray burst efficiency and possible physical processes shaping the early afterglow. Mon Not Roy Astron Soc, 2006, 369(1): 197–206
21 Wei D M, Fan Y Z. The synchrotron-self-compton radiation accompanying shallow decaying X-ray afterglow: The case of GRB 940217. Chin J Astron Astrophys, 2007, 7: 509–515
22 Corsi A, Mészáros P. Gamma-ray burst afterglow plateaus and gravitational waves: Multi-messenger signature of a millisecond magnetar? Astrophys J, 2009, 702(2): 1171–1178
23 Xu R X. Can cold quark matter BE solid? Int J Mod Phys D, 2010, 19(08-10): 1437–1446
24 Xu R X. Solid quark stars? Astrophys J, 2003, 596(1): 59–62
25 Xu R X, Liang E W. X-ray flares of -ray bursts: Quakes of solid quark stars? Sci China Ser G-Phys Mech Astron, 2009, 52(2): 315–320
26 Yu M, Xu R X. Toward an understanding of thermal X-ray emission of pulsars. Astrophysics, 2010, 34(6): 493–502
27 Shuryak E V. Physics of strongly coupled quark-gluon plasma. Prog Part Nucl Phys, 2009, 62: 48–101
28 Lai X Y, Xu R X. Lennard-Jones quark matter and massive quark stars. Mon Not Roy Astron Soc, 2009, 398: 31–35
29 Mohazzabi P, Behroozi F. The Lindemann law of melting for rare gas solids. J Mater Sci Lett, 1987, 6: 404–406
30 DeWitt H, Slattery W, Baiko D, et al. Harmonic lattice theory of coulomb solids and comparison with monte carlo simulations. Contrib Plasma Phys, 2001, 41: 251–254
31 Horowitz C J, Berry D K, Brown E F. Phase separation in the crust of accreting neutron stars. Phys Rev E, 2007, 75: 066101
32 Usov V V. On the nature of nonthermal radiation from cosmological gamma-ray bursters. Mon Not Roy Astron Soc, 1994, 267: 1035–1038
33 Mészáros P, Rees M J. Poynting jets from black holes and cosmological gamma-ray bursts. Astrophys J, 1997, 482: L29–L32
34 Zhang B, Mészáros P. Gamma-ray burst Afterglow with continuous energy injection: signature of a highly magnetized millisecond pulsar. Astrophys J, 2001, 552(1): 35–38
35 Zhang B, Mészáros P. Gamma-ray bursts with continuous energy injection and their afterglow signature. Astrophys J, 2002, 566(2): 712–722
36 Dean J A. Lange's Handbook of Chemistry. New York: McGraw-Hill; Beijing: World Pub Corp, 1999