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The superflares of soft γ-ray repeaters: giant quakes in solid quark stars?

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ABSTRACT

Three supergiant flares from soft γ-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 a magnetohydrodynamic process, in which a significant part of the short–hard γ-ray bursts could also be the result of magnetars. Based on various observational features (e.g. precession, glitches, thermal photon emission) and the underlying theory of strong interaction (quantum chromodynamics), it cannot yet be ruled out that pulsar-like stars might be actually solid quark stars. Strain energy develops during the life of a solid star, and starquakes could occur when stellar stresses reach a critical value, with a huge amount of energy released. An alternative model for supergiant flares of soft γ-ray repeaters is presented, in which the energy release during a starquake of a solid quark star is calculated. Numerical results for spherically asymmetric solid stars show that the gravitational energy released 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 anomalous X-ray pulsars/soft γ-ray repeaters are accreting solid quark stars with mass $\sim$1–2 $M_{\odot}$.

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

1 INTRODUCTION

Pulsar-like stars have continued to manifest surprising observational features since their first discovery in 1967. One of their extraordinary behaviours, the origin and astrophysical implications of which are hotly debated, is superflares from soft γ-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) and 2004/12/27 of SGR 1806−20 ($P = 7.45$ s). The released energy could be $\sim 10^{44-45}$ erg in the first two flares, and $\sim 10^{47}$ erg in the third. A peculiar characteristic of superflares is the initial brief ($\sim$0.2 s) spikes of γ-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. 2005). 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. 2005), in SGR 1900+14 ($f \sim$ 84 Hz, Strohmayer & Watts 2005) and in SGR 0526−66 ($f \sim 43$ Hz, Barat et al. 1983). Higher frequency oscillations at about 150, 625 and 1840 Hz have also been detected from the superflare of SGR 1806−20 (Strohmayer & Watts 2006).

Current models for superflares involve magnetars, a kind of neutron star with polar magnetic field in the range 10^{14}–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^{-1} and the superflares of SGRs are supposed to be powered by magnetic field decay (e.g. Woods & Thompson 2005). However, there is still some debate on magnetars (see Section 3 for more discussion on their existence), although they are really popular in the astrophysical community. 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 predominantly of quark matter which is a direct consequence of the asymptotic freedom nature of 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 cool and dense) quark matter because of the strong and attractive QCD quark–quark interaction. A condensate of the pairs may then result in a colour superconductivity (CSC) phase in this case (and references therein Alford & Rajagopal 2006). However, a solid state with quark clusters in periodic lattices was also conjectured in a parametric region where the density could be lower than that of a CSC state (Xu 2003, 2005). This hypothetical state could still not be ruled out by simple QCD principles or astrophysical observations (and references therein Xu 2006b). Unfortunately, because of the nonlinear nature of QCD, one *cannot* now obtain with certainty the

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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. Although 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 energies, the remaining free energy for a solid quark star includes additional elastic and quake–gravitational energies (Horvath 2005; Xu 2006b). In this Letter, we will show that these additional free energies of solid quark stars could be high enough to power the superflares of SGRs. Although we focus on the energy budget of superflares, we also discuss the radiative mechanisms as well as the astrophysical implications of such events.

2 THE MODEL

It is 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 a perfect fluid. However, for solid quark stars, since the local pressure could 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. Karlovini & Samuelsson 2004). 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 non-negligible, and may have significant astrophysical implications.

Let us numerically calculate the structure of solid quark stars as follows. For the sake of simplicity, we only deal with spherically symmetric sources in order to make sense of the possible astrophysical consequences 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 (Herrera & Santobs 1997 equation 2.4 there): $\mathrm{d}P/\mathrm{d}r = -Gm(r)\rho/r^2 + 2(P_\perp - P)/r$, where ρ, $m(r)$ and G denote, respectively, the mass density, the mass interior to the radius r and the gravitational constant. However, in Einstein's gravity, this equilibrium equation is modified (e.g. Liu 1999),

$$\frac{\mathrm{d}P}{\mathrm{d}r} = -\frac{Gm(r)\rho}{r^2}\frac{\left(1+\frac{P}{\rho c^2}\right)\left[1+\frac{4\pi r^3 P}{m(r)c^2}\right]}{1-\frac{2Gm(r)}{rc^2}} + \frac{2\epsilon}{r}P, \tag{1}$$

where $P_\perp = (1+\epsilon)P$ is introduced. In the case of isotropic pressure, $\epsilon = 0$, equation (1) turns out to be the TOV equation. It is evident from equation (1) that the radial pressure gradient, $|\mathrm{d}P/\mathrm{d}r|$, decreases if $P_\perp > P$, which may result in a higher maximum mass of compact stars. Whether the 2.1-$\mathrm{M}_\odot$ millisecond pulsar (Nice et al. 2005) in a binary system with a helium white dwarf secondary is relevant to this property of solid stars could be an interesting topic of study. One can also see that a sudden decrease of $P_\perp$ in a star may cause a substantial energy release, since the radius of the star 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 Bc^2 could be between 60 and 110 MeV fm^{-3}. Since no equation of state for solid quark matter is available, we may just approximate the radial pressure by equation (2) in the following calculations. Also the equation below holds:

$$\frac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2\rho. \tag{3}$$

We have to integrate numerically these differential equations (1)–(3), which are complete for P, ρ and $m(r)$ if B and ϵ are certain, in order to determine the ϵ-dependent global structure (e.g. radius and mass) of a solid quark star.

Substituting equation (2) into equations (3) and (1), we have

$$\begin{cases} \dfrac{\mathrm{d}m(r)}{\mathrm{d}r} = 4\pi r^2\left(4B + \dfrac{3P}{c^2}\right), \\ \dfrac{\mathrm{d}P}{\mathrm{d}r} = -\dfrac{Gm(r)\left(4B+\frac{3P}{c^2}\right)}{r^2}\dfrac{\left[1+\frac{P}{\left(4B+\frac{3P}{c^2}\right)c^2}\right]\left[1+\frac{4\pi r^3 P}{m(r)c^2}\right]}{1-\frac{2Gm(r)}{rc^2}} + \dfrac{2\epsilon}{r}P. \end{cases} \tag{4}$$

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

$$\begin{aligned} \mathrm{d}E &= -\frac{Gm(r)}{r}\mathrm{d}m(r) = -\frac{Gm(r)}{r}(4\pi r^2\rho\mathrm{d}r) \\ &= -4\pi\left(\frac{3P}{c^2} + 4B\right)Gm(r)r\mathrm{d}r, \end{aligned} \tag{5}$$

$$\begin{aligned} \mathrm{d}I &= \frac{2}{3}r^2\mathrm{d}m(r) = \frac{2}{3}r^2(4\pi r^2\rho\mathrm{d}r) \\ &= \frac{8\pi}{3}\left(\frac{3P}{c^2} + 4B\right)r^4\mathrm{d}r. \end{aligned} \tag{6}$$

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

Some issues are worth noting during the numerical process. It is necessary to improve the precision in order to obtain the differences, in which we are interested, of $E(\epsilon \neq 0) - E(\epsilon = 0)$ and $I(\epsilon \neq 0) - I(\epsilon = 0)$ by numerical integration, since both the related numbers and the domains in this problem vary by seven orders of magnitude. The computing error comes mainly from the choice of the boundary of a star. To improve the precision of integration, we have to divide the domain into smaller and smaller sections near the boundary, until the quantities calculated are credible.

The results of our calculations are shown in Figs 1–3. Starquakes may result in a sudden change of ϵ, with a 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 the stellar mass and the parameter ϵ. This means that an event should be more important for a bigger change of ϵ in a quark star with higher mass. It is shown in Fig. 1 that the stellar radius varies insignificantly when small ϵ is considered [$R(\epsilon) - R(0)$ goes only from 10^{-4} to 10 cm for $\epsilon = 10^{-8}$ to 10^{-4} if the stellar mass is $\sim$1 $\mathrm{M}_\odot$]. Fig. 2 considers only gravitational energy release, which could be as high as 10^{48} erg if $\epsilon \sim 10^{-4}$

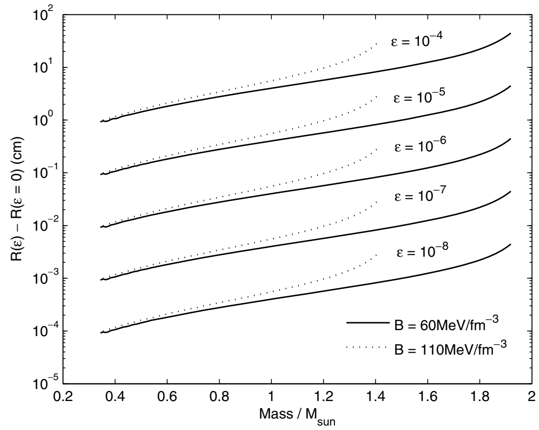

Figure 1. The difference $R(\epsilon \neq 0) - R(\epsilon = 0)$ in stellar radius as a function of stellar mass. Solid lines are for bag constant $B = 60$ MeV fm^{-3}, and dotted lines for $B = 110$ MeV fm^{-3}. The quantity ϵ is defined by introducing $P_\perp = (1 + \epsilon)P$, where $P_\perp$ and P are the radial and tangential pressures, respectively.

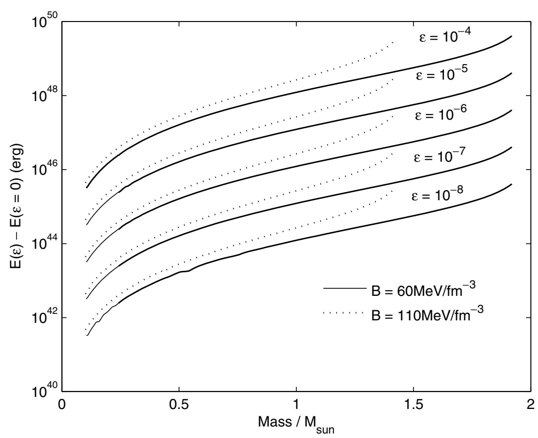

Figure 2. As in Fig. 1, but for the difference in gravitational energy.

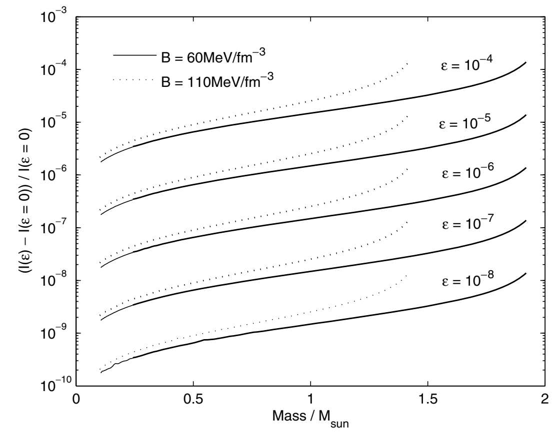

Figure 3. As in Fig. 1, but for the ratio difference in moment of inertia.

and $M \sim 1\,\mathrm{M}_\odot$. A typical energy of 10^{44-47} erg is released during superflares of SGRs, and we may then propose that a giant starquake with $\epsilon \lesssim 10^{-4}$ could produce such a flare. A sudden change of ϵ can also result in a jump of spin frequency, $\Delta\Omega/\Omega = -\Delta I/I$. We may expect from Fig. 3 that glitches with $\Delta\Omega/\Omega \sim 10^{-10}$ to 10^{-4} could occur for parameters of $M = 0.1$–$1.4\,\mathrm{M}_\odot$ and $\epsilon = 10^{-9}$ to 10^{-4}. It is suggested that a giant flare may accompany a high-amplitude glitch.

3 DISCUSSION

We suggest, in an alternative to the conventional model, that the superflares of SGRs could be the result 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 pressure in a star with mass $\sim 1\,\mathrm{M}_\odot$. However, a detailed 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 of the model here is that, besides giant quakes, much smaller quakes especially of aged quark stars (both their magnetospheric and thermal radiation 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 apparently decrease with the pulse period when the pulsars become old (Lyne et al. 2000). No glitch pulsar with a period longer than 0.7 s has been detected. According to the law of seismology, no big quake occurs if 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 a 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 γ-ray bursts could probably be seen as rare flares of medium or low amplitude of starquakes in the galactic halo. More such events could be recorded by *Swift* or the future *HXMT* (*Hard X-ray Modulation Telescope*).

AXPs/SGRs are supposed to be magnetars. However, an alternative suggestion is that they are normal-field pulsar-like stars which are in an accretion propeller phase (Chatterjee, Hernquist & Narayan 2000; Alpar 2001). The difficulty for the latter viewpoint is to reproduce the irregular bursts, even with a peak luminosity $\sim 10^7 L_{\mathrm{Edd}}$ (SGR 0525−66, where L_{Edd} is the Eddington luminosity). The possibilities of the bombardment by comet-like objects (e.g. strange planets, Xu 2005) of bare strange stars, and of giant quakes in solid quark stars could remove the difficulty during superbursts since the interaction in quark matter should be very strong. Based on the calculation in Fig. 2, it is conjectured that SGRs/AXPs could be quark stars with masses of the order of $1\,\mathrm{M}_\odot$, since more energy would be released during their quakes as bursts. Other pulsar-like stars (compact centre 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 that do not favour the magnetar idea.

(i) The superstrong fields of magnetars are supposed to be created by magnetohydrodynamic dynamo action of rapidly rotating protoneutron stars with spin period <3 ms. The Poynting flux and the relativistic particle ejection of such a star should effectively power the supernova remnants. Such energetic remnants are expected in magnetar models, but have not been detected (Vink & Kuiper 2006).

(ii) Dust emission around pulsar-like stars (e.g. AXPs) has been proposed to test observationally the propeller scenarios of quark stars with *Spitzer* or the SCUBA instrument (Xu 2005, 2006a). Actually, a recent discovery of mid-infrared emission from a cool disc around an isolated young X-ray pulsar, 4U 0142+61, has been reported (Wang, Chakrabarty & Kaplan 2006), although it is still a matter of debate whether a significant propeller torque of matter falling back acts on the central 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 (Martnez, Rojas & Cuesta 2003).

(iv) It is still a matter of debate whether the absorption features in SGR 1806−20 can be interpreted as 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 lines.

(v) Malov & Machabeli (2004) suggested that the persistent X-ray emission of AXPs/SGRs could originate 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 AXP/SGR phenomena are necessary.

How can this starquake model and the magnetar model for AXPs/SGRs be tested? 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 time-scale and other features of the waves should be very different. The observed QPOs could also hint at the nature of superflares of SGRs. A detailed investigation of stellar torsional vibration and a comparison between the QPO characteristics in starquake and magnetar models (e.g. Glampedakis, Samuelsson & Andersson 2006; Beloborodov & Thompson 2006) are necessary. In our model for SGRs, glitches may occur during gravity-induced superflares. This could be applied to distinguish between the models. Interestingly, a glitch of $\Delta\nu/\nu = 4.2 \times 10^{-6}$ was discovered in 1E 2259+586, which preceded the 2002 outburst activity (Woods et al. 2004). Actually, four occasional glitches had been detected in three AXPs; sometimes they were associated with radiative events (Kaspi 2006). However, only the gravitational energy change is calculated in this Letter. 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. What 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 & Qiao 2006) or maybe other reasons. Weber et al. (2006) showed that, depending on the amount of electric charge, the structure and specifically the mass–radius relationship of the star might be drastically modified. A loss of electric charge could also increase the parameter ϵ (i.e. the tangential pressure becomes higher than the radial one as the electricity decreases). A starquake would occur as the star discharges, which we have not included in our calculations.

3.1 Astrophysical links between AXPs and SGRs?

The persistent X-ray emission from AXPs/SGRs is alternatively suggested to be accretion-powered (i.e. an accretor with conventional magnetic fields: Alpar 2001), but how can naturally SGR-like bursts be reproduced in this scenario? Quark stars with low masses ($\ll 1\,M_\odot$) are self-confined by the strong interactions between quarks, whereas gravitational binding cannot be negligible for quark stars with much higher masses ($\sim 1\,M_\odot$). This results in an approximate relation of $M \propto R^3$ for low masses but violation for higher masses in the mass–radius (M–R) diagram. It is well known that the stellar radius decreases as the mass increases for pure gravitationally confined fermion stars (e.g. white dwarfs of perfect electron gases). An accreting solid quark star may undergo blazing quakes if it has a mass of $\gtrsim 1\,M_\odot$ when gravitational binding dominates, since, in this case, the gravitationally induced shear force becomes stronger and stronger as the star accretes. Therefore it is proposed (Xu 2006a) that SGRs/AXPs might be solid quark stars with masses of $\sim$1–2 $M_\odot$, while other pulsar-like stars could be of low mass. In order to make sense of the values of mass and radius of gravitationally dominated quark stars, we calculate these two parameters for fluid quark stars, using simply the equation of state of equation (2). It is shown in Fig. 4 that the difference between the masses of quark stars with maximum mass ($dM/dR = 0$) and those with maximum radius ($dR/dM = 0$) could be $\Delta M \sim 0.1\,M_\odot$ for a 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

$$E_{\rm quake} \sim G\left[\frac{M(M+\Delta M)}{R-\Delta R} - \frac{M^2}{R}\right] \sim 10^{52}\ {\rm erg}.$$

However, the total energy release for the persistent X-ray emission is $E_{\rm persistent} \sim GM\Delta M/R \sim 10^{52}$ erg. For AXPs/SGRs with persistent X-ray luminosity $L_{\rm x} \sim 10^{35}$ erg s^{-1}, the lifetime of such sources could be $E_{\rm persistent}/L_{\rm x} \sim 10^{10}$ yr. This means that it would take 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.

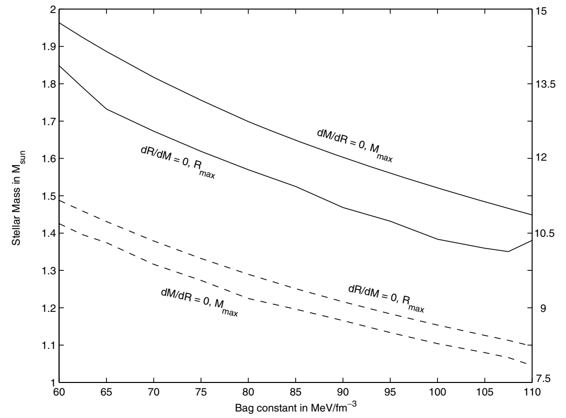

Figure 4. An illustration of stellar mass (solid lines, in $M_\odot$) and radius (dashed lines, in km) of gravitationally dominated quark stars, as a function of the bag constant. The masses as well as the radii of quark stars with maximum radius ($dR/dM = 0$) or maximum mass ($dM/dR = 0$) are shown. It is evident that the mass and radius differences could be about 0.1 $M_\odot$ and 0.4 km, respectively.

3.2 Radiative mechanisms of starquake-induced flares

Because of the starquakes of neutron stars, a 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 being observed. A 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 (Tu 1988). It is interesting to know whether such Alfvénic fluctuations, originating from stellar torsional oscillations, could result in the observed QPOs. In the conventional magnetar model, the field should be at least $B \simeq 8 \times 10^{16}$ G in order to reproduce the superflare of SRG 1806−20, if the efficiency of transforming magnetic energy to burst emission during the flare is $\sim 10^{-2}$. This low limit means that magnetic field dominates (i.e. the motion is controlled by magnetic field rather by crust) in the part of the crust with density $\rho < \rho_{\rm max} \sim 2.7 \times 10^{11}$ g cm^{-3}. Note that $\rho_{\rm max}$ is of the same order as the density of the neutron drip $\rho_{\rm drip} = 4.3 \times 10^{11}$ g cm^{-3}. It is possible, if $\rho_{\rm max} < \rho_{\rm drip}$ (or not, if $\rho_{\rm max} > \rho_{\rm drip}$) that a starquake could occur in the outer crust (with density $\rho < \rho_{\rm drip}$) of normal neutron stars, but the disadvantage is that the shear modulus (Fuchs 1926), $\mu \propto Z^2$, in the deep crust might not be high enough to crack neutron stars, since the atomic charge Z becomes smaller and smaller in the deeper crust owing 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 a field as strong as 10^{16} G.

4 CONCLUSIONS

In conclusion, starquakes of solid quark stars are proposed for soft γ-ray superflares, with the persistent X-ray emission being 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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