A MAGNETIC FLUX TUBE OSCILLATION MODEL FOR QPOs IN SGR GIANT FLARES

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ABSTRACT

Giant flares from soft gamma-ray repeaters (SGRs) are one of the most violent phenomena in neutron stars. Quasi-periodic oscillations (QPOs) with frequencies ranging from 18 to 1840 Hz have been discovered in the tails of giant flares from two SGRs and were ascribed to seismic vibrations or torsional oscillations of magnetars. Here we propose an alternative explanation for the QPOs in terms of standing sausage mode oscillations of flux tubes in the magnetar coronae. We show that most of the QPOs observed in SGR giant flares could be well accounted for except for those with very high frequencies (625 and 1840 Hz).

Subject headings: stars: magnetic fields — stars: neutron — stars: oscillations

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1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) are neutron stars that exhibit sporadic burst activities most prominently in soft gamma rays (Norris et al. 1991). Besides normal bursts with energy $E \sim 10^{41}$ ergs, enormously energetic giant flares (with $E \sim 10^{44} - 10^{46}$ ergs) have also been observed, for example, from SGR 0526−66 in 1979 (Mazets et al. 1979), from SGR 1900+14 in 1998 (Hurley et al. 1999; Feroci et al. 1999), and from SGR 1806−20 in 2004 (Hurley et al. 2005; Terasawa et al. 2005; Palmer et al. 2005). The giant flares generally start with an initially rising spike lasting $\sim 1$ s and then evolve into a decaying phase which lasts hundreds of seconds. Theoretically, SGRs are thought to be magnetars, neutron stars with surface magnetic fields strengths of $\sim 10^{14} - 10^{15}$ G (Thompson & Duncan, 1993, 1996, 2001; Duncan & Thompson, 1994), or neutron stars with normal magnetic fields accreting from a disk formed from the fallback in supernova explosions (e.g., Alpar 2001).

During the three SGR giant flares mentioned above, quasi-periodic oscillations (QPOs) were identified both in the initially rising spike and in the decaying tail (Barat et al. 1983; Terasawa et al. 2005, 2006; Palmer et al. 2005; Israel et al. 2005; Strohmayer & Watts 2005; Watts & Strohmayer 2006). These QPOs seem to provide independent evidence for superstrong magnetic fields in SGRs (Vietri et al. 2007). In the most popular models, they are explained as global seismic vibration modes of magnetars (Hansen & Cioffi 1980; Schumaker & Thorne 1983; McDermott et al. 1988; Strohmayer & Watts 2005; Watts & Strohmayer 2006). These QPOs seem to provide independent evidence for superstrong magnetic fields in SGRs (Vietri et al. 2007). In the most popular models, they are explained as global seismic vibration modes of magnetars (Hansen & Cioffi 1980; Schumaker & Thorne 1983; McDermott et al. 1988; Strohmayer & Watts 2005; Watts & Strohmayer 2006). Other explanations have also been proposed. Levin (2006) argued that the QPOs may be driven by the global mode of the MHD fluid core of the neutron star and its crust, rather than the mechanical mode of the crust. Following this idea, Sotani et al. (2008) recently made two-dimensional numerical simulations and found two families of torsional Alfvén oscillations which may explain some of the observed QPOs. Coupling neutron stars’ elastic crust and fluid core, Glampedakis et al. (2006) used a simple toy model to provide explanations for some of the QPOs observed. Magneto-hydrodynamic current variation induced by the crust oscillation was proposed for the modulation of X-ray flux by Timokhin et al. (2008), and they showed that radial oscillation with an amplitude of $1/100$ of the neutron star radius can account for the observed QPO flux fraction.

In this paper we propose an alternative explanation for the QPOs observed in the SGR giant flares. We assume that part of the plasma ejected during the giant flares is trapped by the magnetic fields and then forms magnetic flux tube structures, similar to what is seen in the solar corona. Oscillations of magnetic loops or tubes in the solar corona have been observed by a lot of authors (see Aschwanden et al. 1999, for a review). We argue that tube oscillations in SGR magnetospheres may give rise to some of the QPOs observed during the giant flares. We discuss possible tube oscillation modes in the SGR magnetosphere in § 2 and compare the preferred oscillation frequencies with observations based on the fireball model of Thompson & Duncan (1995) in § 3. The physical implications of our model are discussed in § 4.

2. MAGNETIC FLUX TUBE OSCILLATIONS

In solar physics QPOs with periods of several minutes have been detected in coronal loops and successfully interpreted in terms of MHD waves (Aschwanden et al. 1999; Nakariakov et al. 1999). Following this idea, we suppose that these MHD waves could also be excited in the magnetar corona when starquakes of a magnetar shear its external magnetic field, which becomes nonpotential and threaded by an electric current (Beloborotov & Thompson 2007). As pointed out by Roberts et al. (1984), MHD tube oscillations in the sausage mode can modulate the cross section of the tube, and hence its density and radiation flux, while oscillations in the kink mode do not change the loop density in the first order and thus cannot modulate the plasma radiation (Aschwanden et al. 1999). So we rule out the kink mode oscillations for the QPOs observed in SGRs. Furthermore, observations of the QPOs show that they can last hundreds to thousands of cycles of the oscillation periods (Israel 2005; Terasawa et al. 2005; Palmer et al. 2005; Strohmayer & Watts 2005; Watts & Strohmayer 2006). Accordingly, we exclude the propagating kink mode oscillations because of their rather short damping timescale (about tens of the oscillation period) and consider only the standing sausage mode oscillations.

The flux tube can be roughly described as a cylinder of radius $a$ and length $L$. The magnetic field strength, temperature, mass, and number densities are denoted as $B_0$, $T_0$, $\rho_0$, and $n_0$ inside the tube, and $B_r$, $T_r$, $\rho_r$, and $n_r$ outside the tube, respectively. Magneto-acoustic oscillations of a magnetic tube have been studied thoroughly, and the derived oscillation periods $\tau_{fast}$ for the fast standing sausage mode (Edwin & Roberts 1983;
In this section, we investigate how well the slow sausage mode oscillation frequencies can match the QPOs frequencies observed in SGR giant flares. The QPOs observed in the initial spike phase and in the flare tail phase are treated separately.

3.1. QPOs in the Initial Flare Spike Phase \((t < 1\text{ s})\)

The \textit{Geotail} spacecraft mission was originally meant to study the structure and dynamics of the tail region of the magnetosphere of the Earth. With it 50 and 48 Hz QPOs were detected at \(t = 45\)–175 and 430–567 ms after the onset of the giant flare in SGR 1806–20 in 2004 (Terasawa et al. 2006). The oscillation periods (\(\tau \sim 20\text{ ms}\)) are similar to the period \(20\text{ ms}\) of the QPOs from SGR 0526–66’s giant flare in 1979 (Barat et al. 1983), but no similar phenomena have been seen in the SGR 1900+14 flare.

The physical picture in our flux tube oscillation scenario is as follows: after the onset of the giant flare, hot plasma was ejected into the magnetosphere above the surface of the SGR. Because of the superstrong field strength of the magnetar, the plasma could only move along the field lines, from one to another footpoint of each field line on the star’s crust, and could not get out of the confined structure of the field. This is why a fireball is formed. We assume that the magnetic tubelike structure(s) were subject to various types of oscillations excited by the turbulence at the footpoints. For the slow sausage mode oscillation, the period is related to the initial \(e\)-folding rising time \(t_{\text{rise}} = L/c_s\), which is 9.4 ms\(^1\) in the giant flare from SGR 1806–20 according to \textit{Geotail} spacecraft observations (Tanaka et al. 2007), i.e.,

\[
\tau_{\text{slow}} = \frac{2L}{j c_t} \simeq \frac{2L}{j c_s} \sim 2t_{\text{rise}} \sim 18.8\text{ ms}
\]

for \(j = 1\) (we do not need to consider the gravitational redshift effect in \(t_{\text{rise}}\) here because the observed rising time \(t_{\text{rise}}\) has already included the redshift factor). This period is very close to the observed value \(\sim 20\text{ ms}\).

Unfortunately, there was no QPO detected in the initial rising phase of the giant flare in SGR 1900+14 with rising time \(t_{\text{rise}} \sim 3.1\text{ ms}\), and no rising time was measured in the 1979 March giant flare event with an initial \(~34\text{ Hz}\) QPO. So in the three largest flares ever detected we have only one event in SGR 1806–20 to examine our explanation for the QPOs in the initial spike phase, which should be tested by future detailed monitoring of SGR’s giant flares.

3.2. QPOs in the Flare Tail Phase \((t > 20\text{ s})\)

In the tail phase of the giant flare, declining of the radiation flux is explained as the shrinking of the fireball surface area (Thompson & Duncan 1995). After the fireball has evaporated to a somewhat smaller size, the plasma left from the fireball may form flux tubes above the fireball, and the slow sausage oscillations of such tubes may cause the QPO phenomena. The pulse phase dependence of the QPO amplitude indicates that these oscillations are intrinsic to the neutron star surface (Israel et al. 2005; Strohmayer & Watts 2006). This could be naturally explained by the magnetic flux tube’s footpoints being anchored at certain regions of the neutron star’s crust. A sketch of the structure of the flux tubes is shown in Figure 1.

The length of the tube \(L\) is related to its height \(H\) as

\[
L \simeq b\pi H,
\]

with the geometry factor \(b \sim 1\). Combining equations (2) and (4), we have the oscillation frequency in the slow sausage mode:

\[
f_{\text{slow},j} \simeq 21 \left[1 - \frac{2GM_{\text{NS}}}{(R_{\text{NS}} + H)^2} \right]^{1/2} \frac{1}{J_{10}^{1/2}/H_6}\text{ Hz},
\]

where \(H_6 = H/10^6\text{ cm}\), and the term in brackets is attributed to the gravitational redshift effect \((M_{\text{NS}}\text{ and } R_{\text{NS}}\text{ are neutron star mass and radius, respectively})\).

We then choose typical values of \(T\) and \(H\) in the tail phase of the giant flare to estimate the QPO frequencies. In Feroci et al. (2001), a blackbody component with \(T = 9.3\text{ keV}\), which accounts for \(~85\%\) of the total energy released above 25 keV, was derived at \(t = 65–195\text{ s}\) after the onset of the SGR 1900+14 giant flare. So we may set \(kT \sim 10\text{ keV}\) for the flare in the pulsating tail phase (Thompson & Duncan 1995, 2001; Hurley et al. 2005; Boggs et al. 2007). Previous studies of giant flares suggested a typical length scale \(L \sim 10\text{ km}\) for the “fireball” formed in the burst (Thompson & Duncan 1995, 2001; Hurley et al. 2005).

\(^1\)Schwartz et al. (2005) measured the \(e\)-folding rising time to be \(\sim 4.9\text{ ms}\) from the observations on a giant flare from SGR 1860–20 with the Chinese Double Star polar spacecraft.
2005; Boggs et al. 2007), so we may take $H_0 \simeq 1$ for the flux tube. These values give $f_{\text{slow}} \approx 19$ Hz for the fundamental mode $(j = 1)$ in a neutron star of mass $M_{\text{NS}} = 1.4 \, M_{\odot}$ and radius $R_{\text{NS}} = 10$ km. Considering its harmonic oscillations, most of the observed QPOs (summarized in Table 1) may be well explained, except those with very high frequencies of 625 and 1840 Hz, because excitations of oscillations with $j > 20$ must be very difficult.

### 3.3. Modulation of the Radiation

In § 3.2 we showed that the slow sausage mode oscillations of flux tubes seem to be consistent with the QPOs observed. Now we move to the question how such tube oscillations modulate the radiation observed in the tail phase of the giant flare. The mass of the plasma in the flux tube can be estimated to be $\Delta M \sim 10^{23}$ g from equation (22) in Thompson & Duncan (1995), assuming the total giant flare energy $E \sim 3 \times 10^{46}$ ergs (Cameron et al. 2005). The plasma density is then $\rho = \Delta M / \Delta V \sim 10^{23} / 10^{18} \sim 10^5$ g cm$^{-3}$, where $\Delta V$ is the tube volume. The Rosseland mean scattering cross section in the direction parallel to the magnetic field is (Thompson & Duncan 1995)

$$\sigma_{\text{es}} = 2.2 \times 10^9 T^2 B^{-2} \sigma_T$$

$$\simeq 1.5 \times 10^{-15} T^2 B^{-2} \ \text{cm}^2,$$

where $\sigma_T = (8\pi/3)(e^2/m_e c^2)^2$ is the Thomson scattering cross section. Then the optical depth of the tube is

$$\tau = n \sigma_{\text{es}} L = \rho \sigma_{\text{es}} L \sim 10^9 T_{10 \text{keV}}^{-2} B_{14}^{-2} L_6,$$

suggesting that the flux tube is optically thick. Since the fireball itself is also optically thick (Thompson & Duncan 1995), the ratio of the radiation fluxes from tube and from the fireball can be simply expressed as the ratio of their cross section areas,

$$\frac{F_{\text{tube}}}{F_{\text{frb}}} \sim \frac{S_{\text{tube}}}{S_{\text{frb}}} \sim \frac{2\alpha L}{\pi r_{\text{frb}}^2} \sim \frac{2\alpha}{r_{\text{frb}}},$$

if we assume that the thermal temperatures of the fireball and the tube are roughly the same (about 10 keV). Here $r_{\text{frb}}$ is the radius of the fireball, and $L \sim \pi r_{\text{frb}}^2$. As the flux tube oscillates, its cross section and surface areas vary, and so does the thermal emission from the tube. The amplitude of the QPOs can be derived to be

$$\frac{\delta F_{\text{tube}}}{F_{\text{frb}}} \sim \frac{\delta \alpha}{a} \frac{S_{\text{tube}}}{S_{\text{frb}}} \sim \frac{2\delta \alpha}{r_{\text{frb}}},$$

This amplitude is compatible with the observational values $\sim 10\%$–$20\%$ (Israel et al. 2005; Strohmayer & Watts 2006; Watts & Strohmayer 2006) only when the radial oscillation amplitude of the tube is in the range $\delta \alpha / r_{\text{frb}} \sim 5\%$–$10\%$. This may explain why the QPOs emerged from the light curve after about $\sim 100$ s from the onset of the giant flare: at the very beginning of the giant flare, the fireball was so big that the tube radiation was too weak, compared with that from the fireball, to produce detectable QPOs.

It is noted that the QPOs are more likely to be detected in hard X-ray bands (Strohmayer & Watts 2005; Watts & Strohmayer 2006), and their amplitudes in soft X-rays are not as strong as in hard X-rays. One example is the 84 Hz QPO from SGR 1900+14 (Strohmayer & Watts 2005): its amplitude increased from $< 14\%$ in the $< 18$ keV band, to $20\% \pm 3\%$ in the $12$–$90$ keV band, and $26\% \pm 4\%$ in the $> 30$ keV band. There are several possible reasons for this QPO amplitude-energy band dependence. The first is the photon splitting mechanism (Thompson & Duncan 1995). Diffusion of photons from the fireball is primarily in $E$-mode due to the different scattering cross sections between the two polarization modes. Before the $E$-mode photons reach the flux tube, the photons with energy higher than 40 keV still suffer serious photon splitting effect in the magnetic fields higher than the quantum magnetic field ($B_{\text{QED}} = 4.4 \times 10^{13}$ G). This will produce an excess in the $10$–$20$ keV band in the spectrum from the fireball (Lyubarsky 2002), decreasing the ratio of the photon fluxes from the tube and from the fireball in this energy band and hence the QPO amplitude. The second is that the cross section of electron scattering decreases with decreasing photon energy, so the low-energy photons seen by us come from a deeper region in the fireball, where temperature is higher (see Fig. 2 in Ulmer 1994). This may also increase the low-energy photon flux from the fireball and reduce the amplitude of the QPOs in the same energy band. The third is cyclotron scattering of thermal photons in the
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In this subsection we derive the energy needed to excite the oscillations of the flux tube, and the constraints on the possible energy source. From Wang et al. (2003), the energy needed to excite the slow sausage mode oscillations can be estimated to be

$$
\Delta E \sim \frac{1}{2} \Delta M \sigma^2 \sim \frac{1}{2} \Delta M \left( \frac{2 \pi c_s}{a} \right)^2
$$

$$
\sim \Delta M kT/m_p \sim 10^{38} \text{ergs},
$$

where $\Delta M \sim 10^{23} \text{g}$ and $kT = 10 \text{keV}$ have been adopted for the plasma in the flux tube.

According to recent investigations on the excitation of standing slow mode oscillations in a flux tube (Taroyan et al. 2004, 2005), the excitation energy should be injected into the tube within a timescale similar to the oscillation period $\tau$ if the oscillations are excited by the energy deposition at the footpoint of the tube. If the energy deposition is through thermal conduction (Spitzer 1962), the deposited energy would be $\Delta E \sim F_c \sigma T \tau$, with $F_c \simeq (1.84 \times 10^{-5} T^{5/2} \sqrt{T} \gamma) \ln \Lambda \text{ergs}^{-1} \text{cm}^{-2}$ being the heating flux and $\gamma$ the heating area. Taking $T \sim 10^6 \text{K}$, $\sqrt{T} \sim 10^5 \text{K}^{-1/2}$, $S \sim 10^7 \text{cm}^2$, and $\tau \sim 0.01 \text{s}$, we get $\Delta E \sim 10^{24} \text{ergs}$, which is far less than that needed to excite the oscillations. So we conclude that the excitation energy is unlikely to be deposited through thermal conduction, but most likely by flare activities at the footpoint(s) of the tube. Hence QPOs are not expected to be detected during the quiescent phase of SGRs.

4. DISCUSSION

We have suggested the slow sausage oscillation modes of magnetic flux tubes to explain most of the QPOs detected in SGRs during giant flares. These QPOs generally last several rotational cycles, i.e., tens of seconds, and present useful constraints on the damping mechanisms for the QPOs. The damping of magnetic loop oscillations in the solar corona has been extensively studied (Cally 1986; Nakariakov et al. 1999; Ruderman & Roberts 2002; Stenuit et al. 1999; Taroyan et al. 2004). Radial wave leakage and resonant absorption are considered to be the main damping mechanisms. In our case, we consider only the effect of resonant absorption; as Ruderman & Roberts (2002) pointed out, if the mass density inside the tube is greater than that outside, the wave leakage effect is not important. Considering the curvature of the tube, we can use the damping timescale of kink mode oscillations as that of sausage mode oscillation (Roberts 2000), which is given by (Ruderman & Roberts 2002)

$$
\tau_{d} = \frac{2a \rho \rho_r + \rho_k}{\pi f \rho_0 - \rho_e} \tau.
$$

Here we assume that the mass density varies in the annulus region $a - l \leq r \leq a$ from $\rho_0$ to $\rho_e$. From equations (18) and (22) in Thompson & Duncan (1995), we have $a \sim 2 \gamma_B^2 l \sim 10^4 l$.

So $\tau_d \sim 10^4 \tau$, which is roughly consistent with the observational result $\tau_d \sim 5 \times 10^3 \tau$ for the 92 Hz QPO in SGR 1806–20 lasting about 50 s. Note that the damping timescale is proportional to oscillation period $\tau$, so higher frequency oscillations should decay more quickly, which is also compatible with observations (Strohmayer 2008). However, the above results are based on the assumption that the flux tube is thin and axisymmetric with homogeneous mass distribution, which may not be satisfied in the real situation. Nonideal effects, like the density stratification, magnetic field curvature and twist, and thick tube limitation have been studied in both theories and numerical simulations (Van Doorsselaere et al. 2004a, 2004b; Andries et al. 2005; Erdélyi & Fedun 2006; Arregui et al. 2007). These works show that the above effects may only change the oscillation frequency by as much as 10%–15%, but seriously damp the oscillation mode and reduce the damping timescale.

So the damping timescale with equation (12) should be taken as an upper limit.

Observations indicate that the QPO frequencies seem to remain almost constant, with slight variations. For example, Israel et al. (2005) found a possible time evolution of the QPO in SGR 1806–20 with the frequency increasing from 92.5 to 95 Hz. From equation (2) it is seen that the oscillation frequency is determined by the length and temperature of the flux tube. Since the flux tube’s footpoints are anchored at the surface of the star and confined by the superstrong magnetic fields that dominate the plasma’s motion, its structure and length may not change much in the tail phase of the giant flare. If there is no extra energy injected into the flux tube, the temperature of the flux tube is likely to remain nearly unchanged during the lifetime of the QPOs (less than tens of seconds), as also indicated by observations (Feroci et al. 1999, 2001). So we would not expect a considerable change in the QPO frequency. The QPO amplitude, however, depend on the size of the fireball and the oscillation amplitude of the flux tube (see eq. [9]), both of which decrease with time in the tail phase of the giant flare. The fact that the QPO’s lifetime (≤50 s) is less than the evaporation time of the fireball (∼200–400 s) implies that the oscillations damp faster than the shrinking of the fireball. So in this model the QPO amplitude is predicted to decrease with time, which could be testified in the future high time resolution observations.

The seismic vibration model has been quite successful in explaining the QPOs in SGRs, but there are some important issues needing to be resolved. In the tube oscillation model the oscillation frequency is $f_j \propto j$, while in the seismic vibration model $f_j \propto (j+1)^{1/2}$, where $j$ is the number of nodes (McDermott et al. 1988). To account for the observed frequencies with seismic vibration, one has to use the $j = 2, 4$, and 6 modes but ignore the $j = 3$ and 5 modes (Watts & Strohmayer 2006). Recently, Samuelsson & Andersson (2007) have derived a modified relation $f_j \propto (j-1)(j+2)^{1/2}$ for the torsional seismic modes using a general relativistic formulation, but the problem of why the $j = 3$ and 5 modes do not exist still remains. In this point of view, the tube oscillation model seems to be more natural, since the $j = 1, 2$, and 3 modes have all been used.

There seem to exist three QPOs with different fundamental frequencies (18, 26, and 30 Hz) in SGR 1806–20 (Watts & Strohmayer 2006). In the seismic vibration model, only one fundamental oscillation mode can exist (Israel et al. 2005; Watts & Strohmayer 2006). However, in the tube oscillation model this could be explained if there are several flux tubes oscillating in slightly different fundamental modes. The existence of the multi-frequencies might be due to the deviations in the temperature, density, and strength or topology of the magnetic field around the active regions in the magnetosphere. It is noted, however, that it is difficult to explain the 625 and 1840 Hz QPOs observed in SGR
1900+14 in the tube oscillation model. For these extremely high frequencies, the $n = 1$ and 3 torsional shear mode vibration (Piro 2005) might be a more reasonable explanation. This also suggests that the QPOs in the giant flares may not be homogeneous, and may have different origins.

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