RADIO EMISSION FROM MAGNETARS

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ABSTRACT

We discuss properties of the expected radio emission from soft gamma-ray repeaters (SGRs) during their bursting activity in the framework of the model of Thompson, Lyutikov, & Kulkarni, in which the high-energy emission is powered by the dissipation of superstrong magnetic fields in the magnetospheres through reconnection-type events. Drawing on analogies with solar flares, we predict that coherent radio emission resembling solar type III radio bursts may be emitted in SGRs during X-ray bursts. The radio emission should have correlated pulse profiles with X-rays, a narrowband-type radio spectrum with $\Delta f \leq f$, with the typical frequency $f \geq 10$ GHz, and, possibly, a drifting central frequency. We encourage sensitive radio observations of SGRs during the bursting activity.

Subject headings: radiation mechanisms: nonthermal — stars: flare — stars: neutron

1. INTRODUCTION

Soft gamma-ray repeaters (SGRs) and anomalous X-ray pulsars (AXPs) have been identified as isolated magnetized neutron stars—magnetars (for recent reviews, see, e.g., Thompson 2002). Both SGRs and AXPs have spin periods in the range of $P = 6$–12 s, spin-down rates in the range from $P = 10^{-11}$ to $10^{-12}$ s$^{-1}$, and X-ray luminosities $L_X = 3 \times 10^{33}$–$10^{34}$ ergs s$^{-1}$. SGRs are characterized primarily by occasional repeating bursts of soft gamma rays as well as by rare giant gamma-ray outbursts that are at least 2 orders of magnitude higher in fluence than the smaller events (two have been detected so far). The more common small-amplitude bursts have durations of less than $\sim 1$ s, have rise times of typically a few tens of milliseconds, and have fluences that are roughly correlated with duration (Gügüş et al. 2001). In quiescence, SGRs display X-ray pulsations with periods in the range of 5–8 s, spin-down rates in the range from $10^{-11}$ to $10^{-12}$, and X-ray emission, most prominent below $\sim 10$ keV, that is well described by a power law with a photon index of $\sim 2$.

Recently, Gavriil, Kaspi, & Woods (2002) reported an observation of bursts from AXPs. If confirmed, this would establish a close relation between AXPs and SGRs; the similarity between the burst properties of both classes is an argument in favor of their mechanisms for X-ray burst production being the same. Below we concentrate on a better studied case of SGR bursts, but most of the arguments given may be applied to AXP bursts as well.

The radio counterpart status of SGRs has been controversial. Shitov, Pugachev, & Kutuzov (2000) reported the detection of pulsed emission from SGR 1900+14 at 111 MHz with the PushchinoRadio Observatory. However, using Arecibo in 1998, Lorimer & Xilouris (2000) observed SGR 1900+14 yet detected no such radio pulsations. Indeed, no radio pulsations have been detected from any of the SGRs. This is somewhat surprising since recent radio surveys have discovered pulsars with polar magnetic fields approaching $10^{14}$ G (Camilo et al. 2000), continuous with the lower range of fields deduced from AXP spin-down.

Recently, Thompson, Lyutikov, & Kulkarni (2002) have proposed a model of the SGRs based on the dissipation of the internal superstrong magnetic field, generated by a hydromagnetic dynamo as the star is born, by external currents flowing in the magnetosphere. They argued that the currents supporting the strongly twisted field inside the neutron stars are gradually transported into the external magnetosphere, where they can be efficiently dissipated. The rate with which the currents are transported into the magnetosphere depends on the tensile strength of the neutron star crust and the strength of the nonpotential (current carrying) magnetic fields. Two regimes are possible: for plastic-type deformations of the crust, the twist is implanted at a more or less constant rate, while for fracturing-type deformations, the twist is implanted in sudden events. Overall, the behavior of the magnetic field resembles that of the Sun, as the current is transported from the matter-dominated star into the magnetically dominated corona. The parallels between the dynamics of the solar and magnetar field loops extend even further: in both cases, the footpoints are believed to be moved by the torques acted upon them by the twisted magnetic fields (in addition, on the Sun, some footpoints are moved around by the convective motions).

With reservation for our understanding of reconnection and particle acceleration, we propose here that the bursting activity of AXPs and SGRs is due to the reconnection-type events in which magnetic energy stored in the nonpotential magnetic field is released in the magnetosphere. Pushing the analogies with the Sun even further, we argue that both the persistent emission and the flares, including giant flares, may result from discreet energy-releasing events, in which the external field relaxes to a lower energy state with a different field-line topology. This requires that the external magnetic shear be built up gradually and that the outer crust of the neutron star be deformed plastically by internal magnetic stresses. The energy stored in the external twist then does not need to be limited by the tensile strength of the crust but instead by the total external magnetic field energy.

Any suggestion of the importance of reconnection in astrophysical sources may only be based on the empirical relations obtained from solar observations. The solar magnetosphere structure and temporal behavior are extremely complicated; it seems almost impossible to predict the behavior of the magnetosphere. Yet there seem to be fairly general scaling laws, which extend from the smallest scales of the solar flares to magnetically active stars (e.g., T Tauri). The two such correlations that we will rely on are (1) the linear dependence of...
the X-ray luminosity on the magnetic flux (e.g., Johns-Krull & Valenti 2000), which shows over 10 decades in X-ray and magnetic fluxes, and (2) a strong correlation between the radio activity and the high-energy activity, also extending from solar flares to stars. On the Sun, the radio intensity of large solar flares, when observed, is linearly proportional to the X-ray flux (Sakurai 1974).

The direct consequence of the reconnection is the generation of radio emission, which always accompanies solar X-ray flares. The natural prediction then is that the radio emission should be observed from SGRs during bursts. Below we concentrate on SGRs, keeping in mind that bursts may have already been observed from AXPs (Gavriil et al. 2002). Here we discuss the expected properties of the radio emission of the SGRs, offer the best strategy for their detection, and discuss possible effects that may prevent the detection of radio emission from SGRs.

2. SOLAR FLARES

Energy dissipation in solar flares is a generically nonlinear phenomena: explosive-type instabilities initially grow exponentially (and thus are often called “avalanches”) and saturate after a few e-folding growth times, after all locally available free energy has been exhausted (Priest & Forbes 2002). The mechanism responsible for impulsive reorganization is not established, yet it seems that the dissipation takes place in spatially separated, unresolved complex structures, including small-scale structures.

Statistical studies of solar energy release events, e.g., the distribution of event number versus energy content as observed at hard X-rays, have led to a description in terms of avalanches in a corona that has stored energy and is in a state of self-organized criticality (Lu & Hamilton 1991). The power-law distribution $N(E) \sim E^{-q}$ naturally follows from such a model since the system under consideration has no characteristic spatial scale above the elementary scale of the smallest avalanche (the smallest energy release event), up to the system size, the size of active regions.

3. PERSISTENT AND BURST EMISSION FROM RECONNECTION

A number of facts point to the magnetospheric origin of SGR burst (and possibly persistent) emission. The short rise time of SGR bursts may be explained in the magnetar model only if it originates in the magnetosphere. In case of persistent emission, the initial energy release may also happen in the magnetosphere as a result of unresolved small-scale events. Later, the energetic particles will heat the crust that will produce the thermal emission.

The studies of the statistics of the SGR bursts from SGR 1900+14 (Göğüş et al. 1999) have found a dependence similar to that of solar flares of the number of bursts on their fluences with a power-law index of 1.66 over 4 orders of magnitude. The distribution of time intervals between successive bursts from SGR 1900+14 is also consistent with a lognormal distribution.

Another type of correlation, expected in the reconnection model, is that between the burst duration and the total release energy. This is a natural correlation since larger bursts are required to tap into larger volumes of the energy reservoir. Such a correlation indeed was seen in the SGR bursts by Göğüş et al. (1999).

Other circumstantial evidences favoring magnetospheric emission include the following: (1) SGR bursts come at random phases in the pulse profile (Palmer 2000); this is naturally explained if (even only one!) emission site is located high in the magnetosphere, so that we see all the bursts (if the bursts were associated with a particular active region on the surface of the neutron star, one would expect a correlation with a phase). (2) A pulsed fraction increases in the tails of the strong bursts, keeping the pulse profile similar to the persistent emission (P. Woods 2002, private communication); this is easier to explain if the energy-release processes occurring high in the magnetosphere, after the giant burst, are connected to the same hot spot on the surface of the neutron star as the field, which is active during the quiescent phase. (3) The weak blackbody component in the tail of the strong bursts is more consistent with the magnetospheric emission. (4) Smaller fluence SGR events have harder spectra than the more intense ones (Göğüş 2002; this is also true for the spikes of multistructured bursts); this is consistent with short events being due to reconnection, while longer events have a large contribution from the surface, heated by the precipitating particles.

4. RADIO EMISSION FROM FLARES

Solar flares release magnetic energy in three equally important channels: in thermal heat, in the bulk motion of plasma, and in energetic suprathermal (and/or accelerated) particles. Solar flares are often accompanied by radio bursts, most often by what are called type III bursts (Bastian, Benz, & Gary 1998). Type III radio bursts are signatures of energetic electrons generated during solar flares, traveling along the magnetic coronal field lines. As a result, electrostatic plasma turbulence develops. Electromagnetic radio emission is generated in the collision of two plasma waves. The resulting emission is a narrowband emission above the second plasma harmonic $\omega \sim 2\omega_p$. We propose that similar coherent emission may be generated in SGRs. Since the radio emission is generated by the electrons accelerated at the reconnection site, we predict that if the radio emission is detected during the bursting phases of SGRs, its intensity and profile will be strongly correlated with the X-ray bursts.

5. EXPECTED PROPERTIES OF SGR RADIO FLARES

5.1. Temporal Behavior

Energy release in reconnection appears to be a nonstationary transient phenomenon resulting, presumably, from the spatially fragmented structure. The temporal behavior of solar flares has several timescales, associated with different spatial scales of the reconnecting structures. Similarly, the radio emission is expected to be nonstationary and multitime-scaled, keeping the memory of the energy-release history.

In reconnection, the shortest timescale is related to the Alfvén crossing time of the magnetic structures of length $L$: $\tau_c \sim L/v_A$ (for the Sun, this is $\sim 1$ s). The scale $L$ corresponds to the length of the reconnecting arc, which for the SGRs may be as small as a fracturing of radius and as large as the light-cylinder radius. For flares occurring close to the surface, we may assume that $L \sim R_{SS}$. The Alfvén velocity $v_A$ equals the speed of light in the force-free magnetosphere. The observed rise time of the SGR X-ray flares, $\lesssim 10$ ms, is consistent with being related to the Alfvén timescale. For the observed bursts, the rise time is limited by the intensity of the burst—less bursts are expected to have shorter rise times (Göğüş 2002). The shortest rise time is expected to be of the order of the light-travel time across the neutron star—tens of microseconds. This timescale also gives the duration of the shortest spikes in the burst structure. Radio bursts
should have similar rise times, with a possible time delay to allow for the plasma instabilities to develop after the main X-ray burst. The overall duration of the burst depends on the global structure of the reconnection region—the reconnection at one point may trigger reconnection at other points.

Radio emission should be more intermittent than X-ray emission, reflecting the fact that its intensity depends both on the production rate, monitored well by the X-ray flux, and on the often subtle conditions for the development of kinetic instabilities (e.g., the requirement that the beam velocity be larger than the thermal velocity of the plasma particles).

5.2. Spectra

Thompson et al. (2002) discuss the properties of the strongly twisted magnetosphere of the SGRs. Qualitatively, the maximum current that the magnetosphere can support corresponds to the toroidal field, reaching in strength approximately a potential that the magnetosphere can support corresponds to the sum of the fields, 

$$B_{\text{max}} \approx B_{\text{tor}} + B_{\text{pol}}.$$ the typical velocity of the charge carriers is weakly relativistic, \(\gamma \approx 0.8c\). From the induction equation, we then find the current \(j\):

$$j \sim \epsilon n \sim \frac{cB}{4\pi R}.$$ the plasma density \(n\), and the plasma frequency \(\omega_p = (4\pi e^2 n/m)^{1/2}:

$$n \sim \frac{B}{4\pi e R}, \quad \omega_p^2 \sim \frac{\omega_B c}{R}.$$ Here \(e\) and \(m\) are the charge and the mass of an electron, respectively, \(B\) is the magnetic field, \(\omega_p = eB/mc\) is the cyclotron frequency, and \(R\) is the radius. Below we assume that such strong currents are indeed flowing in the SGR magnetospheres. Numerical estimates then give for the surface magnetic field \(B_{\text{NS}} = 10^{14} \text{G}\), \(\omega_p = \omega_{\text{pla}} \tilde{r}^{-3/2}\), where \(\tilde{r} = R/\sqrt{R_{\text{NS}}}\), and the surface cyclotron frequency \(\omega_{\text{pla}} = 2 \times 10^{13} \text{rad s}^{-1},$$

$$\omega_p = \frac{\eta \omega_{\text{pla}} c R_{\text{NS}}}{\tilde{r}^2} = 1.2 \times 10^{9} (\tilde{r}/10)^{-2} \text{rad s}^{-1}. \quad (3)$$ The self-similar model of Thompson et al. (2002) predicts that most of the nonpotential energy of the magnetosphere is concentrated near the stellar surface, at \(R \leq 10R_{\text{NS}}\). In order to tap this energy, the energy-release site should be located at similar low heights, but the fast electrons that produce radio may propagate both upward and downward in the magnetosphere along the closed magnetic field lines. Equation (3) then may explain why the radio emission from SGRs has not been detected yet and suggests a strategy for further searches. If the coherent radio emission is generated near the stellar surface and is associated with the local plasma frequency \(\omega_p\), then from equation (3) we may expect that the coherent radio emission should be generated at relatively high frequencies, \(\nu \geq 10 \text{ GHz}\) and reaching \(\sim 1000 \text{ GHz}\) (this will fall into the submillimeter range). The upper limit (\(\sim 1000 \text{ GHz}\)) is set by the maximal current (eq. [1]) that a magnetosphere with a given surface field can support. On the other hand, the low-frequency bound \(\nu \gtrsim 10 \text{ GHz}\) is not very well defined: it depends on precisely what fraction of the maximal current is indeed flowing in the magnetosphere and on how high the fast particles can propagate in the magnetosphere.

The radio emission of SGRs is expected to be qualitatively different from the normal radio pulsar emission. In conventional radio pulsars, the presence of the primary beam with superrelativistic Lorentz factors is imperative for the generation of radio emission. In SGRs, this primary beam may not be created since the Goldreich-Julian density is much smaller than the density of the currents required to support the twisted magnetic field. If a large charge density is indeed generated on the open field lines, the particle accelerator, operating in the rotationally powered pulsars, may be swamped, and no pulsar-type radio emission is generated. This may be another reason why radio emission has not yet been detected in SGRs.

The radio emission of SGRs during bursting activity will resemble the solar radio type III bursts. In solar type III bursts, the energy is consecutively converted from the magnetic energy into fast particles, then into electronstatic plasma waves, and finally into escaping electromagnetic waves. The frequency of the generated emission measure waves is the double of the plasma frequency \(\nu \sim 2\nu_p\). Thus, one expects a narrowband emission \(\Delta\nu/\nu \lesssim 1\). The growth rate of Langmuir instability,

$$\Gamma(\nu) \sim (\eta_{\text{be}} \nu^{5/2} \omega_p \lesssim \nu_p,$$

where \(\eta_{\text{be}}\) is the beam density), is indeed much higher than the dynamical time,

$$\Gamma(\nu) \sim (\nu_{\text{be}} \nu)^{5/2} \nu_p \lesssim \nu_p.$$ Thus, the plasma instability has enough time to develop.

A distinct feature of the type III burst is the drift of the central frequency that is due to the spatial propagation of the emitting beam in the inhomogeneous plasma. Since the velocities of the emitting electrons are likely to be weakly relativistic, the resulting emission may not be narrowband emission, since the electrons propagate in the inhomogeneous plasma. Still, one may expect the frequency drift of the peak of radio emission, characteristic of type III bursts. Since the plasma density in the SGR magnetosphere is \(\omega_p \sim \tilde{r}^{-3/2}\), then, if fast electrons propagate with \(\nu \sim c\), the central frequency will move as \(\omega_{\text{max}} \sim \tilde{r}^{-2}\), taking into account the possibility of upward and downward movement. The multipolar structure of the magnetosphere may change this simple dependence.

It may also be possible to observe the U-type subclass of the type III bursts: in this subclass, the central frequency first decreases and then starts to increase as emitting electrons move along the closed field lines, reach the maximum height above the stellar surface (at this point, the density is minimal and so is the frequency of emission), and then return to the stellar surface.

5.3. Expected Flux

The radio brightness of SGR bursts may be estimated using the energy partitioning in the solar flares, where the energy release in radio is typically \(10^{-4}\) of the energy released in hard X-rays (plus an approximately similar amount of energy is released in bulk motion, thermal heating, and cosmic rays). Since the X-ray luminosity of flares is \(\sim 10^{36} \text{ erg s}^{-1}\), the expected radio luminosity is \(\sim 10^{32} \text{ erg s}^{-1}\), which, at a distance of \(\sim 10 \text{ kpc}\) and with an observing frequency of
~10 GHz, will produce a flux of ~0.1–100 Jy (assuming a bandwidth of emission $\Delta \nu \sim \nu$), which may be easily detectable.

6. DISCUSSION

We encourage radio observations of SGRs and AXPs during their active phase at high frequencies (i.e., greater than several gigahertz). This requires catching a burst in simultaneous radio and X-ray observations. During its active phase, SGR 1900 + 14 produces bursts every ~50 s, emitting an $\sim 10^{48}$ erg s$^{-1}$ burst every ~10 minutes (Gögüş 2002). The radio flux from such a burst (~10 Jy) can be easily detected. Although larger flares are less likely, a radio burst is more likely to be detected than an X-ray burst, which may be easily detectable. During its active phase, SGR 1900 + 14 usually produces bursts once per hour. The search should be done in a pulsar mode with fast timing. Initial detection will naturally require a search in the dispersion measure space; the frequency drift of the emission may complicate the dispersion measure search. A strong correlation with the X-ray burst may provide additional help in detecting radio bursts, especially after the first one is seen and after the time delay between X-rays and radio, due to the interstellar medium propagation, is measured.

Persistent radio emission from SGRs may also be observed, although the expected fluxes of ~1–10 mJy (based on the same radio/X-ray luminosity ratio of $10^{-4}$ and the persistent X-ray emission from SGRs of $\sim 10^{34}$–$10^{35}$ erg s$^{-1}$) may be too faint.

A number of factors may preclude the detection of radio emission from SGR burst: (1) Reconnection in SGRs may be qualitatively different from the reconnection on the Sun. (2) Radio emission may be strongly absorbed (or scattered at $r < r_c$) at the cyclotron resonance inside the SGR magnetosphere. Incidentally, if we assume that an ~6 s pulsar strongly scatters or absorbs radio waves inside the light cylinder, then one would expect a sharp cutoff above ~100 MHz, consistent with the claims of detection of SGR 1900 + 14 frequencies and of nondetection at higher frequencies (Shitov et al. 2000; Gil, Khechinashvili, & Melikidze 1998). (3) Abundant pair production during the burst may significantly increase the plasma density and the plasma frequency, pushing the radio emission to higher frequencies.

Another possible mechanism of radio emission generation—due to the loss-cone instability and at the anomalous cyclotron-Cerenkov resonance—is not likely to operate in SGRs. In the superstrong magnetic fields of SGRs, electrons lose their transverse energy almost immediately. Thus, we do not expect any adiabatically trapped electrons to exist near the neutron star radius (the adiabatic radius, where the cyclotron decay time becomes equal to the rotational period, is $r_v \sim 5 \times 10^{11} R_{\text{NS}} \sim 0.15 R_{\text{NS}}$). So no loss-cone instability will develop. Since the difference of the refractive index of plasma from unity is negligible ($n - 1 \sim c/\omega_0 p_{\text{e}} \sim 10^{-18}$), no anomalous cyclotron-Cerenkov instability (Lyutikov, Blandford, & Machabeli 1999) will develop either. We can also neglect the (frequency-independent) dispersion inside the magnetosphere.

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