The superflares of soft $\gamma$-ray repeaters: giant quakes in solid quark stars?

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ABSTRACT

Three times of supergiant flares from soft $\gamma$-ray repeaters are observed, with typical released energy of $\sim 10^{44-47}$ erg. A conventional model (i.e., the magnetar model) for such events is catastrophic magnetism-powered instability through magnetohydrodynamic process, in which a significant part of short-hard $\gamma$-ray bursts could also be the results of magnetars. Based on various observational features (e.g., precession, glitch, thermal photon emission) and the underlying theory of strong interaction (quantum chromodynamics, QCD), it could not be ruled out yet that pulsar-like stars might be actually solid quark stars. Strain energy develops during a solid star’s life, and starquakes could occur when stellar stresses reach a critical value, with huge energy released. An alternative model for supergiant flares of soft $\gamma$-ray repeaters is presented, in which energy release during a star quake of solid quark stars is calculated. Numerical results for spherically asymmetric solid stars show that the released gravitational energy during a giant quake could be as high as $10^{48}$ erg if the tangential pressure is slightly higher than the radial one. Difficulties in magnetar models may be overcome if AXPs/SGRs are accreting solid quark stars with mass $\sim (1-2)M_\odot$.

Key words: dense matter — X-rays: bursts — pulsars: general — stars: neutron

1 INTRODUCTION

Pulsar-like stars keep to manifest surprising observational features since their first discovery in 1967. One of their extraordinary behaviors, whose origin and astrophysical implications are hotly debated about, is the superflare from soft $\gamma$-ray repeaters (SGRs). Only three such events have been detected in three of the four SGRs: 1979/03/05 of SGR 0525-66 (spin period $P=8.1$ s), 1998/08/27 of SRG 1900+14 ($P=5.16$ s), 2004/12/27 of SGR 1806-20 ($P=7.45$ s). The released energy in the former two flares could be $\sim 10^{44-45}$ erg, while $\sim 10^{47}$ erg in the third. A peculiar nature of superflare is the initial brief ($\sim 0.2$ s) spikes of $\gamma$-rays with energies up to several MeV, which contain most of the flare energy and are followed by tails lasting minutes (e.g., Hurley et al. 2003). Additionally, quasi-periodic oscillations (QPOs) during superflares were found soon after the onsets of the superflares in SGR 1806-20 (at frequency $f \sim 93$ Hz, Israel et al. 2003), in SGR 1900+14 ($f \sim 84$ Hz, Strohmayer & Watts 2003), and in SGR 0526-66 ($f \sim 43$ Hz, Barat et al. 1987). Higher frequency oscillations at about 150, 625, and 1,840 Hz are also detected from the superflare of SGR 1806-20 (Strohmayer & Watts 2004).

Current models for the superflares are in the scenario of magnetars, a kind of neutron stars with polar magnetic fields in the range $10^{14} \sim 10^{15}$ G, including the SGRs and the anomalous X-ray pulsars (AXPs). The quiescent X-ray emission with luminosity $\sim 10^{34-36}$ erg/s as well as the superflares of SGRs are supposed to be powered by magnetic field decay (e.g., Woods & Thompson 2003). However, there are still some debates on magnetars (see §3 for more discussion on their existence), although they are really popular in the astrophysical society. Alternatively, we propose here that a giant quake in a solid quark star may result in a superflare and reproduce the general observational features.

A quark star is composed dominantly by quark matter which is a direct consequence of the asymptotic freedom nature in quantum chromodynamics (QCD), the underlying theory believed for the elementary strong interaction. It is worth noting that this stellar quark matter at low temperature should be very different from the hot quark matter to be searched in relativistic heavy ion colliders. A degenerate Fermi gas of quarks is expected at extremely high density and temperature, while Cooper pairing of quarks near the Fermi surface occurs in cool and dense (but not asymptotically) quark matter because of the strong and attractive QCD quark-quark interaction. A condensate of the pairs may then result in a color superconductivity (CSC) phase in this case (Alford & Rajagopal 2002, and references therein). However, a solid state with quark-clusters in periodic lat-
tices was also conjectured in a parametric region where the density could be lower than that of CSC state \cite{Xu2003}. This hypothetic state could still not be ruled out by simple QCD principles as well as astrophysical observations \cite{Xu2006} and references therein). Unfortunately, due to the non-linear nature of QCD, one can not now obtain with certainty the critical parameters (e.g., baryon density and temperature) for the asymptotically free quark phase, the CSC phase, and the (solid) quark-cluster phase.

Pulsar-like stars, including SGRs and AXPs, are compact remnants of evolved stars, the nature of which is still a matter of controversy. Though these stars are popularly thought to be normal neutron stars, no convincing work, either theoretical from first principles or observational, has excluded the possibility that they are actually quark stars. Besides the rotational, thermal, magnetic, and accretion-gravitational ones, the remaining free energy for a solid quark star includes additional elastic and quake-gravitational energies \cite{Horbath2002,Xu2006}. In this paper, we will show that these additional free energies of solid quark stars could be high enough to power the superflares of SGRs. Though the energy budget quest of the superflares is focused on, the radiative mechanisms as well as astrophysical implications of such events are discussed too.

2 THE MODEL

It is very fundamental to study static and spherically symmetric gravitational sources in general relativity, especially for the interior solutions. The Tolman-Oppenheimer-Volkoff (TOV) solution is only for perfect fluid. However, for solid quark stars, since the local press can be anisotropic in elastic matter, the radial pressure gradient could be partially balanced by the tangential shear force although a general understanding of relativistic, elastic bodies has unfortunately not been achieved (e.g. \cite{Karlovini2004}). The origin of this local anisotropic force in solid quark stars could be from the development of elastic energy as a star (i) spins down (its ellipticity decreases) and (ii) cools (it may shrink). Release of the elastic as well as the gravitational energies would be not negligible, and may have significant astrophysical implications.

Let’s numerically calculate the structure of solid quark stars as following. For the sake of simplicity, we only deal with spherically symmetric sources in order to make sense of possible astrophysical consequence of solid quark stars. By introducing respectively radial and tangential pressures, \( P \) and \( P_\perp \), the stellar equilibrium equation of static anisotropic matter in Newtonian gravity is \cite{Herrera1995}. Eq. (2.4) there): \( dP/dr = -Gm(r)\rho/r^2 + 2P_\perp - P \), where \( \rho \), \( m(r) \) and \( G \) denote, respectively, mass density, mass interior the radius \( r \) and the gravitational constant. However, in Einstein’s gravity, this equilibrium equation is modified (e.g., \cite{Liu1999}),

\[
\begin{align*}
\frac{dP}{dr} & = \frac{-Gm(r)\rho}{r^2} \left( 1 + \frac{P}{m(r)} \right) \left( 1 + \frac{4\pi r^3 P}{m(r)c^2} \right) + \frac{2\varepsilon}{r} P,
\end{align*}
\]

where \( P_\perp = (1 + \varepsilon)P \) is introduced. In case of isotropic pressure, \( \varepsilon = 0 \), Eq. (1) turns out to be the TOV equation. It is evident from Eq. (1) that the radial pressure gradient, \( |dP/dr| \), decreases if \( P_\perp > P \), which may result in a higher maximum mass of compact stars. Whether the \( 2.1M_{\odot} \)-millisecond pulsar \cite{Nice2005} in a binary system with a helium white dwarf secondary is relevant to this nature of solid stars could be an interesting topic. One can also see that a sudden decrease of \( P_\perp \) in a star may cause substantial energy release, since the star’s radius decreases and the absolute gravitational energy increases.

A quark star would initially be in a fluid state well approximated by a perfect fluid. In a simplified version of the bag model for quark matter, the equation of state for fluid quark matter could be

\[
P = \frac{1}{3}(\rho - 4B)c^2, \tag{2}
\]

where the bag constant \( B \cdot c^2 \) could be between 60 MeV/fm\(^3\) and 110 MeV/fm\(^3\). Since no equation of sate for solid quark matter is available, we may just approximate the radial pressure by Eq. (1) in the following calculations. Also the equation below holds,

\[
\frac{dm(r)}{dr} = 4\pi r^2 \rho. \tag{3}
\]

We have to integrate numerically these differential equations of Eq. (1), which are complete for \( P \), \( \rho \) and \( m \) if \( B \) and \( \varepsilon \) are certain, in order to know the \( \varepsilon \)-dependent global structure (e.g., radius and mass) of a solid quark star.

Substituting Eq. (2) into Eq. (1) and Eq. (3), we have

\[
\begin{align*}
\frac{dm(r)}{dr} & = 4\pi r^2 (4B + \frac{2\varepsilon}{3}), \\
\frac{dP}{dr} & = -\frac{Gm(r)(4B + \frac{2\varepsilon}{3})}{r^2} \left( 1 + \frac{P}{m(r)c^2} \right) \left( 1 + \frac{4\pi r^3 P}{m(r)c^2} \right) + \frac{2\varepsilon}{r} P. \tag{4}
\end{align*}
\]

The precision of numerical solution should be very high in order to obtain the small-\( \varepsilon \)-dependent features from Eq. (1). Initially, the core of a star is supposed to be homogeneous, with the density \( \rho = \rho_0 \), the radius \( r = 0.1 \) cm, \( m(0.1) = 4\rho_0\pi r^3/3 \), and \( P(0.1) = (\rho_0 - 4B)c^2/3 \) in the computation. Numerical method can then be used to integrate Eq. (4) from \( r = 0.1 \) cm to the boundary, \( r = R \), of the star, step by step (with index \( n \)). At the star’s boundary, \( P(R) = 0 \) and \( M = m(R) \), with \( R = r_n \) if and only if \( P(R_n) > 0 \), \( P(R_{n+1}) < 0 \). Approximated in a flat spacetime, the total gravitational energy \( E \) and the stellar moment of inertia \( I \) could also have been obtained in the numerical process, by integrating the following equations,

\[
\begin{align*}
dE & = -\frac{Gm(r)}{r} \frac{dm(r)}{dr} = -\frac{Gm(r)}{r} (4\pi r^2 \rho) dr, \\
& = -4\pi \frac{3P}{c^2} (4B + 4B) Gm(r) dr, \tag{5}
\end{align*}
\]

\[
\begin{align*}
dI & = \frac{2}{3} r^2 dm(r) = \frac{2}{3} (4\pi r^2 P) dr, \\
& = \frac{8\pi}{3} \frac{3P}{c^2} (4B + 4B) r^4 dr. \tag{6}
\end{align*}
\]

The Runge-Kutta method of order-4 is used in the code.

Some issues are worth noting during the numerical process. It is very necessary to improve the precision in order to obtain the differences, which we are interested, of \( E(\varepsilon) \) and \( I(\varepsilon) \) by numerical integration, since both the related numbers and the domains in this problem vary in 7 orders of magnitudes. Computing error comes mainly from the decision of a star’s boundary. To improve the precision of
tangential strain energy. Generally, it is evident that the energy release of the gravitational energy as well as the important for a bigger change of $\epsilon$ from $10^{-4}$ is smaller near the boundary, until the quantities calculated by introducing $P_\perp = (1 + \epsilon) P$, where $P_\perp$, $P$ are the radial and tangential pressures, respectively.

![Figure 1](image1.png)
**Figure 1.** The difference of stellar radius as a function of stellar mass. Solid lines are for bag constant $B = 60$ MeV/fm$^3$, and dashed lines for $B = 110$ MeV/fm$^3$. The quantity of $\epsilon$ is defined by introducing $P_\perp = (1 + \epsilon) P$, where $P_\perp$, $P$ are the radial and tangential pressures, respectively.

![Figure 2](image2.png)
**Figure 2.** Same as in Fig.1, but for the difference of gravitational energy.

integration, we have to divide the domain to be smaller and smaller near the boundary, until the quantities calculated are credible.

Our calculation results are shown in Fig.1 to Fig.3. Starquakes may result in a sudden change of $\epsilon$, with an energy release of the gravitational energy as well as the tangential strain energy. Generally, it is evident that the differences of radius, gravitational energy, and moment of inertia increase proportionally to stellar mass and the parameter $\epsilon$. This means that an event should be more important for a bigger change of $\epsilon$ in a quark star with higher mass. It is shown in Fig.1 that the stellar radius varies insignificantly when small $\epsilon$ is considered ($R(\epsilon) - R(0)$ is only from $10^{-4}$ cm $\sim$ 10 cm for $\epsilon = 10^{-8} \sim 10^{-4}$ if stellar mass is $\sim M_\odot$). Only gravitational energy release is considered in Fig.2 which could be as high as $10^{48}$ erg if $\epsilon \sim 10^{-4}$ and $M \sim M_\odot$. Typical energy of $10^{44} \sim 10^{47}$ erg is released during superflares of SGRs, and we may then propose a giant starquake with $\epsilon \lesssim 10^{-4}$ could produce such a flare. A sudden change of $\epsilon$ can also result in a jump of spin frequency, $\Delta \Omega / \Omega = -\Delta I / I$. We may expect from Fig.3 that glitches with $\Delta \Omega / \Omega \sim 10^{-10} \sim 10^{-8}$ could occur for parameters of $M = (0.1 \sim 1.4) M_\odot$ and $\epsilon = 10^{-9} \sim 10^{-4}$. It is suggestive that a giantflare may accompany a high-amplitude glitch.

![Figure 3](image3.png)
**Figure 3.** Same as in Fig.1, but for the ratio difference of moment of inertia.

### 3 CONCLUSIONS AND DISCUSSIONS

We suggest alternatively that the superflares of soft $\gamma$-ray repeaters could be the results of giant quakes of solid quark stars. Numerical calculations for spherically asymmetric solid stars show that the released gravitational energy during a giant quake could be as high as $10^{48}$ erg if the tangential pressure is slightly higher (only $\sim (1 + 10^{-5})$ times) than the radial one in a star with mass $\sim M_\odot$. However, a detail process by which the released energy is transformed into radiation is still not clear during a quake. The quake-calculation presented in this paper is different from that of Zhou et al. (2004).

A direct consequence in the model here is that, besides giant quakes, much small quakes especially of aged quark stars (both their magnetospheric and thermal radiations would be low enough not to be detected regularly by recent facilities) with low masses are expected to occur as hard X-ray transients. There is a rough tendency that both the jump amplitudes and the frequency of the glitches are apparently decreased with the pulse period when the pulsars become older (Lyne et al. 2004). No glitch pulsar with the period longer than 0.7 second has been detected. According to the law of seismology, no big quake occurs if many small ones happen frequently, but a giant quake may take place after a long time of silence (i.e., no quake period). If this law applies, an old solid quark star with long spin period ($\gg 1$ s), which may have enough time to leave its host galaxy, could have a big quake (crash) after a long time of silence. Part of short $\gamma$-ray burst could probably rare flares of middle or low amplitudes of starquakes in the galactic halo. More such events could be recorded by the Swift or the future HXMT (hard X-ray modulation telescope).

Anomalous X-ray pulsars/Soft $\gamma$-ray repeaters (AXPs/SGRs) are supposed to be magnetars. But an alternative suggestion is that they are normal-field pulsar-like stars which are in an accretion propeller phase (Alpar 2001; Chatterjee, Hernquist & Narayan 2000). The very
difficulty in the later view point is to reproduce the irregular bursts, even with peak luminosity $\sim 10^{47} L_{\text{Edd}}$ (SGR 0526-66: $L_{\text{Edd}}$ the Eddington luminosity). Both the possibilities of the bombardments of comet-like objects (e.g., strange planets, [Xu 2005b]) to bare strange stars and of giant quakes in solid quark stars could remove the difficulty during super-bursts since the interaction in quark matter should be very strong. Based on the calculation in Fig. 4 it is conjectured that SGRs/AXPs could be quark stars with masses in order of $M_{\odot}$, since more energy would be released during their quakes as bursts. Other pulsar-like stars (compact center objects and dim thermal “neutron stars”), which have small bolometric radii and low surface temperatures, could be quark stars with lower masses. Actually, there could be observations as well as theoretical arguments which do not favor the magnetar idea. (i). The superstrong field of magnetars are supposed to be created by MHD-dynamo action of rapid rotating protoneutron stars with spin period $\sim 3$ ms. The Poynting flux and the relativistic particle ejection of such a star should power effectively the supernova remnants. Such energetic remnants are expected in magnetar models, but had not been detected (Vink & Kuiper 2006). (ii). Dust emission around pulsar-like stars (e.g., AXPs) was proposed to test observationally the propeller scenarios of quark stars with Spitzer or SCUBA (Xu 2005, 2006). Actually a recent discovery of mid-infrared emission from a cool disk around an isolated young X-ray pulsar, 4U 0142+61, is reported (Wang, Chakrabarty & Kaplan 2004) although it is still a matter of debate whether significant propeller torque of fallback matter acts on the center star. (iii) The pressure should be very anisotropic in a relativistic degenerate neutron gas in equilibrium with a background of electrons and protons when the magnetic field is stronger than the critical field. The vanishing of the equatorial pressure of the gas would result in a transverse collapse, and a stable magnetar could then be unlikely (Martinez, Rojas & Cuesta 2003). (iv). It is still a matter of debate whether the absorption features in SGR 1806-20 can be interpreted by proton or electron cyclotron resonance (Xu, Wang & Qiao 2003). The field is only $\sim 5 \times 10^{11}$ G in the context of electron cyclotron line. (v). Malov & Machabeli (2004) suggested that the persistent X-ray emission of AXPs/SGRs could be originated from the cyclotron mechanism acting near the surface of a star with normal field $\sim 10^{12}$ G, while short-time-scale cataclysmic events on the neutron star could lead to the bursts. Considering these criticisms, we think that alternative ideas for understanding AXPs/SGRs phenomena are very necessary.

How to test this starquake model and the magnetar model for AXPs/SGRs? Because of the change of mass momentum, gravitational wave radiation may accompany a giant starquake of a solid quark star, but such radiation may not be significant in the magnetar model, at least the timescale and other feature of the waves should be very different. The observed QPOs could also hint the nature of superflares of SGRs. A detail investigation on stellar torsional vibration and a comparison between the QPO-characters in starquake and magnetar models (e.g., Glampedakis, Samuelson & Andersson 2004; Beloborodov & Thompson 2003) are very necessary. In our model for SGRs, glitches may occur during gravity-induced superflares. This could be applied to distinguish the models. Interestingly, an glitch of $\Delta \nu/\nu = 4.2 \times 10^{-6}$ was discovered in 1E 2259+586, which preceded the the 2002 out-burst activity (Woods et al. 2004). Actually, occasional 4 glitches had been detected in 3 AXPs; sometimes they were associated with radiative events (Kaspi 2006). However, only gravitational energy change is calculated in this paper. It is worth noting that stress energy developed in solid quark stars should be another kind of free energy. No significant frequency glitch occurs if a superflare originates from the release of stress energy. How much is the stress energy during the evolution of a solid quark star? Is it comparable to the gravitational energy? These are questions to be answered in the future.

A pulsar-like star could be monopole-charged electrically, due to either the global structure of current flows in pulsar magnetospheres (Xu, Cui & Qin 2004) or maybe other reasons. Weber et al. (2004) showed that, depending of the amount of electric charge, the star’s structure and specifically the mass-radius relationship might be drastically modified. A loss of the electricity could also increase the parameter $\epsilon$ (i.e., the tangential pressure becomes higher and higher than the radial one as the electricity decreases). A starquake would occur as the star discharges, which we have not included in calculations.

Astrophysical links between AXPs and SGRs? The persistent X-ray emission from AXPs/SGRs are alternatively suggested to be accretion-powered (i.e., accretor with conventional magnetic fields. Alpar 2001). But how to reproduce naturally SGR-like bursts in this scenario? Quark stars with low masses ($\ll M_{\odot}$) are self-confined by the strong interactions between quarks, whereas gravitation-binding can not be negligible for quark stars with much higher masses ($\sim M_{\odot}$). This results in an approximate relation of $M \propto R^3$ for low masses but violation for higher masses in the mass($M$)-radius(R) diagram. It is well known that the stellar radius decreases as the mass increases for pure gravitation-confined Fermion stars (e.g., white dwarfs with state of perfect electron gases). An accreting solid quark star may undergo blazing quakes if it has a mass of $\gtrsim M_{\odot}$ when gravitation-binding dominates, since, in this case, the gravitation-induced shear force becomes stronger and stronger as the star accretes. Therefore, it is proposed (Xu 2006) that SGRs/AXPs might be solid quark stars with $\sim (1 - 2) M_{\odot}$, while other pulsar-like stars could be of low-mass. In order to make sense about the values of mass and radius of gravitation-dominated quark stars, we calculate these two parameters for fluid quark stars, using simply an equation of state of Eq. 2. It is shown in Fig. 4 that the difference between the mass of quark stars with maximum mass ($dM/dR = 0$) and that with maximum radius ($dR/dM = 0$) could be $\Delta M \sim 0.1 M_{\odot}$ for possible bag constant (60 – 110) MeV·fm$^{-3}$. The corresponding radius difference is about $\Delta R \sim 0.4$ km. The maximum gravitational-energy release during successive quakes of an accreting solid quark star from the point of “$dR/dM = 0$” to the point of “$dM/dR = 0$” could typically be $E_{\text{quake}} \sim G(M(M+\Delta M) - M_{\odot}^2) / R$ $\sim 10^{52}$ erg. But the total energy release for the persistent X-ray emission is $E_{\text{persistent}} \sim GM_{\odot} \Delta M / R \sim 10^{52}$ erg. For AXPs/SGRs with persistent X-ray luminosity $L_x \sim 10^{35}$ erg/s, the lifetime of such sources could be $E_{\text{persistent}} / L_x \sim$
10^{10} \text{ yrs}. This means that it would cost nearly the Hubble time to increase the stellar mass to the maximum value (so that the star may collapse to a black hole) if the accretion rate is a constant.

**Radiative mechanisms of star-quake-induced flares.** Because of the starquakes of neutron stars, self-induction electric field is created (Thompson, Lyutikov & Kulkarni 2002; Beloborodov & Thompson 2006). The strong electric field could initiate avalanches of pair creation in the magnetosphere and certainly accelerate particles, resulting in high energy bursts observed. Similar mechanism would also work when starquakes occur in solid quark stars. The only difference should be that no ions can be supplied from the surface of bare quark stars (i.e., lepton-dominated plasma forms above quark surfaces). The energy of oscillations excited by starquakes could be transported to the plasma corona by, e.g., Alfvén waves, being similar to the case of heating the solar wind (1988). It is interesting to know if such Alfvénic fluctuations, originated from stellar torsional oscillations, could result in the observed QPOs. In the conventional magnetar model, the field should be at least 8 \times 10^{15} \text{ G} in order to reproduce the superflare of SRG 1806-20, if the efficiency of transforming magnetic energy to the burst emission during the flare is \sim 10^{-2}. This low limit means that magnetic field dominates (i.e., to control the motion by magnetic field rather by crust) in the part of crust with density \rho < \rho_{\text{max}} \approx 2.7 \times 10^{11} \text{ g/cm}^3. Note that \rho_{\text{max}} is in a same order of the density of neutron drip \rho_{\text{drip}} = 4.3 \times 10^{11} \text{ g/cm}^3. It is possible (or not) that starquake could occur in the outer crust (with density \rho < \rho_{\text{drip}}) of normal neutron stars, but the disadvantage is that the shear modulus (Fuchs 1992), \mu \propto Z^2, in the deep crust might not be high enough to crack, since the atomic charge Z becomes smaller and smaller in deeper crust due to neutronization. However, for solid quark stars, starquakes could certainly exist because of high shear modulus as well as high density, even if the stars have field as strong as 10^{16} \text{ G}.

In conclusion, starquakes of solid quark stars are proposed for the soft \gamma-ray superflares, with the persistent X-ray emission to be fallback accretion-powered, for AXPs/SGRs. Those problems in the magnetar models could be circumvented if AXPs/SGRs are accreting solid quark stars with masses \sim (1-2) M_{\odot}. The rigidity of solid quark stars should be high enough for strong quakes to occur, and the energy budget would not be a problem.

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