

X-ray flares of γ -ray bursts: Quakes of solid quark stars?

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A star-quake model is proposed to understand X-ray flares of both long and short γ -ray bursts (GRBs) in a solid quark star regime. Two kinds of central engines for GRBs are available if pulsar-like stars are actually (solid) quark stars, i.e., the SNE-type GRBs and the SGR-type GRBs. It is found that a quark star could be solidified about 10^3 to 10^6 s later after its birth if the critical temperature of phase transition is a few MeV, and then a new source of free energy (i.e., elastic and gravitational ones, rather than rotational or magnetic energy) could be possible to power GRB X-ray flares.

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

Swift, a multi-wavelength γ -ray burst (GRB) mission^[1], has led to great progress in understanding the nature of the GRB phenomenon (see recent reviews by Meszaros^[2] and Zhang^[3]). With its promptly slewing capacity and high sensitivity, it catches the early afterglows and the extended prompt emission in details for the first time. This not only provides an opportunity to examine the conventional models established in the pre-Swift era^[4–8], but also facilitates studies of the transition between the prompt emission and the afterglow^[8–10], and even gives insight into the properties of both the progenitors and the GRB central engines^[5,11].

The GRB survey with CGRO (Compton γ -ray Observatory)/BATSE identified two types of GRBs, long-soft and short-hard GRBs, separated with burst duration of about 2 s^[12]. On one hand, with firmed detections of GRB-supernovae connections for four nearby cases^[13–17], it is now generally accepted that long GRBs are associated with energetic core-collapse supernovae^[18,19] (see a recent review by Woosley et al.^[20]). Interestingly, Li^[21] found that the peak spectral energy of GRBs is correlated with the peak bolometric luminosity of the underlying supernovae (SNe), based on the four pair GRB-SNe connections. The X-ray transient 080109 associated with a normal core-collapse SN 2008D^[22] also complies with this relation^[23]. Signatures of long

GRB-SNe connection may be also derived from a red bump in late optical afterglow lightcurves^[14,24] and a long time lag between the GRB precursor and the main burst observed in some GRBs^[25]. On the other hand, short GRBs coincide with the early-type stellar population with no or little current star formation^[26–31] (see a recent review by Nakar^[32]), favoring mergers of compact object binaries as the progenitors of the short GRBs^[33–36].

Although the progenitors of the long and short GRBs are different, the models for their central engines are similar, and essentially all can be simply classed as a rotating compact object that drives an ultra-relativistic outflow to produce both the prompt γ -rays and afterglows in lower energy bands. These models are highly constrained by the observations of the prompt γ -rays and multi-wavelength afterglows. It is well believed that the prompt γ -rays are produced by the internal shocks, and the burst duration is a measure of the central engine active timescale. In the merger models of compact object

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binaries for the short GRBs, the duration of the bursts is expected to be less than 1 s^[37]. This is challenged by the observations with Swift. One of the remarkable advances made by Swift is the discovery of erratic X-ray flares for both long and short GRBs, happening at very early time or hours even one day after the GRB trigger in the light curves observed with the X-ray telescope^[38–40]. The X-ray flares are a superimposed component of the underlying afterglows, with a feature of rapid rise and fall times ($\delta t \ll t_{\text{peak}}$). Multiple flares are observed in some bursts. They are similar to the pulse of the prompt γ -rays, but the fluence of the flares decrease with time and the durations of the flares at later time become broader than early flares. These properties generally favor the idea that most of them are of internal origin, having nothing to do with external-shock related events^[38,41–43]. This indicates that the central engine should live much longer than the burst duration or it was re-restarted by an un-recovered mechanism. Several models have been proposed, such as magnetic explosions of a millisecond pulsar from NS-NS merger^[44], fragmentation or gravitational instabilities in the massive star envelopes^[45] or in the accretion disk^[46], or magnetic barrier around the accretor^[47].

The facts that X-ray flares are observed for both long and short GRBs motivate us to speculate that the central engines of the two kinds of GRBs are physically similar. We know that an accretor-disk system is hard to sustain a long lived engine for the short GRBs^[37], except a fraction of materials is lunched to a large orbit. However, the fall-back of the materials cannot produce the observed erratic flares^[48]. We therefore propose alternatively that the mechanism should be harbored in the central star (i.e., the engine).

Actually, the essential difficulty of reproducing two kinds of astronomical bursts are challenging today's astrophysicists to find realistic explosive mechanisms. Besides the puzzling center engines of GRBs, it is still a long-standing problem to simulate supernovae successfully in the neutrino-driven explosion model^[49]. Nevertheless, it is shown now that both kinds of explosions could be related to the physics of cold matter at supra-nuclear density, which is unfortunately not well understood because of the uncertainty of non-perturbative QCD (quantum chromo-dynamics). We still do not know the nature of pulsars with certainty even more than 40 years after the discovery, which is also relevant to the

physics of cold dense matter. Nuclear matter (related to neutron stars) is one of the speculations, but quark matter (related to quark stars) is an alternative^[50]. Strange stars are quark stars with strangeness. We will speculate about the physical reasons that make the mechanisms for both long-soft and short-hard GRBs, which are related to the elemental strong interaction, say, the physics of the cold dense matter at supra-nuclear density. In fact GRBs and strange stars are related in previous researches (e.g., the work by Cheng & Dai^[51] and Wang et al.^[52]). In this paper, we suggest that GRB X-ray flares could be the results of quakes of solid quark stars^[53–55] (see, e.g., ref. [56] for a general review about astrophysical quark matter and quark stars).

1 An idea of understanding GRB X-ray flares

Based on different manifestations of pulsar-like stars, a conjecture of solid cold quark matter was addressed a few years ago^[53]. Consequently, a variety of observational features, which may challenge us in the hadron star model, could be naturally understood in the solid quark star model^[56], including the giant flares of soft γ -ray repeaters^[55,57].

What if pulsar-like stars are actually quark stars? One of the direct and important consequences could be the low baryon-loading energetic fireballs formed soon after quark stars, which would finally result in both supernova and GRBs. As addressed by Xu^[58], the *bare* quark surfaces could be essential for successful explosions of both types of core and accretion-induced collapses. The reason is that, because of the strong binding of baryons, the photon luminosity of a quark surface is not limited by the Eddington limit, and it is thus possible that the prompt reverse shock could be revived by photons, rather than by neutrinos. This point was then noted too by Paczynski and Haensel^[59] who proposed that classical long-duration γ -ray bursts could be from the formation of quark stars several minutes after the initial core collapse, emphasizing the surface as a *membrane* allowing only ultrarelativistic non-baryonic matter to escape. Actually, a 1-dimensional (i.e., spherically symmetric) calculation by Chen et al.^[60] showed that the lepton-dominated fireball supported by a bare quark surface do play a significant role in the explosion dynamics under a photon-driven scenario. Recently, the QCD phase

transition for quark matter during the post-bounce evolution of core collapse supernovae was numerically investigated¹⁾, and it is found that the phase transition produces a second shock wave that triggers a delayed supernova explosion. However, what if the expanding of a fireball outside quark surface is not spherically symmetric? An asymmetric explosion may result both in a GRB-like fire jet and in a kick on quark stars, and the statistical result of Cui et al.^[61] indicated that the kick velocity of pulsars could be consistent with an asymmetric explosion of GRBs.

Another consequence of quark star in a solid state is spontaneous quake occurring when elastic energy develops to a critical value there, if cold quark matter is actually in a solid state. A nascent quark star could be in a fluid state since quarks are just de-confined from hadrons, though it is still not sure whether the quarks are clustered in a fluid state initially. Anyway such a quark star should have to be solidified soon due effective cooling through both neutrino and photon, and we may use a toy model to estimate the timescale for a transition from fluid to solid states.

For the sake of simplicity, we may approximate a quark star as a star with homogenous density of $\rho=3\rho_0$ ($\rho_0 \approx 2 \times 10^{14}$ g/cm³ is the nuclear density) and in a radius of R , and its mass is then $M=4\pi R^3 \rho/3=1.3R_6^3 M_\odot$, where $R=R_6 \times 10^6$ cm. The total quark number is 4.5×10^{57} , and the total number of quark clusters could be $N_{qc}=4.5 \times 10^{56} R_6^3$ if the average quark number in clusters is the order of 10. The total thermal energy of a quark star is then

$$Q = \frac{3}{2} k T N_{qc} = 1.1 \times 10^{51} T_1 R_6^3 \text{ ergs}, \quad (1)$$

where the stellar temperature $T(t)=T_1$ MeV is assumed to be constant at certain age t .

In high temperature, neutrino emissivity via pair annihilation ($\gamma + \gamma \leftrightarrow e^\pm \rightarrow \bar{\nu} + \nu$) dominates. As an indication, we just consider this mechanism for neutrino cooling since the ν -emissivity of clustered quark matter is hitherto unknown. The emissivity was presented by Itoh et al.^[62] who used the Weinberg-Salam theory in their calculation, which is

$$\varepsilon_{\text{pair}} = 1.089 [1 + 0.104 q(\lambda)] g(\lambda) e^{-2/\lambda}$$

$$\times f(\lambda) \text{ erg} \cdot \text{s}^{-1} \cdot \text{cm}^{-3}, \quad (2)$$

where $\lambda=T/(5.9302 \times 10^9 \text{ K})$, $\xi=[\rho \mu_e^{-1}/(10^9 \text{ g} \cdot \text{cm}^{-3})]^{1/3} \lambda^{-1}$, and,

$$q(\lambda) = (10.7480 \lambda^2 + 0.3967 \lambda^{0.5} + 1.0050)^{-1.0} \\ \times [1 + (\rho/\mu_e)(7.692 \times 10^7 \lambda^3 + 9.715 \times 10^6 \lambda^{0.5})^{-1.0}]^{-0.3}, \\ g(\lambda) = 1 - 13.04 \lambda^2 + 133.5 \lambda^4 + 1534 \lambda^6 + 918.6 \lambda^8,$$

$$f(\lambda) = \frac{(a_0 + a_1 \xi + a_2 \xi^2) e^{-c\xi}}{\xi^3 + b_1 \lambda^{-1} + b_2 \lambda^{-2} + b_3 \lambda^{-3}},$$

where $a_0=6.002 \times 10^{19}$, $a_1=2.084 \times 10^{20}$, $a_2=1.872 \times 10^{21}$; $b_1=0.9383$, $b_2=-0.4141$, $b_3=0.05829$, $c=5.5924$ for $T < 10^{10}$ K; $b_1=1.2383$, $b_2=-0.8141$, $b_3=0.0$, $c=4.9924$ for $T \geq 10^{10}$ K. According to the calculation²⁾ in the bag model, the ratio of number density of electron to that of quark is $< 10^{-4}$. We thus choose the electron mean molecular weight $\mu_e = 10^5$ for strange quark matter in following calculation.

Assuming the optical depth of neutrinos in proto-quark stars is less than 1, we then have the energy loss rate due to neutrino emission,

$$\dot{Q}_\nu \approx \frac{4}{3} \pi R^3 \varepsilon_{\text{pair}}. \quad (3)$$

Another important cooling mechanism for *bare* quark stars is thermal photon emission from quark surface,

$$\dot{Q}_\gamma \approx 4\pi R^2 \sigma T^4, \quad (4)$$

and the total cooling rate is then,

$$\dot{Q} = \frac{3}{2} k N_{qc} \frac{dT}{dt} = -\dot{Q}_\nu - \dot{Q}_\gamma. \quad (5)$$

A comparison of \dot{Q}_ν and \dot{Q}_γ is shown in Figure 1. It is evident that the neutrino loss dominates at high temperatures, while the photon emissivity dominates at low temperatures. The critical temperature T_{crit} , at which the energy loss rates of neutrinos and photons are equal, depends on stellar radius (or mass). Low mass quark stars have higher T_{crit} .

According to eq. (5), we can also calculate the cooling curves of quark stars in the toy model, which is shown in Figure 2. It was suggested that quark-clusters in cold quark matter could be localized at lattices, breaking then the translational invariance, to form solid quark matter with rigidity^[53], but we are not sure about the critical temperature T_c , at which the solidification phase transition happens because of lacking a reliable

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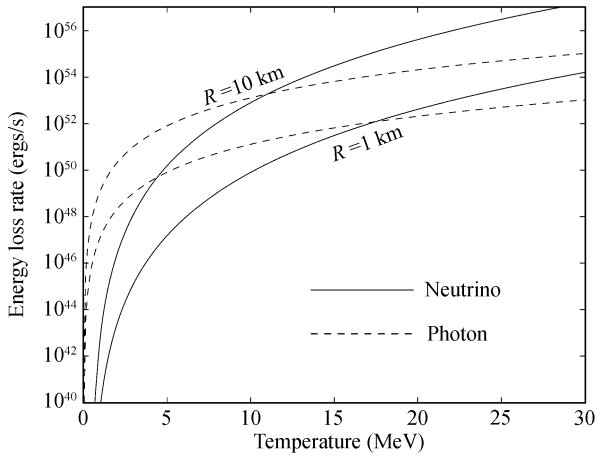


Figure 1 Cooling rates due to neutrino and photon emissivities for quark stars with radii of 10 km (solid lines) and 1 km (dashed lines). It is evident that photon emissivity dominates except at the very beginning of stars with high temperature, and the critical temperature is higher for quark stars with lower masses.

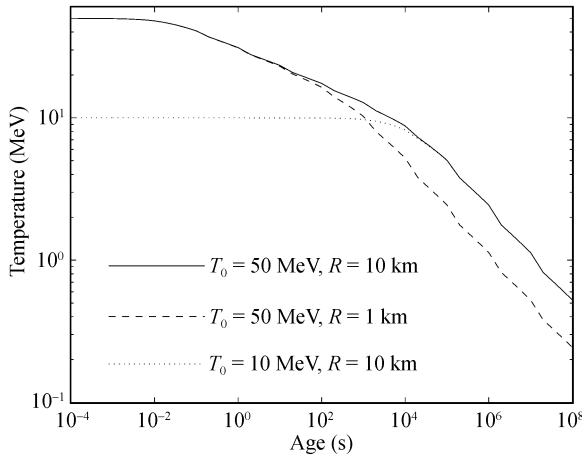


Figure 2 Cooling curves based on eq. (5) for initial temperature $T_0 = 50, 10$ MeV and stellar radii of 10, 1 km. For a star with $T_0 = 10$ MeV and $R = 1$ km, its cooling curve fits the dotted line before age $t \sim 10^2$ s, but fits the dashed line after $t \sim 10^3$ s.

way to calculate with the inclusion of non-perturbative QCD effects. Nevertheless, a quark star could be solidified about 10^3 to 10^6 s later after its birth if the critical temperature is $T_c \sim 1$ to 10 MeV, as is illustrated in Figure 2. That T_c is the order of a few MeV could be reasonable and not surprising since the interacting strength of nuclei, where the non-perturbative QCD effects dominate, is also of this energy scale.

What if quark stars are in a solid state? Star-quake is a natural consequence when strains accumulate to a critical value. Two types of stress force could develop inside solid stars^[63]: the bulk-variable and bulk-invariable forces. Both these forces could result in gravitational and elastic energy releases (to be in a same order), with

an order of

$$E \approx \frac{GM^2}{R} \sim 10^{53} \frac{\Delta R}{R} \text{ ergs} \quad (6)$$

for $M \sim M_\odot$, where ΔR is the radius-change during quakes. An energy release of $\sim 10^{50}$ ergs could be possible if stellar radius changes suddenly ~ 10 m during a quake of a solid quark star with radius of ~ 10 km. The rise time of a burst could be $> \hat{t} \sim \hat{R}/c \sim 1$ ms, where \hat{R} is the scale of a quake-induced fireball in a magnetosphere and could be a few tens of stellar radius. The rise time would be $\gg \hat{t}$ if energy is ejected into fireball by a series of small quakes. The duration would actually depend on detail radiative process in magnetosphere. The star-quark induced energy release process could be similar to the case of corona of magnetars presented theoretically by Beloborodov & Thompson^[64]. Star-twisted oscillation may result in a strong self-induction electric field in magnetosphere, which could initiate avalanches of pair creation and acceleration. The resonant inverse Compton scattering of relativistic electrons off thermal photons could play an essential role to form effectively a fireball in the scenario proposed above.

In the regime of quark star, there could be two kinds of mechanisms for γ -ray bursts. The first one, we call as ‘‘SNE-type’’, is relevant to the birth of quark stars and supernovae. A very clean (i.e., lepton-dominated) fireball forms soon above quark surface. In addition, more energy would be ejected into the fireball when star-quakes occur. The discovery of erratic X-ray flares in long-soft GRBs, happening at very early time or hours even one day after the GRB trigger, is consistent with this picture.

The second one, we call as ‘‘SGR-type’’, is relevant to the later evolution of quark stars, especially in an accretion phase. An accretion-induced star-quake (AIQ) model was suggested to understand the huge energy bursts of soft γ -ray repeaters (SGRs), based on several calculations of the static, spherically symmetric, and interior solution^[57,65,66]. It is found that the energy released during star-quakes could be as high as $\sim 10^{47}$ ergs if the tangential pressure is $\sim 10^{-6}$ higher than the radial one. A big star-quake could power energetic relativistic outflow to produce the observed prompt emission of short-hard GRBs, and this quake may trigger a few smaller and stochastic quakes, which may result in following X-ray flares observed.

2 Conclusions

An idea to understand the X-ray flares of both long and soft γ -ray bursts is proposed in the quark star regime. We suggest an SNE-type GRB scenario when quark stars are born, and an SGR-type GRB scenario if giant quakes occur in solid quark stars during their latter accretion phases. However, stochastic quakes after initial GRBs could be responsible to the X-ray flares of both types of GRBs.

According to a toy model of cooling quark stars, we

find that a quark star could be solidified about 10^3 to 10^6 s later after its birth if the critical transition temperature is ~ 1 to 10 MeV. This means that star-quakes could occur at a time of hours (even one day) after the GRB trigger, and the star-quake induced energy ejection would then results in the observed X-ray flares of SNE-type GRBs.

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