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Are Soft γ-Ray Repeaters Strange Stars?

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The soft γ-ray repeaters (SGRs) are proposed to 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 flux 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 and pull parts of the broken platelet into the quark core. The deconfinement of crustal matter into strange quark matter will release energy. The model burst energy, duration, time interval, spectrum, and the persistent x-ray emission from SGRs are shown to be in agreement with observed results. [S0031-9007(97)05016-3]

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The soft γ-ray repeaters (SGRs) are a small, enigmatic class of γ-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 time scale of $\sim$1 month [1]. SGR 0525 $-$ 66, the source of the 5 March 1979 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-yr span [3] and recently became active again [4], appears to be coincident with 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 $\sim 10^4$ yr 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 of magnitudes higher than the standard Eddington value for a star with a mass of $\sim 1M_\odot$. 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 γ rays, the persistent x-ray emission was also detected from SGRs [5,7,9]. The luminosities of the persistent x-ray sources are $\sim 7 \times 10^{35}$ ergs s^{-1} for SGR 0525 $-$ 66, $\sim 3 \times 10^{35}$ ergs s^{-1} for SGR 1806 $-$ 20, and $\sim 10^{35}$ ergs s^{-1} for SGR 1900 + 14. The observations show that the repeaters may be young, magnetized neutron stars which power the surrounding luminous plerionic nebulas.

There have been 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 Ref. [10]). Since the highly super-Eddington flux requires the accretion inflow and radiation outflow to be channeled in different directions, 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] seem to give glitching intervals and durations much larger than those of SGRs. Moreover, no SGR bursts have so far been detected from young pulsars, e.g., the Crab pulsar, the Vela pulsar, etc. Third, it was argued [13] that SGRs are magnetars, a kind of neutron star with superstrong magnetic fields of $\geq 5 \times 10^{14}$ G . Although this model can explain some important features of the famous 5 March 1979 γ-ray transient, e.g., rapid spin down to 8 s period in 10^4 yr and correlating the peak luminosity to this 8 s periodicity, there are still 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. Furthermore, this model also cannot provide a satisfactory explanation for burst duration, time scale between bursts, synchrotron self-absorption feature, and the persistent x-ray emission for SGRs. Alternatively, we suggest that SGRs may be rapidly rotating magnetized strange stars with superconducting cores. The 8 s periodicity may result from an effect similar to that of subpulse drift phenomenon in pulsars which also have a periodicity of the order of seconds [14]. Our model is actually stimulated by the work of Alcock, Farhi, and Olinto [15], who explained the 5 March 1979 burst by assuming the burster is a strange star collided by a lump of strange matter. However, although they can successfully explain many key features of this γ-ray transient, their model did not provide a good explanation for the burst duration, time scale between bursts, synchrotron self-absorption feature, and the persistent x-ray emission for SGRs. Our model will provide a detailed explanation of these observed features.

The structure of strange stars has been studied [16]. Strange stars near $1.4M_\odot$ have thin crusts with a thickness of $\sim 10^4$ cm and mass of $\sim 10^{-5}M_\odot$. However, some objections against the existence of strange stars result from

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astrophysical arguments. It has been argued that the disruption of a single strange star can contaminate the entire galaxy, and essentially all "neutron" stars are strange stars [17]. This conflicts with the relaxation behavior of pulsar glitches because the current strange-star models scarcely explain it [18]. Furthermore, if strange stars can be created directly in supernovas, then some strange stars should have compact companions, and the merging of such binaries will lead to the Caldwell-Friedman effect [19]. Here we want to point out that these arguments do not necessarily disprove the existence of strange stars for several reasons described in [20]. It has been argued [20] 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 γ-ray bursts. Here we suggest that strange stars may be formed during the core collapse of massive stars or during the accretion phase of newly born neutron stars. One reason for this suggestion is that if the initial masses of some compact stars are about $1.73M_\odot$ [21] then these massive stars, as argued in [20], may be strange stars. Again, strange stars born in this mechanism may not result in the Caldwell-Friedman effect. According to the current theories, the close neutron star-neutron star binaries, e.g., Hulse-Taylor binary, are evolved from high-mass binaries. We believe that the strange star-neutron star binaries should also be evolved from high-mass binaries, if they exist. However, there are two reasons which might make these binaries difficult to form. We have just suggested that the strange stars may be formed by a supernova explosion, in which the core mass of the progenitor is about $1.73M_\odot$ [21]. This requires the mass of the progenitor star to be about $19M_\odot$. In this case, the companion star will either be rejected during the supernova explosion, if the orbit is too wide, or spiral in and merge with the massive core of the progenitor during the phase of common envelope evolution.

After its birth, a strange star must start to cool due to neutrino emission. As with neutron stars, the strange star core may become superconducting when its interior temperature is below the critical temperature. Using a relativistic treatment of BCS theory, Bailin and Love [22] suggested that strange matter becomes 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 to be s wave and that of the latter p wave. The superconducting transition temperature is about 400 keV. Therefore, a strange star with age older than 10^3 yr after its supernova birth should have a core temperature lower than the normal superconducting temperature [23]. The quark superconductor is likely to be marginally type-II with zero temperature critical field $B_c \sim 10^{16}$–10^{17} G [22,23] which depends sensitively 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 formalism, Chau [24] 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 [25], he argued that the vortex bundles 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 $E_p \sim 690N_{\rm flux}^{1/2}$ MeV, where $N_{\rm flux}$ is the number of flux quanta in a flux tube. Such strong binding between vortex lines and flux tubes implies that, when the vortex lines are moving outward due to spinning down of the star, it will induce the decay of the magnetic field [24]. One of the important consequences of this coupling effect will be discussed below.

We now propose a plate tectonic model for strange stars which is, in principle, similar to that proposed by Ruderman [26] for neutron stars. As described above, there might exist two different types of quantized flux tubes in the core of a strange star. The first type of flux tube is formed when the stellar magnetic field penetrates through the superconducting core. The second type of flux tube (vortex lines) results from the requirement of minimizing the rotating energy of the core superfluid. When the star spins 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 the highly conducting crystalline crust. When the stellar spin-down time scale $\tau_s = \Omega/2\dot{\Omega}$ is shorter than the typical Ohmic diffuse time scale,

$$\tau_D \sim \frac{\sigma A}{4\pi c^2} \sim 3 \times 10^4 \sigma_{21} R_6^2 \text{ yr}, \tag{1}$$

where σ 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,

$$\frac{BB_c}{8\pi} \sin\theta > \mu\theta_s \frac{l}{R}, \tag{2}$$

where B is the stellar magnetic field, θ is the angle between the stellar magnetic moment and the flux tubes, μ is the shear modulus, θ_s is the shear angle, and l is the crustal thickness. Substituting the typical values of strange star parameters into Eq. (2), we obtain

$$\sin\theta \sim \theta > \theta_c \equiv 3 \times 10^{-6} B_{c,17}^{-1} B_{12}^{-1} \theta_{s,-3} \times \mu_{27} l_4 R_6^{-1} \text{ rad}, \tag{3}$$

where $B_{c,17}$ is in 10^{17} G, B in 10^{12} G, $\theta_{s,-3}$ in 10^{-3}, μ_{27} in 10^{27} dyn cm^{-2}, and l_4 in 10^4 cm. When $\theta > \theta_c$, the stellar crust will crack and θ will be reduced by an amount $\delta\theta \sim \min(\theta, \Delta l/R)$ (Δl is the displacement of the crustal plate). In the case of neutron stars, Ruderman [26] estimated that $\Delta l \sim 2 \times 10^2$ 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

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

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

$$\tau_{\rm int} \sim \frac{R\delta\theta}{v} \sim 10^6 B_{c,17}^{-1} B_{12}^{-1} \theta_{s,-3} \mu_{27} l_4 R_6^{-1} \tau_{s,4} \text{ s}. \tag{5}$$

This value is consistent with the typical interval time scale of SGRs.

When the crust cracks, the flux tubes will contract by a length scale δR and drag some broken platelets into the core, which is only 10^4 cm from the surface. The energy of each nucleon (E_p) in the platelets carried by the flux tubes into the core can be estimated as $E_p \sim (BB_c A_p \delta R/8\pi)/N_n \sim B_{12} B_{c,17} (A_p \delta R)_{12} N_{n,46}^{-1}$ MeV, where A_p is the area of the cracking surface and N_n is the total number of nucleon dragged into the core. As normal matter is pulled into the core, electron capture for the nuclei in the matter will occur continuously and then neutrons dripped out of the nuclei will fall into the core and deconfine to quarks. This time scale is of the order of milliseconds because of the high electron density in the region between the normal crust and the quark core [15]. As described by [15], this hole will be gradually refilled by readjusting the normal matter on the surface of the strange star by the strong gravitational force.

In the following, we make an estimate of the time scale for the platelet motion. The force pulling the cracking platelet horizontally by the flux tubes is

$$F_p = \frac{BB_c}{8\pi} \theta A_p . \tag{6}$$

Thus, the time scale opening a hole with area $\sim A_p$ is approximated by

$$\tau_{\rm drag} = \left(2l \frac{A_p M_{\rm cr}}{4\pi R^2} \frac{1}{F_p}\right)^{1/2} \sim 80 \left(\frac{M_{{\rm cr},-5}}{\theta_{s,-3} \mu_{27} R_6}\right)^{1/2} \text{ ms}, \tag{7}$$

where $M_{{\rm cr},-5}$ is the total mass of the crust in units of $10^{-5} M_\odot$. The durations of SGRs are expected to be of the same order as this time scale.

Because each baryon can release $\sim$(20–30) MeV the accurate value is dependent upon the quantum chromodynamics parameters), which are a sum of gravitational energy and deconfinement energy, the total amount of energy released is estimated as

$$\Delta E \sim 3 \times 10^{42} \eta_{-1} M_{{\rm cr},-5} A_{p9} R_6^{-2} \text{ ergs}, \tag{8}$$

where η_{-1} is the fractional mass in units of 0.1 in the cracking area Ap which is dragged into the core. 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 time scale of $\sim\tau_{\rm drag}$. In the presence of a strong magnetic field, the thermal photons will convert into electron-positron pairs when

$$\frac{E_\gamma}{2mc^2} \frac{B}{B_q} \sin\Phi \sim \frac{1}{15}, \tag{9}$$

where E_γ is the photon energy, $B_q = m^2c^3/\hbar e = 4.4 \times 10^{13}$ G, and Φ 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

$$E_{\rm syn} \sim \frac{3}{2} \gamma_e^2 \hbar \frac{eB}{mc} \sin\Phi \sim 3.0 \text{ MeV}, \tag{10}$$

where γ_e is the Lorentz factor of the pairs ($\sim$30). These synchrotron photons will be converted into secondary pairs because the optical depth of photon-photon pair production is much larger than one. The Lorentz factor of the secondary pairs is about 3.0. Liang and Fenimore [28] have shown that, in a strong magnetic field ($\sim 10^{12}$ G), self-absorbed synchrotron emission from a cooling distribution of these mildly relativistic pairs provides excellent fits to the spectral data of SGRs: soft spectra with exponential decay with decay energy $\sim$20–30 keV and, in the case of SGR 1806 − 20, a steep turnover of the photon spectrum below $\sim$14 keV. We would like to make two remarks about the radiation mechanism. (1) Electron/positron cascade, initiated by a few tens of MeV photons, also occurs in the polar cap region of pulsars, but its radiation spectrum is known to be a power law (e.g., Ref. [29]). The key difference between polar cap γ-ray emission in pulsars and the γ-ray emission in soft γ-ray repeaters is the direction of the emitted γ rays. In the former case, γ rays are curvature photons emitted by relativistic electrons/positrons moving along the magnetic field lines. These photons have to move a certain distance away from where they are emitted before their pitch angle becomes large enough and the local perpendicular component magnetic field w.r.t. photons become strong enough to convert the high energy photons into pairs. In the latter case, the high energy photons are thermal photons and are emitted in all directions from the hot spot. Thus they can be converted into electron-positron pairs by the magnetic field immediately. (2) Our radiation mechanism is different from that of Alcock *et al.* [15], who considered radiation from a relativistic expanding fireball by neglecting the trapping effect of a strong magnetic field, so that their spectrum did not show a synchrotron self-absorption feature. This is mainly because the energy releasing mechanism in [15] is almost instantaneous, but it takes a finite time ($\approx \tau_{\rm drag}$) in our model. Thus the magnetic energy density is higher than that of the photon energy density in our model.

Finally, we want to discuss an astrophysical implication of our model. The persistent x-ray emission from 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 SGRs may not be explained by the surface blackbody radiation. This is because calculations for the cooling of neutron stars [30] predict that after $(0.5-1) \times 10^4$ yr the bolometric luminosities will be at least two orders of magnitude smaller than for the persistent x-ray luminosities from SGRs. Recently, Usov [31] suggested that if the sources of 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, roughly 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

$$L_x \sim \frac{\xi \Delta E}{\tau_{\rm int}} \sim 3 \times 10^{36} \xi M_{{\rm cr},-5} (A_p/l^2) l_4 R_6^{-1} \times B_{c,17} B_{12} \theta_{s,-3}^{-1} \mu_{27}^{-1} \tau_{s,4}^{-1} \ {\rm ergs\,s^{-1}}, \tag{11}$$

where ξ 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 $B_{c,17}^{-1} B_{12}^{-1} \theta_{s,-3} \mu_{27} \sim 3$ to account for $\tau_{\rm int} \sim 3 \times 10^6$ s, we have $L_x \sim 5 \times 10^{35}$ erg s^{-1}. This estimated luminosity seems to agree with those observed from SGRs. On the other hand, the persistent x-ray emission produced by refilling the hole [15] will be an order of magnitude less than the observed value.

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