A New Model for Soft Gamma-Ray Repeaters

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We consider a model in which the soft gamma-ray repeaters (SGRs) result from young, magnetized strange stars with superconducting cores. As such a strange star spins down, the quantized vortex lines move outward and drag the magnetic field tubes because of the strong coupling between them. Since the terminations of the tubes interact with the stellar crust, the dragged tubes can produce sufficient tension to crack the crust. Part of the broken platelet will be dragged into the quark core, which is only $10^4$ cm from the surface, leading to the deconfinement of crustal matter into strange quark matter and thus the release of energy. We will show that the burst energy, duration, time interval and spectrum for our model are in agreement with the observational results. The persistent X-ray emission from the SGRs can be well explained by our model.

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The soft gamma-ray repeaters (SGRs) are a small, enigmatic class of gamma-ray transient sources. There are three known SGRs which are characterized by short rise times (as short as 5 ms) and duration ($\sim$ 50-150 ms, FWHM, some less than 16 ms), spectra with characteristic energies of $\sim$ 30-50 keV and little or no evolution, and stochastic burst repetition within a timescale of $\sim$ 1 month [1]. SGR 0525−66, the source of the 1979 March 5 event, appears to be associated with the N49 supernova remnant (SNR) in the Large Magellanic Cloud and hence is apparently the most distant known SGR source at $\sim$ 55 kpc from Earth [2]. The second burster, SGR 1806−20, which produced $\sim$ 110 observed bursts during a 7-year span [3] and recently became active again [4], appears to be coincident with the SNR G10.0−0.3 [5], confirming an earlier suggestion [6]. Thus, this source is at a distance of $\sim$ 15 kpc. The third burster, SGR 1900+14, is associated with SNR G42.8+0.6 [7], and its age is $\sim 10^4$ yrs and its distance from Earth is $\sim 7$ kpc. Accepting these SGR-SNR associations, the burst peak luminosities can be estimated to be a few orders higher than the standard Eddington value for a star with the mass of $\sim 1 M_\odot$. For example, SGR 1806−20 has produced events that are $\sim 10^4$ times the Eddington luminosity [8].

In addition to short bursts of both hard X-rays and soft $\gamma$-rays, the persistent X-ray emission was also detected from SGRs [5,7,9]. The luminosities of the persistent X-ray sources are $\sim 7 \times 10^{35}$ erg s$^{-1}$ for SGR 0525−66, $\sim 3 \times 10^{35}$ erg s$^{-1}$ for SGR 1806−20, and $\sim 10^{35}$ erg s$^{-1}$ for SGR 1900+14. These observations show that the repeaters may be young, magnetized neutron stars which power the surrounding luminous plerionic nebulae.

There may be three classes of models for explaining the energy source of SGRs. In the first class of models, SGRs were thought to result from accretion of neutron stars (for a brief review see [10]). Since the highly super-Eddington flux requires the accretion inflow and radiation outflow to be channeled in different directions so that it makes any accretion model very difficult. Second, it was suggested [11] that glitches of normal pulsars are an energy source of SGRs. However, the current models for pulsar glitches [12,13] seem to give glitching intervals and durations much larger than those of SGRs. Moreover, no SGR bursts have so far been detected from the Crab pulsar.

These two facts may disfavor the glitch model for SGRs. Third, it was argued [14] that SGRs are magnetars, a kind of neutron stars with superstrong magnetic fields of $\geq 5 \times 10^{14}$ G. Although the motivations for this model (e.g., rapid spin-down to 8 s period in $10^4$ years) sound attractive, there may be several unsettled issues [10], e.g., (i) a power output from such a strong magnetic field may be inconsistent with the plerion energy range; (ii) in such a strong field the radiation output is highly anisotropic but the observed shape seems to be angle independent. In this letter we suggest that SGRs result from young, magnetized strange stars with superconducting cores.

The structure of strange stars has been studied [15]. Strange stars near $1.4 M_\odot$ have thin crusts with thickness of $\sim 10^4$ cm and mass of $\sim 10^{-5} M_\odot$. Some arguments may be unfavorable to the existence of strange stars. First, most important, the relaxation behavior of glitches of pulsars which seem to be isolated neutron stars with masses of $\sim 1.4 M_\odot$ is well described by the neutron superfluid vortex creep theory [12], but the current strange
star models scarcely explain the observed pulsar glitches [16]. This may also mean that at least pulsars in which glitches occur must be neutron stars, not strange stars. Second, the conversion of a neutron star to a strange star requires the formation of a strange matter seed at a density (6-9 times the nuclear matter density) much larger than the central density of the $1.4M_\odot$ star with a rather stiff equation of state [17]. This shows that strange stars are not easy to be produced in the universe.

However, it was argued [18] that when neutron stars in low-mass X-ray binaries accrete sufficient mass, they may convert to strange stars. This mechanism was further suggested as a possible origin of cosmological gamma-ray bursts. In this Letter we suggest that strange stars may also be formed during the core collapse of massive stars or during the accretion phase of newly born neutron stars. The birth rate of strange stars due to these processes must be low. This is because (i) if the rate were high, the number of resulting strange stars would be too high to explain the observed glitch phenomena; (ii) although the current type II supernova models believe that neutron stars can be produced during the core collapse of massive stars in some controversial mass range and the evolution of more massive stars can result in the formation of black holes, these models have neither given the upper limit of the masses of massive stars which evolve to neutron stars nor the lower limit of the masses of massive stars which evolve to black holes. We conjecture that massive stars in a narrow mass range may finally evolve to strange stars. There are two cases for this evolution: (i) during the core collapse the nucleon matter directly convert into strange matter [19], in which case the shock wave for the supernova can obtain more energy; (ii) the central density of a newly born neutron star may reach the deconfinement density due to hypercritical accretion in a supernova circumstance [20] and then the whole neutron star may undergo a phase transition to a strange star.

After the birth, a strange star must start to cool due to neutrino emission. As a neutron star does, the strange star core may become superconducting when its interior temperature is below the critical temperature. Using a relativistic treatment of BCS theory, Bailin & Love [21] suggested that strange matter forms superconducting. They showed that the pairing of quarks is most likely to occur in both $ud$ and $ss$ channels. The pairing state of the former is likely in $s$-wave and that of the latter is in $p$-wave. The superconducting transition temperature is about 400 keV. Therefore, a strange star with age older than $10^3$ years after its supernova birth should have a core temperature lower than the normal-superconducting temperature [22]. The quark superconductor is likely to be marginally type II with zero temperature critical field $B_c \sim 10^{16}-10^{17}$ G [21,23] which sensitively depends on the interactions between quarks.

On the other hand, the existence of quantized vortex lines in the rotating core of a strange star is unclear. Since different superconducting species inside a rotating strange star try to set up different values of London fields in order to compensate for the effect of rotation. Using the Ginzburg-Landau formulism, Chau [23] showed that instead of setting a global London field vortex bundles carrying localized magnetic fields can be formed. The typical field inside the vortex core is about $10^{16}-10^{17}$ G (the accurate value depends on strong interaction parameters). Using the similar idea proposed for the interaction between the proton fluxoids and magnetic neutron vortices in the core of a neutron star [24], he argued that the vortex bundle and the flux tubes can interpin to each other by interaction of their core magnetic fields. He estimated that the pinning energy per intersection is

$$E_p \sim 690N_{\text{flux}}^{1/2} \text{MeV},$$

where $N_{\text{flux}}$ is the number of flux quantum in a flux tube. Such strong binding between vortex lines and flux tubes implies that when the vortex lines moving outward due to spinning-down of the star will induce the decay of the magnetic field [23]. One of the important consequences of this coupling effect will be discussed next text.

We now propose a plate tectonic model for strange stars which is, in principle, similar to that proposed by Ruderman [24] for neutron stars. As described in last subsection, there might exist two different types of quantized flux tubes in the core of a strange star. The first type of flux tubes are formed when the stellar magnetic field penetrates through the superconducting core. The second type of flux tubes (vortex lines) result from the requirement of minimizing the rotating energy of the core superfluid. When the star spin down due to magnetic dipole radiation, the vortex lines move outward and pull the flux tubes with them. Inductive currents do not strongly oppose this flux tube motion because of current screening by the almost perfectly diamagnetic superconducting quarks. However, the terminations of flux tubes are anchored in the base of highly conduct-
ing crystalline stellar crust. When the stellar spin-down timescale \( \tau_s = \Omega/2\dot{\Omega} \) is shorter than the typical ohmic diffuse timescale,

\[
\tau_d \sim \frac{\sigma A}{4\pi c^2} \sim 3 \times 10^4 \sigma_{21} R_6^2 \text{ yrs},
\]

where \( \sigma \) is the conductivity and \( R_6 \) is the radius in units of \( 10^6 \) cm. The motion of flux tubes is limited by their terminations in the crust unless the resulting pull on the crust by these flux tubes exceeds the crustal yield strength, namely,

\[
\frac{BB_c}{8\pi} \sin \theta > \mu \theta_s \frac{l}{R},
\]

where \( B \) is the stellar magnetic field, \( \theta \) is the angle between the stellar magnetic moment and the flux tubes, \( \mu \) is the shear modulus, \( \theta_s \) is the shear angle, and \( l \) is the crustal thickness. Substituting the typical values of strange star parameters into equation (3), we obtain

\[
\sin \theta \sim \theta > \theta_c \equiv 3 \times 10^{-6} B_{c,17}^{-1} B_{12}^{-1} \theta_s^{-3} \mu_{27} l_4 R_6^{-1} \text{ rad},
\]

where \( B_{c,17} \) is in \( 10^{17} \) G, \( B_{12} \) in \( 10^{12} \) G, \( \theta_s^{-3} \) in \( 10^{-3} \), \( \mu_{27} \) in \( 10^{27} \) dyn cm\(^{-2} \), and \( l_4 \) in \( 10^4 \) cm. When \( \theta > \theta_c \), the stellar crust will crack and \( \theta \) will be reduced by an amount \( \delta \theta \sim \min(\theta, \Delta l/R) \) (\( \Delta l \) is the displacement of the crustal plate). In the case of neutron stars, Ruderman [25] estimated that \( \Delta l \sim 2 \times 10^9 \) cm for the Crab and Vela pulsars. For a strange star with a much thinner crust than that of a neutron star, we expect that \( l > \Delta l > 2 \times 10^2 \) cm, which implies \( \delta \theta \sim \theta \). Since the flux tubes move outward with the same speed as the vortex lines which is given by

\[
v \sim \frac{R}{\tau_s} = 3 \times 10^{-6} R_6 \tau_{s,4}^{-1} \text{ cm s}^{-1},
\]

where \( \tau_{s,4} \) is in \( 10^4 \) yrs, the time interval between two successive cracking events is estimated to be

\[
\tau_{int} \sim \frac{R \delta \theta}{v} \sim 10^6 B_{c,17}^{-1} B_{12}^{-1} \theta_s^{-3} \mu_{27} l_4 R_6^{-1} \tau_{s,4} \text{ s}.
\]

This value is consistent with the typical interval timescale of SGRs.

When the crust cracks, a small platelet could be dragged from the crust into the strange matter core which is only \( 10^4 \) cm from the surface. In the following we make an estimate of the timescale for the platelet motion. The force pulling the cracking platelet horizontally by the flux tubes is

\[
F_p = \frac{BB_c}{8\pi} \theta A_p,
\]

where \( A_p \) is the area of the platelet. Thus, the timescale opening a hole with area \( \sim A_p \) is approximated by

\[
\tau_{drag} = \left( \frac{2l \theta M_{cr} \delta}{4\pi R^2 F_p} \right)^{1/2} \sim 80 \left( \frac{M_{cr,-5}}{l_4 \theta_s^{-3} \mu_{27} R_6} \right)^{1/2} \text{ ms},
\]

where \( M_{cr,-5} \) is the total mass of the crust in units of \( 10^{-5} M_\odot \). The durations of the SGRs are expected to be of the same order as this timescale. As normal matter falls into the core continuously, the baryons will deconfine into quarks. Because each baryon can release \( \sim (20-30) \) MeV (the accurate value is dependent upon the QCD parameters), which are a sum of gravitational energy and deconfinement energy, the total amount of energy release is estimated as

\[
\Delta E \sim 3 \times 10^{42} M_{cr,-5} (A_p/l^2) \tau^{2} R_6^{-2} \text{ ergs}.
\]

where \( M_{cr,-5} \) is the total mass of the crust in units of \( 10^{-5} M_\odot \). At least half of this amount will be carried away by thermal photons with the typical energy \( kT \sim 30 \) MeV. These thermal photons will be released continuously in a timescale of \( \sim \tau_{drag} \). In the presence of a strong magnetic field, the thermal photons will convert into electron-positron pairs when

\[
\frac{E_\gamma}{2mc^2} = \frac{B}{2mc^2 B_q} \sin \Phi \sim \frac{1}{15},
\]

where \( E_\gamma \) is the photon energy, \( B_q = m^2 c^3 / \hbar = 4.4 \times 10^{13} \) G and \( \Phi \) is the angle between the photon propagation direction and the direction of the magnetic field [27]. The energies of the resulting pairs will be lost via synchrotron radiation. The characteristic synchrotron energy is given by

\[
E_{syn}^{(1)} \sim \frac{3}{2} \gamma_e^2 \hbar \left( \frac{eB}{mc} \right) \sin \Phi \sim 1.5 \text{ MeV},
\]

where \( \gamma_e \) is the Lorentz factor of the electron (\( \sim 30 \)). The first generation of synchrotron photons will be converted into the secondary pairs because the optical depth of photon-photon pair production is much large than 1. The characteristic synchrotron energy of the secondary pairs is given by

\[
E_{syn}^{(2)} \sim \frac{3}{2} \left( \frac{E_{syn}^{(1)}}{2mc^2} \right)^2 \hbar \left( \frac{eB}{mc} \right) \sim 37 B_{12} \text{ keV}.
\]
Since the depth of photon-electron scattering near the star is also much larger than 1, a radiation-pair fireball in thermal equilibrium will have an initial temperature of the same order as $E_{\text{syn}}^{(2)}$, and will expand adiabatically as a fluid. During the expansion the radiation energy is converted into a bulk kinetic energy of the outflow. The fireball will cool with $T = T_0(R_0/R)$, and the relativistic Lorentz factor $\Gamma$ of the bulk motion is $\Gamma = T_0/T = R/R_0$ [28]. Therefore, when the optical depth of the fireball is one, an observer at infinity will see a blueshifted spectrum with the typical energy of $\sim E_{\text{syn}}^{(2)}$ due to the relativistic bulk motion of the fireball.

Finally, we want to discuss an astrophysical implication of our model. The persistent X-ray emission from the SGRs was detected. If the sources are normal neutron stars with typical magnetic fields of $\sim 10^{12}$ G, it is obvious that the persistent X-ray luminosities from the SGRs may not be explained by the surface blackbody radiation. This is because calculations for the cooling of neutron stars [29] predict that after $(0.5 - 1) \times 10^4$ yrs the bolometric luminosities will be at least two orders smaller than the persistent X-ray ones from the SGRs. Recently Usov [30] suggested that if the sources of the SGRs are magnetars the persistent X-ray emission may be the thermal radiation of these stars which is enhanced by a factor of 10 or more due to the effect of ultrastrong magnetic fields. We can also explain the observed persistent X-ray emission by using our model. After each cracking event, at least half of the resulting thermal energy from the deconfinement of normal matter into strange quark matter will be absorbed by the stellar core and thus the surface radiation luminosity at thermal equilibrium may be estimated to be

$$L_x \sim \frac{\xi \Delta E}{\tau_{\text{int}}} \sim 3 \times 10^{36} \xi M_{\text{cr}, -5} (A_p / l^2) l_4 R_0^{-1} \times B_{\text{c}, 17} B_{\text{12}}^{-1} \theta_{s, -3}^{-1} \mu_{27}^{-1} \tau_{s, 4}^{-1} \text{ ergs s}^{-1},$$

where $\xi$ is a parameter which accounts for both the ratio of the absorbed thermal energy to the released total energy during a cracking event and the ratio of the surface blackbody radiation energy to the absorbed thermal energy. We expect that this parameter is of the order of 0.5. Taking $B_{\text{c}, 17} B_{\text{12}}^{-1} \theta_{s, -3}^{-1} \mu_{27}^{-1} \sim 3$ to account for $\tau_{\text{int}} \sim 3 \times 10^6$ s, we have $L_x \sim 5 \times 10^{38}$ erg s$^{-1}$. This estimated luminosity seems to agree with the observed ones from the SGRs.

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