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GRAVITATIONAL RADIATION FROM NEWBORN MAGNETARS IN THE VIRGO CLUSTER

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ABSTRACT

There is growing evidence that two classes of high-energy sources, the soft gamma repeaters and the anomalous X-ray pulsars, contain slowly spinning "magnetars," i.e., neutron stars whose emission is powered by the release of energy from their extremely strong magnetic fields ($>10^{15}$ G). We show here that the enormous energy liberated in the 2004 December 27 giant flare from SGR 1806−20 ($\sim 5 \times 10^{46}$ ergs), together with the likely recurrence time of such events, requires an internal field strength of $\gtrsim 10^{16}$ G. Toroidal magnetic fields of this strength are within an order of magnitude of the maximum fields that can be generated in the core of differentially rotating neutron stars immediately after their formation, if their initial spin period is on the order of a few milliseconds. A substantial deformation of the neutron star is induced by these magnetic fields and, provided the deformation axis is offset from the spin axis, a newborn fast-spinning magnetar would radiate for a few weeks a strong gravitational wave signal, the frequency of which (∼0.5–2 kHz range) decreases in time. The signal from a newborn magnetar with internal field $>10^{16.5}$ G could be detected with Advanced LIGO-class detectors up to the distance of the Virgo Cluster (characteristic amplitude $h_c \sim 10^{-21}$). Magnetars are expected to form in Virgo at a rate of ≥ 1 yr^{-1}. If a fraction of these have sufficiently high internal magnetic fields, then newborn magnetars constitute a promising new class of gravitational wave emitters.

Subject headings: gravitational waves — stars: individual (SGR 1806−20) — stars: magnetic fields — stars: neutron

1. INTRODUCTION

The two classes of pulsating high-energy sources that are believed to host magnetars, the soft gamma repeaters (SGRs) and the anomalous X-ray pulsars (AXPs), share a number of properties (see, e.g., Mereghetti & Stella 1995; Kouveliotou et al. 1998; Woods & Thompson 2004). They have fairly long spin periods in the ∼5–10 s range, spin-down secularly with timescales $\sim 10^4$–10^5 yr, do not have a companion star, and are in some cases associated with supernova remnants with ages $\sim 10^3$–10^4 yr. Rotational energy losses are 1–2 orders of magnitude too low to explain the persistent emission of these sources, which is typically $\sim 10^{34}$–10^{35} ergs s^{-1}. Both AXPs and SGRs show periods of activity in which recurrent short bursts ($\ll 1$ s) are emitted, with peak luminosities in the $\sim 10^{38}$–10^{41} ergs s^{-1} range. The initial spikes of giant flares are second-long events of exceptionally high luminosity, 3–6 orders of magnitude larger than that of the brightest recurrent bursts. Giant flares are rare; only three have been observed so far, and might well be specific to SGRs. Given the highly super-Eddington luminosities of recurrent bursts, and especially, giant flares, accretion power is not an option.

The magnetar model envisages that SGRs and AXPs are powered by the release of energy from their extremely high magnetic fields (Duncan & Thompson 1992; Thompson & Duncan 1993, 1995, 1996, 2001). It has been largely successful in interpreting the unique features of these sources. According to this model, a twisted, mainly toroidal magnetic field characterizes the neutron star interior ($B > 10^{15}$ G), only partially threading the crust. The emerged (mainly poloidal) field makes up the neutron star magnetosphere, with dipole strengths $B_d \sim$ a few $\times\ 10^{14}$ G, as required to generate spin-down at the observed rate (Thompson & Duncan 1993). Energy is fed to the neutron star magnetosphere through Alfvén waves driven by local "crustquakes" of various amplitude and producing recurrent bursts. Giant flares may result from large-scale rearrangements of the core magnetic field or catastrophic instabilities in the magnetosphere (Thompson & Duncan 2001; Lyutikov 2003). These events occur more rarely and lead to the sudden release of very large amounts of energy. Most of this energy breaks out of the magnetosphere in the form of a fireball of plasma expanding at relativistic speeds and giving rise to the initial spike of giant flares. The oscillating tail that follows this spike, displaying up to ∼50 cycles of the neutron star spin, is interpreted as due to that part of the flare energy that remains trapped in the magnetosphere. The total energy released in this tail ($\sim 10^{44}$ ergs in all three events detected so far) provides an independent estimate of $\gtrsim 10^{14}$ G for the external field of magnetars (Thompson & Duncan 1995, 2001).

2. THE INTERNAL *B*-FIELD OF MAGNETARS

The 2004 December 27 giant flare from SGR 1806−20 provides a new estimate of the internal field strength of magnetars. About 5×10^{46} ergs were released in the ∼0.6 s main spike of this event (Terasawa et al. 2005; Hurley et al. 2005), i.e., a 2 decade higher energy than that of the other giant flares observed so far (the 1979 March 5 event from SGR 0526−66 [Mazets et al. 1979] and the 1998 August 27 event from SGR 1900+14 [Hurley et al. 1999; Feroci et al. 1999]). Only one such powerful flare has been recorded in about 30 yr of monitoring of the ∼5 known magnetars in SGRs. The recurrence time in a single magnetar implied by this event is thus about ∼150 yr (if giant flares were emitted also by AXPs, this recurrence time would increase by a factor of ∼2, as the number of AXPs and SGRs in our Galaxy is comparable). The realization that powerful giant flares could be observed from distances of tens of megaparsecs (and thus might represent a sizable fraction of the short gamma ray burst population) motivated searches for 2004 December 27-like events in the BATSE GRB database (Lazzati et al. 2005; Popov & Stern 2005). The upper limits on the recurrence time of powerful giant flares obtained in these studies range from $\tau \sim 130$ to 600 yr per galaxy, i.e., ~4 to 20 times longer than the time inferred from the 2004 December 27 event. A detailed discussion of the merits of these estimates is beyond the scope of this Letter. However, we note that a 2004 December 27–like event in the Galaxy could not be missed, whereas several systematic effects can reduce the chances of detection from large distances (see, e.g., the discussion in Lazzati et al. 2005; Nakar et al. 2005). Rather than regarding the 2004 December 27 event as statistically unlikely, one can evaluate the chances of a recurrence time of hundreds of years, given the occurrence of the 2004 December 27 hyperflare. We estimate that, having observed a powerful giant flare in our Galaxy in ~30 yr of observations, the Bayesian probability that the Galactic recurrence time is $\tau > 600$ yr is $\sim 10^{-3}$, whereas the 90% confidence upper limit is $\tau \sim 60$ yr. These values are derived for a uniform prior[1] on the rate $1/\tau$. We thus favor smaller values and assume in the following discussion $\tau \sim 30$ yr.

In a timescale of $\sim 10^4$ yr (which we adopt for the SGR lifetime), about 70 very powerful giant flares should be emitted, which release a total energy of $\sim 4 \times 10^{48}$ ergs. We note that if the powerful giant flares' emission were beamed in a fraction b of the sky (and thus the energy released in individual flares a factor of b lower), the recurrence time would be a factor of b shorter. Therefore the total energy released by giant flares would remain the same. For this energy to originate in the magnetar's B-field, this must be $\geq 10^{15.7}$ G. This value should be regarded as a *lower limit* on the initial internal field of a magnetar. First, not all the magnetic energy is released through powerful giant flares. The magnetar model predicts a conspicuous neutrino luminosity, resulting from ambipolar diffusion, of $L_\nu \sim 4 \times 10^{36} t_4^{-8/7}$ ergs s^{-1}, where t_4 is the magnetar age in units of 10^4 yr (Thompson & Duncan 1996). Integrating over $t_4 = (0.01\text{–}1)$ yields a neutrino energy output of $\sim 4 \times 10^{48}$ ergs. Including this energy gives an internal magnetic field of $\geq 10^{15.9}$ G. Second, ambipolar diffusion and magnetic dissipation are expected to take place at a faster rate for higher values of the field (Thompson & Duncan 1996). Therefore, estimates of the B-field based on present-day properties of SGRs (age $\sim 10^4$ yr) likely underestimate the value of their initial magnetic field.

Very strong internal B-fields are expected to be generated in a differentially rotating fast-spinning neutron star, subject to vigorous neutrino-driven convection instants after its formation (Duncan & Thompson 1992). If the initial spin period P_i is in ~1–2 ms range (comparable to the overturn time of convective cells), an efficient α-Ω dynamo is powered by fluid helical motions, which amplifies the field in a predominantly toroidal configuration with a coherence length comparable to the star size. Differential rotation provides a very large free energy reservoir, $\sim 10^{52}(P_i/1\ \text{ms})^{-2}$ ergs, that can be converted into a magnetic field of up to $\sim 3 \times 10^{17}(P_i/1\ \text{ms})^{-1}$ G (Duncan & Thompson 1992). However, the efficiency of the amplification is likely limited by the dynamical influence (back-reaction) of the field which opposes convective motions. This limitation could be circumvented, however, if smoothing of angular velocity gradients by magnetic stresses is very efficient on a timescale shorter than the initial neutrino cooling time (which sets the timescale for convective instability to occur); in this case, a field of several $\times\ 10^{16}$ G can be generated in magnetars that are born with spin periods of a few milliseconds (Thompson & Duncan 1993; Duncan 1998).

In summary, unless powerful giant flares such as the 2004 December 27 event are much rarer than the rate implied by having already detected one of them, newborn magnetars can possess internal fields of $\sim 10^{16}$ G or higher (values up to $\sim 10^{17}$ G cannot be ruled out). Based on current models, fields of this order can be generated only if magnetars are born with spin periods of a few milliseconds. In the following discussion we explore the consequences of this for the generation of gravitational waves from newborn magnetars. We parameterize their (internal) toroidal field with $B_{t,16.3} = B_t/2 \times 10^{16}$ G, (external) dipole field with $B_{d,14} = B_d/10^{14}$ G, and initial spin period with $P_{i,2} = P_i/(2\ \text{ms})$.

3. MAGNETICALLY INDUCED DISTORTION AND GRAVITATIONAL WAVE EMISSION

The possibility that fast-rotating, magnetically distorted neutron stars are conspicuous sources of gravitational radiation has been discussed by several authors (see, e.g., Bonazzola & Marck 1994 and Bonazzola & Gourgoulhon 1996). The path toward a better understanding of the early evolution and gravitational radiation emission properties of such neutron stars was laid out by Cutler 2002, who also discussed the possibility of detecting the gravitational radiation signal from a newborn, $\sim 10^{15}$ G neutron star in our Galaxy. If this value for the internal field pertains to ordinary neutron stars, then such events might be expected at the Galactic rate of neutron star formation, i.e., once every several tens to hundreds of years (see, e.g., Arzoumanian et al. 2002). The formation rate of magnetars is substantially lower than that (see § 4), making the chances of witnessing the birth of a Galactic magnetar in the near future very slim.Below we show that for the range of magnetic fields discussed in § 2, newly born, millisecond-spinning magnetars are conspicuous sources of gravitational radiation that might be detectable up to the distances of the Virgo cluster.

The anisotropic pressure from the toroidal B-field deforms a magnetar into a prolate shape, with ellipticity $\epsilon_B \sim -6.4 \times 10^{-4}(\langle B^2_{t,16.3} \rangle)$, where the brackets indicate a volume average over the entire core (Cutler 2002). In general, the symmetry axis of the magnetically induced deformation will not be coaligned with the rotation axis. Hence, in the neutron star frame the angular velocity vector undergoes free precession with period $P_{\text{prec}} \simeq P/\epsilon_B$ around the (magnetic) symmetry axis, where P is the spin period (Jones 2002; Jones & Andersson 2002). (The rotationally induced distortion is not relevant here, because it is always aligned with the instantaneous spin axis.) As long as the axis of the magnetic distortion is not aligned with the spin axis, the star's rotation will cause a periodic variation of the mass quadrupole moment, in turn resulting in the emission of gravitational waves (GWs) at twice the spin frequency of the star.

A crucial issue is whether the misalignment of the magnetic axis can be maintained in spite of the damping of free precession caused by the star's internal viscosity. In a prolate ellipsoid the rotational energy is minimized when the moment of inertia along the axis of the "frozen-in" distortion, I_3, is orthogonal to the spin axis (Jones & Andersson 2002; Cutler 2002). Hence, viscous damping of precession drives a prolate

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[1] For a uniform prior on $\log(1/\tau)$ and a (conservative) lower cutoff of $1/(10^4$ yr), we obtain $\tau > 600$ yr with probability 0.04, and a 90% confidence upper limit of $\tau \sim 270$ yr.

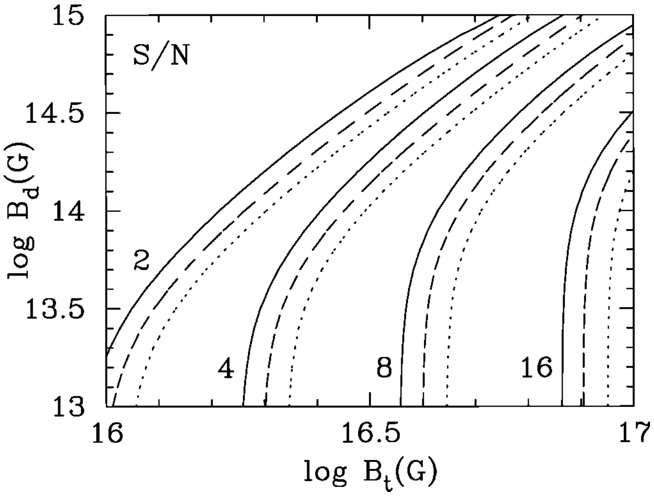

FIG. 1.—Lines of constant S/N for selected values of the initial spin period in the internal toroidal magnetic field, B_t, and external dipole field, B_d, plane for a source at the distance of the Virgo Cluster ($d_{20} = 1$). Solid, dashed, and dotted curves correspond to an initial spin period of $P_i = 1.2$, 2, and 2.5 ms, respectively. The calculations take into account the time required for the toroidal magnetic field axis to become orthogonal to the spin axis. Note that according to Thompson et al. (2004), strong angular momentum losses by relativistic winds set in and dominate the spin down for $B_d > (6–7) \times 10^{14}$ G; the curves for such values of B_d should thus be treated with caution.

neutron star toward a geometry that maximizes the time-varying mass quadrupole moment, and thus GW emission.

As the power emitted in GWs scales as proportional to P^{-6}, the GW signal, for a given internal B-field, depends critically on the initial spin period and its variation thereafter. The spin evolution of a newborn magnetar is determined by angular momentum losses from GWs, electromagnetic dipole radiation, and relativistic winds. According to Thompson et al. (2004), the latter mechanism depends critically on the value of the external dipole and is negligible except for fields $>(6–7) \times 10^{14}$ G, a regime that we do not discuss here. We consider in the following the spin evolution of a newborn magnetar under the combined effects of GW and electromagnetic dipole radiation. When both mechanisms are taken into account, the magnetar angular velocity $\omega = 2\pi/P$ evolves according to

$$\dot{\omega} = -\frac{K_d}{2}\omega^3 - \frac{K_{\rm GW}}{4}\omega^5, \tag{1}$$

where $K_d = (B_d^2 R^6)/(3Ic^3)$ and $K_{\rm GW} = (128/5)(G/c^5)I\epsilon_B^2$, where R is the neutron star radius, G is the gravitational constant and, c is the speed of light. From this equation, we derive a spin-down timescale of

$$\tau_{\rm sd} \equiv \omega/(2\dot{\omega}) \simeq 10P_{i,2}^2(B_{d,14}^2 + 1.15B_{t,16.3}^4 P_{i,2}^{-2})^{-1}\ \text{days}. \tag{2}$$

According to models of neutron star internal viscosity (Alpar & Pines 1985; Alpar & Sauls 1988), orthogonalization of the magnetic axis is expected to take place in $n \simeq 10^4$ precession cycles (Cutler 2002). This translates into a timescale of $\tau_{\rm ort} = nP_i/\epsilon_B \sim 0.4B_{t,16.3}^{-2}P_{i,2}$ days. The condition for the newly formed magnetar to become an orthogonal rotator before losing most of its spin energy is

$$\frac{\tau_{\rm sd}}{\tau_{\rm ort}} \simeq 26\frac{B_{t,16.3}^2}{B_{d,14}^2 P_{i,2}^{-1} + 1.15B_{t,16.3}^4 P_{i,2}^{-3}} > 1. \tag{3}$$

If condition (3) is met, the magnetar quickly becomes a maximally efficient GW emitter, while its spin period is still close to the initial one. The strain is

$$h \sim 3 \times 10^{-26} d_{20}^{-1} P_2^{-2} B_{t,16.3}^2, \tag{4}$$

where the distance $d_{20} = d/(20\ \text{Mpc})$ is in units of the Virgo Cluster distance and the angle-averaged strain is that given by Ushomirsky et al. (2000). We estimate the characteristic amplitude, $h_c = hN^{1/2}$, where $N \simeq \tau_{\rm sd}/P_i$ is the number of cycles over which the signal is observed. Using equation (4) we obtain

$$h_c \simeq 6 \times 10^{-22} d_{20}^{-1} B_{t,16.3}^2 P_{i,2}^{-3/2}(B_{d,14}^2 + 1.15B_{t,16.3}^4 P_{i,2}^{-2})^{-1/2}. \tag{5}$$

Under the conditions discussed above, strong GW losses are not quenched immediately after the magnetar birth but rather extend in time, typically from days to a few weeks, before fading away as a result of the star spin-down.

In order to assess the detectability of this GW signal we compute the optimal (matched-filter) signal-to-noise ratio

$$\text{S/N} = 2\left[\int_{f_f}^{f_i} \frac{|\tilde{h}(f)|^2}{S_h(f)}\,df\right]^{1/2} \tag{6}$$

by extending the formulae by Owen & Lindblom (2002) and Cutler (2002) to include both the electromagnetic and GW torques. In the previous equation $f_i = 2/P_i \approx 2$ kHz and $f_f = 2/P_f \approx 500$ Hz are the initial and final values of the frequency of the signal. Here $\tilde{h}(f)$ is the Fourier transform of the GW strain at the detector (eq. [4] divided by $\sqrt{5}$ in order to account for averaging over source sky position) and $S_h(f)$ is the one-sided noise spectral density of the instrument. In the relevant frequency band, 500 Hz–2 kHz, we approximate $S_h(f)$ according to the current baseline performance of Advanced LIGO: $S_h(f) = 2.1 \times 10^{-47}(f/1\ \text{kHz})^2\ \text{Hz}^{-1}$ (Thorne 2000). We compute $\tilde{h}(f)$ using the stationary phase approximation (see, e.g., Owen & Lindblom 2002) with angle-averaged amplitude and frequency derivative $f = \dot{\omega}/\pi$ given by equations (4) and (1), respectively. Equation (6) yields the following estimate of the optimal signal-to-noise ratio:

$$\text{S/N} \simeq 3d_{20}^{-1} B_{t,16.3}^2 B_{d,14}^{-1}\left[\ln\left(\frac{a^2 + f_f^2}{a^2 + f_i^2}\right) + 2\ln\left(\frac{f_i}{f_f}\right)\right]^{1/2}, \tag{7}$$

where $a^2 \equiv 2K_d/(\pi^2 K_{\rm GW})$. The limit in which the electromagnetic torque dominates corresponds to $a^2 \gg f^2$ (see eq. [1]). In this case, the first logarithmic term in equation (7) is negligible and we recover the result by Cutler (2002). Figure 1 shows lines of constant S/N for a source at $d_{20} = 1$ and selected values of the initial rotation period ($P_i = 1.2$, 2, and 2.5 ms) in the (B_t, B_d)-plane: GWs from newborn magnetars can produce $\text{S/N} > 8$ for $B_t \geq 10^{16.5}$ G and $B_d \leq 10^{14.5}$ G. This is the region of parameter space that offers the best prospects for detection as we now discuss.

The optimal (in the maximum likelihood sense) detection statistic for long-lived signals is the so-called $\mathcal{F}$-statistic (Jaranowski et al. 1998). Its computation involves the correlation of the data stream with a discrete set of filters that probe the relevant space of unknown parameters: the sky position (two parameters) and two parameters that control the evolution of the GW phase (see eq. [1]). A very conservative upper limit on the required number of filters involved in a search can be evaluated ignoring correlations among the parameters: ~100 filters (Brady et al. 1998) are needed to cover the ∼40 deg^2 area of the Virgo cluster for a coherent integration time $T \sim 10^6$ s, and $\sim(Tf_i)^2 \sim 10^{18}$ filters for the phase parameters, giving a total of ∼10^{20} templates. For this number of trials, we estimate that a signal with S/N ∼ 12 can be detected with 1% false alarm and 10% false dismissal (if all the parameters of the signal were known the corresponding S/N would be ≈4.6). Of course, the actual sensitivity limit of such a search is likely set by the available computational resources. In practice, the search for GWs from newborn magnetars is probably best carried out using a "hierarchical search strategy" in which coherent and incoherent stages are alternated in order to achieve (quasi-) optimal sensitivity at affordable computational costs (Brady & Creighton 2000; Krishnan et al. 2004; Cutler et al. 2005; Abbott et al. 2005). Furthermore, the presence of a trigger based on the detection of the newborn magnetar by other means (e.g., the corresponding supernova) could further reduce the region of parameter space that needs to be searched. In addition, the sensitivity will increase with the operation of the network of GW detectors that is coming on line. In any case, the search for this new class of signals represents a challenge that we are investigating in greater depth.

4. DISCUSSION

We have shown that the energy liberated in the 2004 December 27 flare from SGR 1806−20, together with the likely recurrence rate of these events, points to a magnetar internal field strength of ∼10^{16} G or greater. Such a field is sufficient to induce a sizable deformation of the star and is most likely generated in a differentially rotating, millisecond spinning magnetar instants after gravitational collapse. Magnetars with these characteristics are thus expected to be very powerful sources of gravitational radiation during the first weeks of their life. Prospects for revealing their GW signal depend critically on the birthrate of these objects. The three confirmed associations between an AXP and a supernova remnant (ages in the 10^3–10^4 yr range) implies a magnetar birth rate of $\gtrsim 0.5 \times 10^{-3}$ yr^{-1} in the Galaxy (Gaensler et al. 1999). The chances of revealing the signal from a newborn magnetar in our Galaxy are thus very low. A rich cluster like Virgo, containing ∼2000 galaxies, is expected to give birth to magnetars at a rate of $\gtrsim 1$ yr^{-1}. A fraction of these magnetars might have sufficiently high toroidal fields that a detectable GW is produced. A slowly evolving periodic GW signal at ∼1 kHz, whose frequency halves over weeks, would unambiguously reveal the early days of fast-spinning magnetars. We conclude that newborn, fast-spinning magnetars provide a class of GW emitters over Virgo scale distances that might well be within reach for the forthcoming generation of GW detectors.

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