Energy Sources of Soft Gamma-Ray Repeaters

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ABSTRACT

Quiescence and burst emission and relativistic particle winds of soft gamma-ray repeaters (SGRs) have been widely interpreted to result from ultrastrongly magnetized neutron stars. In this magnetar model, the magnetic energy and gravitational energy of the neutron stars are suggested as the energy sources of all the emission and winds. However, Harding, Contopoulos & Kazanas (1999) have shown that the magnetic field should be only $\sim 3 \times 10^{13}$ G in order to match the characteristic spin-down timescale of SGR 1806 $-$ 20 and its SNR age. Here we argue that if the magnetic field is indeed so weak, the previously suggested energy sources seem problematic. We further propose a plausible model in which SGR pulsars are young strange stars with superconducting cores and with a poloidal magnetic field of $\sim 3 \times 10^{13}$ G. In this model, the movement of the flux tubes not only leads to crustal cracking of the stars, giving rise to deconfinement of crustal matter to strange matter, but also to movement of internal magnetic toruses with the flux tubes. The former process will result in burst and quiescence emission and the latter process will produce steady relativistic winds which will power the surrounding supernova remnants.

Subject headings: gamma-ray: bursts – magnetic fields – dense matter – stars: neutron
1. INTRODUCTION

The soft gamma-ray repeaters (SGRs) are a small, enigmatic class of high-energy transient sources, which differ from classical gamma-ray bursts by their durations (typically $0.1 - 1$ s), soft spectra with characteristic energies of $\sim 30 - 50$ keV and their repetition. The other properties of four known SGRs include: (1) all of them are associated with supernova remnants (SNRs). SGR 0525 $-$ 66 appears to be associated with SNR N49 in the Large Magellanic Cloud (Evans et al. 1980; Cline et al. 1982). The second burster, SGR 1806 $-$ 20, which produced $\sim 110$ bursts during a 7-yr span (Laros et al. 1987) and recently became active again (Kouveliotou et al. 1994), appears to be coincident with SNR G10.0 $-$ 0.3 (Murakami et al. 1994), confirming an earlier suggestion (Kulkarni & Frail 1993). The age of this SNR was estimated to be $\sim 10^4$ yr based on angular diameter versus surface brightness argument (Kulkarni et al. 1994). The third burster, SGR 1900 $+$ 14, is associated with SNR G42.8 $+$ 0.6 (Vasisht et al. 1994), whose age is also $\sim 10^4$ yr. The fourth burster, SGR 1627 $-$ 41, was recently discovered to be associated with SNR G337.0 $-$ 0.1 (Hurley et al. 1999; Woods et al. 1999). From these SGR-SNR associations, the burst peak luminosities can be estimated to be a few orders of magnitude higher than the standard Eddington luminosity for a stellar-mass star. For example, SGR 1806 $-$ 20 produced bursts with $\sim 10^4$ times the Eddington luminosity (Fenimore, Laros & Ulmer 1994). (2) In addition to short bursts of soft gamma-ray photons, the persistent X-ray emission has been detected from SGRs (Murakumi et al. 1994; Vasisht et al. 1994; Rothschild, Kulkarni & Lingenfelter 1994). The luminosities of the persistent X-ray emission 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. (3) Recently, a period of $P = 7.47$ s and its derivative $\dot{P} = 8.3 \times 10^{-11}$ s s$^{-1}$ have been detected from SGR 1806 $-$ 20 in quiescent emission (Kouveliotou et al 1998), and a period of $P = 5.16$ s and its derivative $\dot{P} = 6.0 \times 10^{-11}$ s s$^{-1}$ have been discovered from SGR 1900 $+$ 14 in quiescent emission (Kouveliotou et al. 1999). All of these observations clearly show that SGRs are young pulsars. Furthermore, if the period derivatives are driven by magnetic dipole radiation, it can be shown (Pacini 1969)
that the dipolar magnetic field is given by \( B_p = 3.2 \times 10^{19}(P\dot{P})^{1/2} \) G, which would yield dipolar magnetic fields of \( 8 \times 10^{14} \) and \( 5 \times 10^{14} \) G for SGR 1806 – 20 and SGR 1900 + 14 respectively. Therefore, the SGR pulsars are magnetars, “neutron stars” with magnetic fields \( \geq 10^{14} \) G. Such stars were first proposed by Duncan & Thompson (1992), Usov (1992) and Paczyński (1992).

However, the above estimate of dipolar magnetic fields leads to characteristic spin-down ages much smaller than the SNR ages. This difficulty can be alleviated by introducing relativistic particle outflows from SGRs. The existence of such a wind has been inferred indirectly by X-ray and radio observations of the synchrotron nebula G10.0 – 0.3 around SGR 1806 – 20 (Murakami et al. 1994; Kulkarni et al. 1994). Thompson & Duncan (1996) estimated that the particle luminosity from SGR 1806 – 20 is of the order of \( 10^{37} \) erg s\(^{-1}\). Such an energetic wind will also affect the spin-down torque of the pulsar by distorting the dipole field structure near the light cylinder (Thompson & Blaes 1998). Furthermore, Harding, Contopoulos & Kazanas (1999) have found that if SGR 1806 – 20 puts out a continuous particle wind of \( 10^{37} \) erg s\(^{-1}\), then the pulsar age is consistent with that of the surrounding SNR, but the derived surface dipole magnetic field is only \( 3 \times 10^{13} \) G, in the range of normal radio pulsars.

It has been widely thought that ultra-strong magnetic fields are an origin of SGR quiescence and burst emission and relativistic particle winds (Thompson & Duncan 1995, 1996). As analyzed in Section 2, however, a magnetic field of \( 3 \times 10^{13} \) G may be too weak to be considered as an energy source of SGR quiescence emission and relativistic particle winds. Furthermore, the rotational energy, gravitational energy and crustal strain energy of SGR pulsars are not yet suitable. Following Cheng & Dai (1998) and Dai & Lu (1998), in Section 3 we will propose a model in which SGR pulsars are young, magnetized strange stars with superconducting cores. We argue that this model can provide an explanation for all the observed properties of SGRs including steady winds with luminosities of \( \sim 10^{37} \) erg s\(^{-1}\). In the final section, we will discuss some differences between anomalous X-ray pulsars (AXPs) and SGRs in our model.
Observationally, SGRs have both quiescence and burst emission and steady winds. In the following we estimate the energies of the emission and wind from SGR 1806 – 20. First, assuming that the luminosity of the wind is $L_w \sim 10^{37} \text{ erg s}^{-1}$, we obtain the total observed wind energy $E_w = L_w t_{\text{SNR}} \sim 3 \times 10^{48} \text{ ergs}$. Second, the total energy of the persistent X-ray emission is given by $E_x = L_x t_{\text{SNR}} \sim 6 \times 10^{46} \text{ ergs}$, where $L_x$ is the persistent X-ray luminosity ($\sim 2 \times 10^{35} \text{ erg s}^{-1}$). Third, the total observed energy of SGR bursts, assuming isotropic emission, can be estimated by $E_{b, \text{tot}} = E_b (t_{\text{SNR}} / \tau_{\text{int}}) \sim 3 \times 10^{46} (E_b / 10^{41} \text{ ergs}) (t_{\text{int}} / 10^6 \text{ s})^{-1}$, where $E_b$ is the typical energy of a burst ($\sim 10^{41} \text{ ergs}$) and $\tau_{\text{int}}$ is the interval timescale of SGR bursts ($\sim 10^6 \text{ s}$).

Theoretically, there are four energy sources for the persistent X-ray and burst emission and the wind. The first energy source is the rotational energy of the pulsar $E_{\text{rot}} \sim 4 \times 10^{44} (P / 7.47 \text{ s})^{-2} \text{ ergs}$. Second, assuming a uniform poloidal field configuration in the interior, the total magnetic energy is $E_B \sim 3 \times 10^{44} (B_p / (3 \times 10^{13} \text{ G}))^2 \text{ ergs}$. Moreover, the numerical studies of Heyl & Kulkarni (1998) show that a magnetic field with $\sim 3 \times 10^{13} \text{ G}$ doesn’t obviously decay even in $10^6 \text{ yr}$, implying that this magnetic energy cannot be varied in the SGR age. The third energy source is the gravitational energy of the pulsar. It is well known that the available gravitational energy for a rotating star ($\Delta E_G$) is only the difference in the gravitational energy between this star and a nonrotating (spherical) star for the same baryon mass. Assuming that the SGR pulsar is a slowly rotating Maclaurin spheroid, we easily demonstrate $\Delta E_G = 5 E_{\text{rot}} \sim 2 \times 10^{45} (P / 7.47 \text{ s})^{-2} \text{ ergs}$. The final energy source is the crustal strain energy. Assuming that the SGR pulsar is a neutron star, we obtain the strain energy (Baym & Pines 1971): $E_{\text{strain}} \sim 2 \times 10^{45} \epsilon^4 \text{ ergs} \ll \Delta E_G$, where $\epsilon$ is the eccentricity of the star.

Comparing the theoretical energy sources with the observed energies of the persistence and burst emission and the wind, we find that the previously suggested energies are much smaller than required by observations. For example, the magnetic energy is about four
orders of magnitude smaller than the wind energy. Therefore, we conclude that these energy sources are too weak to be considered as origins of SGRs. Furthermore, even if a magnetar-strength field of $\sim 10^{14}$ G, as Harding et al. (1999) argued in the case of an episodic wind with small duty cycle, is assumed, this conclusion remains correct. What are energy sources of SGRs?

3. OUR ENERGY SOURCES

We now propose a plausible model for SGRs, in which SGR pulsars are young, magnetized strange stars with superconducting cores. The structure of strange stars has been widely studied (for a recent review see Cheng, Dai & Lu 1998). An interesting possible signature for the existence of strange stars has been found in a few low-mass X-ray binaries (Stergioulas, Kluzniak & Bulik 1999), in which the kHz quasi-periodic oscillation phenomena were recently observed (Zhang et al. 1998). Another strange star candidate is an unusual hard X-ray burster, GRB J1744–28 (Cheng et al. 1998).

It is well known that supernova explosions are very likely to produce neutron stars. Because of hypercritical accretion, the neutron stars may subsequently accrete sufficient mass ($\sim 0.5M_\odot$) to convert to massive strange stars (Cheng & Dai 1996; Dai & Lu 1999; Wang et al. 1999). Since the density profile of a strange star is much different from that of a neutron star for the same baryon mass, differential rotation may occur in the interior of the newborn strange star. Dai & Lu (1998) have argued that such a differentially rotating strange star could lead to a classical gamma-ray burst. The basic idea of their argument is: In a differentially rotating strange star, internal poloidal magnetic field will be wound up into a toroidal configuration and linearly amplified as one part of the star rotates about the other part. Only when it increases up to a critical field, $B_f \sim 2 \times 10^{17}$ G, will the toroidal field be sufficiently buoyant to overcome fully the stratification in the composition of the strange star core. And then the buoyant magnetic torus will be able to float up to and break through the stellar surface. Reconnection of the surface magnetic field will produce a quickly explosive event as a peak of a gamma-ray burst. This idea is
similar to that of Kluzniak & Ruderman (1998) who discussed the neutron star case. Here we further suggest that after the gamma-ray burst many magnetic toruses with $B_\phi < B_f$ (toroidal field configuration) could remain in the interior of the strange star in a timescale of $\sim 10^4$ yr.

After its birth, a strange star must start to cool due to neutrino emission. As with a neutron star, the strange star core may become superconducting when its interior temperature is below the critical temperature. Bailin & Love (1984) found that the superconducting transition temperature in strange matter is about 400 keV. Therefore, a strange star with age of $\sim 10^4$ yr after its supernova birth must have a core temperature much lower than the superconducting transition temperature. The interior temperature of the strange star decreases as $T \approx 10^8(t/\text{yr})^{1/4}$ K, so $T \sim 10^7$ K when $t \sim 10^4$ yr. The quark superconductor is likely to be marginally type-II with zero temperature critical field $B_c \sim 10^{17}$ G (Bailin & Love 1984; Benvenuto, Vucetich & Horvath 1991; Chau 1997). Furthermore, Chau (1997) argued that after the quark superconductor appears in the strange star, the coupling between quantized vortex lines and (poloidal) magnetic flux tubes in the strange star is so strong that when the vortex lines are moving outward due to spinning down of the star, the magnetic flux tubes are also moving outward with them. According to this argument, Cheng & Dai (1998) proposed a plate tectonic model for strange stars which is, in principle, similar to that proposed by Ruderman (1991) for neutron stars. In this model, when the star spins down due to magnetic dipole radiation and wind emission, the vortex lines move outward and pull the flux tubes with them. However, since the terminations of the flux tubes are anchored in the base of the highly conducting crystalline crust, the flux tubes will produce sufficient tension to crack the crust and pull parts of the broken platelet into the strange quark matter. The time interval between two successive cracking events is estimated to be (Cheng & Dai 1998)

$$
\tau_{\text{int}} \sim 10^6 \left( \frac{B_c}{10^{17}\text{G}} \right)^{-1} \left( \frac{B_\phi}{3 \times 10^{13}\text{G}} \right)^{-1} \left( \frac{\theta_s}{0.03} \right) \times \left( \frac{\mu}{10^{27}\text{dyn cm}^{-2}} \right) \left( \frac{l}{10^4\text{cm}} \right) \left( \frac{R}{10^6\text{cm}} \right)^{-1} \left( \frac{t_{\text{SNR}}}{10^4\text{yr}} \right) \, \text{s},
$$

where $\mu$ is the magnetic moment, $l$ is the length scale of the flux tube, $R$ is the radius of the star, and $t_{\text{SNR}}$ is the supernova remnant age.
where $\theta_s$ and $\mu$ are the shear angle (estimated below) and the shear modulus ($\sim 10^{27}$ dyn cm$^{-2}$) at the base of the crust of the strange star respectively, and $l$ is the crustal thickness ($\sim 10^4$ cm). The melting temperature of the crust is $T_m \approx 10^3 (\rho_b/g \text{ cm}^{-3})^{1/3} Z^{5/3} K \sim 10^9$ K, where $\rho_b$ is the mass density at the base of the crust ($\sim 4 \times 10^{11}$ g cm$^{-3}$) and $Z$ is the charge number of nuclei ($Z = 26$ for iron) (Shapiro & Teukolsky 1983). At age of $\sim 10^4$ yr, the interior temperature of the strange star $T \sim 10^7$ K $\ll 0.1 T_m$ and thus $\theta_s \sim 10^{-1} - 10^{-2}$ (Ruderman 1991). We see that the time given by equation (1) is consistent with the typical time interval between SGR bursts.

Because each baryon can release the deconfinement energy of $\sim 30$ MeV (the accurate value is dependent upon the quantum chromodynamics parameters), the total amount of energy release is estimated as

$$\Delta E_b \sim 3 \times 10^{42} \left( \frac{\eta}{0.1} \right) \left( \frac{M_{cr}}{10^{-5} M_\odot} \right) \left( \frac{l}{10^4 \text{ cm}} \right)^2 \left( \frac{R}{10^6 \text{ cm}} \right)^{-2} \text{ ergs},$$

where $\eta$ is the fractional mass in the cracking area $\sim l^2$ which is dragged into the core (Cheng & Dai 1998). At least half of this amount will be carried away by thermal photons with the typical energy $kT \sim 30$ MeV. In the presence of a strong magnetic field ($\sim 3 \times 10^{13}$ G), these thermal photons will convert into electron/positron pairs when $|E_\gamma/(2m_e c^2)| B \sin \Theta / B_q \sim 1/15$, where $E_\gamma$ is the photon energy, $B_q = m_e^2 c^3/\hbar c = 4.4 \times 10^{13}$ G, and $\Theta$ is the angle between the photon propagation direction and the direction of the magnetic field (Ruderman & Sutherland 1975). The energies of the resulting pairs will be lost via synchrotron radiation. The characteristic synchrotron energy is given by $E_{\gamma syn} \sim 1.5 \gamma_e^2 \hbar c B \sin \Theta / (m_e c) \sim 3.0$ MeV, where $\gamma_e$ is the Lorentz factor of the pairs ($\sim 30$). These synchrotron photons will be converted into secondary pairs because the optical depth for photon-photon pair production is much larger than one. The Lorentz factor of the secondary pairs is about 3.0. Thus, we obtain a cooling distribution of mildly relativistic pairs, whose self-absorbed synchrotron emission has been shown to provide excellent fits to the spectral data of SGR bursts (Liang & Fenimore 1995). In addition, after the cracking event, roughly half of the resulting thermal energy from deconfinement
of normal matter to strange quark matter will be absorbed by the stellar core, and thus the surface radiation luminosity at thermal equilibrium has been found to be consistent with the observed persistent X-ray luminosity (Cheng & Dai 1998).

As the quantized vortex lines move outward during the stellar spinning down and pull the magnetic flux tubes together, the magnetic toruses are also pulled toward the equatorial region with the flux tubes due to the interaction between them (Chau, Cheng & Ding 1992). The upper limit of $B_\phi$ is $B_f$; its lower limit can be given as follows. The magnetic toruses must be sufficiently buoyant to overcome fully the stratification in the composition of the crust, requiring $B_\phi \geq (8\pi \rho c_s^2)^{1/2} \sim 5 \times 10^{15}$ G, where $c_s$ is the speed of sound of the crust ($c_s \sim 2 \times 10^9$ cm s$^{-1}$). The density of the flux tubes is given by $n = B_p/\Phi_v \sim 4 \times 10^{20}$ cm$^{-2}$, where $\Phi_v$ is the magnetic flux of each tube ($\sim 8 \times 10^{-8}$ G cm$^{-2}$) (Chau 1997). Now we define a timescale: $\Delta t = 1/(v\sqrt{n}) \sim 2 \times 10^{-5}$ s, where $v$ is the speed of flux tubes ($\sim 3 \times 10^{-6}$ cm s$^{-1}$) (Cheng & Dai 1998). The physical meaning for $\Delta t$ is that there must be a flux tube to move toward to the surface in the equatorial region in this timescale, implying that there must be magnetic toruses which are pulled simultaneously to the surface in the equatorial region and which break the surface. The reconnection of magnetic toruses leads to an episodic wind. Because $\Delta t$ is much smaller than $\tau_{\text{int}}$, too many episodic winds will constitute a steady wind. The magnetic energy including in each episodic wind can be estimated as $e_w = V_b B^2_\phi/(8\pi)$ where $V_b$ is the volume of a torus. It is important to note that the magnetic torus is emerging from the quark matter core to the surface and subsequently releasing this energy via reconnection in the equatorial region. Such an energy must be contaminated by crustal baryons whose mass is at most $m_w \sim M_c V_b/(4\pi R^2 l)$. In fact, the mass of the contaminating baryons should be a fraction ($\xi$) of $m_w$. Thus, the Lorentz factor of the steady wind is

$$\Gamma \sim \frac{e_w}{\xi m_w c^2} \sim 30 \left(\frac{\xi}{0.1}\right)^{-1} \left(\frac{M_c}{10^{-5} M_\odot}\right)^{-1} \left(\frac{B_\phi}{10^{17} \text{G}}\right)^2 \left(\frac{R}{10^6 \text{cm}}\right)^2 \left(\frac{l}{10^4 \text{cm}}\right). \quad (3)$$
The luminosity of the wind can be estimated as

$$L_w \sim \frac{B^2 \chi R^3}{8\pi t_{SNR}} \sim 10^{37} \left( \frac{\chi}{10^{-2}} \right) \left( \frac{B_\phi}{10^{17} \text{G}} \right)^2 \left( \frac{t_{SNR}}{10^4 \text{yr}} \right)^{-1} \text{erg s}^{-1},$$

where $\chi R^3$ is the volume of all the flux tubes ($\chi R$ is the characteristic length of the velocity gradient and is assumed to be $\sim l$). This relativistic wind will inject into and power the surrounding SNR.

4. DISCUSSION

Quiescence and burst emission and relativistic particle winds of SGRs have been widely interpreted to result from ultrastrongly magnetized neutron stars (Thompson & Duncan 1995, 1996). In such a magnetar model, the SGR bursts are due to readjustment of the magnetic field, possibly accompanied by cracking of the neutron-star crust, and the persistent X-ray emission is due to decay of the magnetic field, while the winds are due to thermal radiation from hot spots and Alfvén wave emission (Thompson & Blaes 1998). It is very clear that the energy sources of all the emission and winds are the magnetic energy and gravitational energy of the neutron star. However, Harding et al. (1999) have shown that the magnetic field must be up to $\sim 3 \times 10^{13}$ G in order to match the characteristic spin-down timescale for SGR 1806–20 and its surrounding SNR age. Here we have argued that if the magnetic field is indeed so low, the previously suggested energy sources seem problematic because they are much smaller than the observed energies for the persistent X-ray and burst emission and the wind. We have further proposed another plausible model in which SGR pulsars are young strange stars with superconducting cores and with magnetic fields of $\sim 3 \times 10^{13}$ G following Cheng & Dai (1998) and Dai & Lu (1998). In our model, the movement of the flux tubes not only leads to crustal cracking, giving rise to deconfinement of crustal matter to strange matter, but also to movement of internal magnetic toruses with the flux tubes. As have shown in the above section, the former process will result in burst and quiescence emission and the latter process will produce relativistic winds which will power the surrounding SNR.
Another group of sources having periods and period derivatives similar to SGRs are the AXPs, pulsating X-ray sources with periods in the range $6 - 12$ s and period derivatives in the range of $10^{-12} - 10^{-11}$ s s$^{-1}$ (Gotthelf & Vasisht 1998). These sources have shown only strong quiescent X-ray emission with no bursting behavior. Moreover, if the sources are highly magnetic pulsars, their characteristic ages ($P/2\dot{P}$) are in excellent agreement with the SNR ages, implying that the sources have no wind emission. Why are there such obvious differences between SGRs and AXPs? We suggest that AXPs be neutron stars with magnetic fields of $\sim 10^{15}$ G but without any toroidal magnetic field. In the case of slowly rotating neutron stars, crustal cracking cannot produce an observed burst because of too low gravitational energy release, and there is no wind in the absence of toroidal magnetic fields.

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