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SEARCH FOR GRAVITATIONAL WAVE BURSTS FROM SIX MAGNETARS

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ABSTRACT

Soft gamma repeaters (SGRs) and anomalous X-ray pulsars (AXPs) are thought to be magnetars: neutron stars powered by extreme magnetic fields. These rare objects are characterized by repeated and sometimes spectacular gamma-ray bursts. The burst mechanism might involve crustal fractures and excitation of non-radial modes which would emit gravitational waves (GWs). We present the results of a search for GW bursts from six galactic magnetars that is sensitive to neutron star *f*-modes, thought to be the most efficient GW emitting oscillatory modes in compact stars. One of them, SGR 0501+4516, is likely ∼1 kpc from Earth, an order of magnitude closer than magnetars targeted in previous GW searches. A second, AXP 1E 1547.0−5408, gave a burst with an estimated isotropic energy $>10^{44}$ erg which is comparable to the giant flares. We find no evidence of GWs associated with a sample of 1279 electromagnetic triggers from six magnetars occurring between 2006 November and 2009 June, in GW data from the LIGO, Virgo, and GEO600 detectors. Our lowest model-dependent GW emission energy upper limits for band- and time-limited white noise bursts in the detector sensitive band, and for *f*-mode ringdowns (at 1090 Hz), are $3.0 \times 10^{44} d_1^2$ erg and $1.4 \times 10^{47} d_1^2$ erg, respectively, where $d_1 = \frac{d_{0501}}{1\,\mathrm{kpc}}$ and d_{0501} is the distance to SGR 0501+4516. These limits on GW emission from *f*-modes are an order of magnitude lower than any previous, and approach the range of electromagnetic energies seen in SGR giant flares for the first time.

Key words: gravitational waves – stars: magnetars

Online-only material: color figures

1. INTRODUCTION

Magnetars are isolated neutron stars (NSs) powered by extreme magnetic fields ($\sim 10^{15}$ G; Duncan & Thompson 1992). The magnetar model explains the observed properties of two classes of rare objects, the soft gamma repeaters (SGRs) and the anomalous X-ray pulsars (AXPs): compact X-ray sources with long rotation periods and rapid spindowns which sporadically emit short (≈0.1 s) bursts of soft gamma rays (for a review see Mereghetti 2008). Fewer than 20 SGRs and AXPs are known. The total isotropic burst energies rarely exceed 10^{42} erg. However, three extraordinary "giant flares" (GFs) have been observed in ∼30 years from SGRs in our Galaxy and the Large Magellanic Cloud: one from SGR 0526−66 in 1979 with an observed total isotropic energy of $\sim 1.2 \times 10^{44} d_{55}^2$ erg (Mazets et al. 1979), one from SGR 1900+14 in 1998 with $4.3 \times 10^{44} d_{15}^2$ erg (Tanaka et al. 2007), and a spectacular one from SGR 1806−20 in 2004 with $\sim 5 \times 10^{46} d_{15}^2$ erg (Terasawa et al. 2005), where $d_n = d/(n\,\mathrm{kpc})$. There is also evidence that some short gamma-ray bursts (GRBs) were in fact extragalactic GFs. GRB 070201 might have been a GF located in the Andromeda galaxy with an isotropic energy of 1.5×10^{45} erg (Mazets et al. 2008; Abbott et al. 2008a) and GRB 051103 might have been a GF in M81 with an energy of 7.5×10^{46} erg (Frederiks et al. 2007).

Although still poorly understood, magnetars are promising candidates for the first direct gravitational wave (GW) detection for several reasons. First, a sudden localized energy release could excite non-radial pulsational NS modes. Bursts may be caused by untwisting of the global interior magnetic field and associated cracking of the solid NS crust (Thompson & Duncan 1995), or global reconfiguration of the internal

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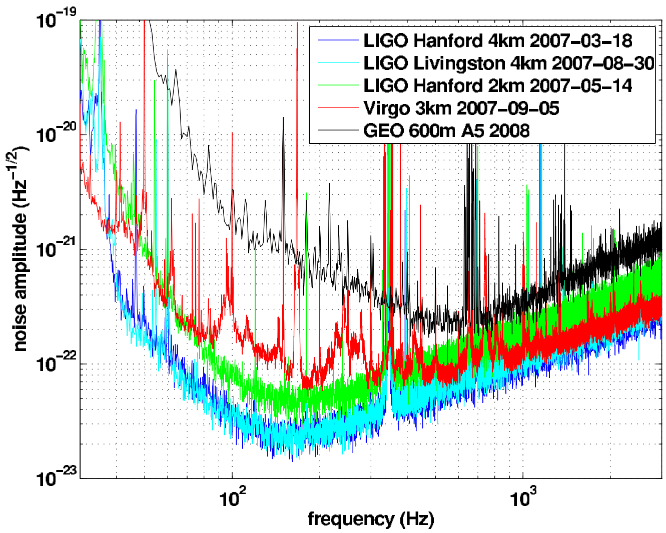

Figure 1. Best detector noise spectra from the LIGO and Virgo detectors during S5/VSR1 and the GEO600 detector during A5.

(A color version of this figure is available in the online journal.)

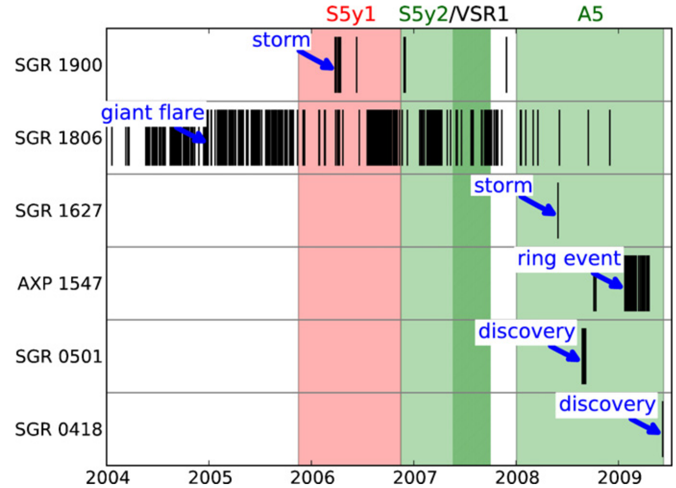

Figure 2. Each mark represents a burst from one of the six magnetar sources. Exceptional events are annotated in the figure; SGR 0501+4516 and SGR 0481+5279 were discovered in the A5 epoch. The LIGO S5y1 epoch was the subject of the first *f*-mode search (Abbott et al. 2008b). The current search includes bursts which occurred during the LIGO S5y2 and Virgo VSR1 epochs for which usable data were available, as well as the A5 *astrowatch* commissioning period. The VSR1 epoch, which is a subset of the S5y2 epoch, is indicated by cross hatching and darker shading. (*Note:* unabbreviated source names are given in Table 1.)

(A color version of this figure is available in the online journal.)

magnetic field and associated deformation of the NS hydrostatic equilibrium (Ioka 2001; Corsi & Owen 2011). The lowest-order GW emitting mode, the *f*-mode, is damped principally via GW emission and would ring down with a predicted damping time of 100–400 ms and with a frequency in the 1–3 kHz range depending on the nuclear equation of state and NS composition (Benhar et al. 2004), putting these signals in the band of interferometric GW detectors (see Figure 1). Second, precise sky locations and trigger times from electromagnetic (EM) bursts allow us to reduce the false-alarm rate and increase sensitivity relative to all-sky all-time searches such as Abadie et al. (2010). Finally, magnetars are among the closest of potential GW burst sources.

GW signals from magnetars would give us a new window through which to probe the stellar physics and structure. However, quantitative predictions or constraints on the amplitude of GW emission associated with magnetar bursts are relatively few and highly uncertain (see, e.g., Ioka 2001; Owen 2005; Horowitz & Kadau 2009; Corsi & Owen 2011; Kashiyama & Ioka 2011; Levin & van Hoven 2011); hence it is not clear when we might begin to expect a detection.

It may turn out that the magnetar burst mechanism does not excite global NS *f*-modes. If the outburst dynamics are confined to surface layer modes, the crust torsional oscillations might emit GWs at frequencies of ∼10–2000 Hz (McDermott et al. 1988). It is also possible that although the crust is a plausible site for triggering, bursts are confined to the magnetosphere (Lyutikov 2006), although even in this case *f*-modes might be excited either directly or via crust/core hydromagnetic coupling. Finally, we note that it is not yet clear if GFs and common bursts are caused by the same mechanism. The lack of theoretical understanding underlines the importance of observational constraints on GW emission.

We present results from a search for GW bursts associated with magnetar EM bursts using data from the second year of LIGO's fifth science run (S5y2; Abbott et al. 2009a), Virgo's first science run (VSR1; Acernese et al. 2008), and the subsequent LIGO and GEO *astrowatch* period (A5), during which the principal goal was detector commissioning, not data collection. The S5y2 epoch involved the three LIGO detectors: a 4 km interferometer in Louisiana and two interferometers (4 km and 2 km) in Washington. The VSR1 epoch added the Virgo 3 km detector to the global network. The A5 epoch included only the LIGO 2 km detector and the GEO 600 m detector (Grote & the LIGO Scientific Collaboration 2010). The Virgo and GEO600 detectors are located in Italy and Germany, respectively.

This is the third search for GWs from magnetars sensitive to *f*-mode ringdowns. The first (Abbott et al. 2008b) included the 2004 SGR 1806−20 GF, a 2006 storm of bursts from SGR 1900+14, and 188 other events from SGRs 1806−20 and 1900+14 occurring before 2006 November. Upper limits on *f*-mode GW energy emission at 1090 Hz ranged from 2.4×10^{48} erg to 2.6×10^{51} erg, and upper limits on band- and time-limited white noise bursts at 100–200 Hz ranged from 3.1×10^{45} erg to 7.3×10^{47} erg. The second (Abbott et al. 2009b) focused on the 2006 SGR 1900+14 storm, "stacking" GW data corresponding to individual bursts in the storm's EM light curve (Kalmus et al. 2009). An upper limit on *f*-mode emission at 1090 Hz of 1.2×10^{48} erg per burst was set on a stack of the 11 brightest storm bursts, an order of magnitude lower than the unstacked limit on the storm.

During the S5y2, VSR1, and A5 epochs of the search we present here, 1217 soft GRBs from six magnetars were listed by the interplanetary network of satellites[118] or IPN (Table 1 and Figure 2). Four of the sources are being examined for GW signals for the first time. Two of those (SGR 0501+4516 and SGR 0418+5729) are thought to be much closer to Earth than SGRs examined in previous GW searches. SGR 0501+4516 might be associated with the supernova remnant HB9 (Gaensler & Chatterjee 2008), which is (800 ± 400) pc from Earth (Leahy & Tian 2007); proper motion measurements could exclude this association. The probable locations of both SGR 0501+4516 and SGR 0418+5729 in the Perseus arm of our Galaxy imply distances of ∼1–2 kpc (van der Horst et al. 2010).

[118] http://ssl.berkeley.edu/ipn3

Table 1
Summary of Source Sky Locations and Estimated Distances

Source	Position (J2000)	Distances (kpc) Estimated	Distances (kpc) Nominal	EM Triggers Total	Analyzed with N Detectors $N = 1$	$N = 2$	$N \geqslant 3$
SGR 0418+5729[a]	$04^{\rm h}18^{\rm m}33^{\rm s}.867 \pm 0^{\rm s}.35$ $+57^\circ 32' 22''.91 \pm 0''.35$	$\sim$2	2	3	3	...	...
SGR 0501+4516[b]	$05^{\rm h}01^{\rm m}06^{\rm s}.8 \pm 1^{\rm s}.4$ $+45^\circ 16' 35''.4 \pm 1''.4$	$\sim$2, 0.8 $\pm$ 0.4	1	166	105	24	...
AXP 1E 1547.0−5408[c]	$15^{\rm h}50^{\rm m}54^{\rm s}.11 \pm 0^{\rm s}.01$ $-54^\circ 18' 23''.7 \pm 0''.1$	4–5, 9, 4	4	844	315	512	...
SGR 1627–41[d]	$16^{\rm h}35^{\rm m}51^{\rm s}.84 \pm 0^{\rm s}.2$ $-47^\circ 35' 23''.31 \pm 0''.2$	11 $\pm$ 0.3	11	56	...	56	...
SGR 1806−20[e]	$18^{\rm h}08^{\rm m}39^{\rm s}.32 \pm 0^{\rm s}.3$ $-20^\circ 24' 39''.5 \pm 0''.3$	$8.7^{+1.8}_{-1.5}$, 6.4–9.8	10	207	11	36	136
SGR 1900+14[f]	$19^{\rm h}07^{\rm m}14^{\rm s}.33 \pm 0^{\rm s}.15$ $+09^\circ 19' 20''.1 \pm 0''.15$	3–9, 12–15	10	3	...	1	...

Notes. The nominal distances d_N are the distance used in the search for setting upper limits. Energy upper limits can be scaled to any distance d via the factor d^2/d_N^2. Some EM triggers occurred when there was no GW data available (i.e., $N = 0$).
[a] Position: Woods et al. (2009); distance: Esposito et al. (2010); van der Horst et al. (2010).
[b] Position: Evans & Osborne (2008); distance: van der Horst et al. (2010); Gaensler & Chatterjee (2008); Leahy & Tian (2007).
[c] Position: Camilo et al. (2007); distance: Tiengo et al. (2010); Camilo et al. (2007); Gelfand & Gaensler (2007).
[d] Position: Wachter et al. (2004); distance: Corbel et al. (1999).
[e] Position: Kaplan et al. (2002); distance: Bibby et al. (2008); Cameron et al. (2005).
[f] Position: Frail et al. (1999); distance: Marsden et al. (2001); Vrba et al. (2000).

AXP 1E 1547.0−5408 (also known as SGR 1550–5418) gave two exceptional bursts on 2009 January 22. Observations of expanding rings around the source, caused by X-ray scattering off of dust sheets, set the source distance at 4–5 kpc and imply an EM energy for one or both of these "ring event" bursts of 10^{44}–10^{45} erg (Tiengo et al. 2010), comparable to the GFs. In addition to the IPN triggers, we include eight triggers from the *Fermi* GBM detector: seven bright AXP 1E 1547.0−5408 bursts and one SGR 0418+5729 burst. We also identified 54 individual peaks in a storm from SGR 1627−41 lasting $\sim$2000 s by combining the 15–25 keV and 25–50 keV *Swift*/BAT 64 ms binned light curves[119,120] and selecting peaks above 450 counts/64 ms. The search thus includes a grand total of 1279 EM triggers.

2. METHOD

We analyze magnetar bursts using the strategy from Abbott et al. (2008b), which is less dependent on a particular emission model than the stacking approach of Abbott et al. (2009b). The analysis is performed by the Flare pipeline (Kalmus et al. 2007; Kalmus 2008), which produces a time–frequency excess power pixel map from calibrated detector data streams in the Fourier basis. Pixels are characterized by excess power relative to the background ("loudness") and loud adjacent pixels are grouped into "events." The generalized pipeline accepts arbitrary networks of GW detectors by including detector noise floor measurements and antenna responses in the detection statistic (Kalmus 2010). We divide the search into three frequency bands: 1–3 kHz where *f*-modes are predicted to ring, and 100–200 Hz and 100–1000 Hz. We include the latter two frequency bands in order to search also at lower frequencies where the detectors are most sensitive (see Figure 1). Although there are no predictions of GW *burst* signals from magnetars at these lower frequencies, we note that quasi-periodic oscillations (QPOs), lasting for tens of seconds and possibly associated with stellar torsional modes, have been observed in GF EM tails at frequencies as low as 18 Hz and as high as 1800 Hz (Strohmayer & Watts 2005; Israel et al. 2005; Steiner & Watts 2009). QPOs in the tail of the 2004 GF were targeted by a tailored GW search (Abbott et al. 2007) distinct from the one presented here.

As in Abbott et al. (2008b), we choose 4 s signal regions centered on each EM trigger time. Delays between EM and GW emission are unlikely to be significant (Kalmus et al. 2009); the 4 s duration accounts for uncertainties in the geocentric EM peak time due to satellite triggering algorithms and rounding. Overlapping signal regions are merged. We analyze 1000 s of background on either side of each signal region (2000 s total) in order to estimate the significance of events in that signal region. Background regions are not necessarily continuous, as we require the same detector network coverage and data quality as for the signal region; in addition, signal regions of other magnetar bursts are masked out. Signal and background regions are chosen after data quality cuts have been applied to the GW data, so as to remove data segments coincident with instrumental or data acquisition problems, or excessive noise due to challenging environmental conditions. For the S5y2 portion of this search, we applied category 1 and 2 data quality cuts (i.e., cutting only data certain to be unfit for analysis) as described in Abadie et al. (2010). For A5, which focused on detector commissioning, the boolean "science mode" designator and other basic data quality treatments were applied to the data, but the full categorical data quality treatment was not performed. Statistically significant events in the signal regions from any epoch are subject to follow-up investigations before being considered detection candidates. Follow-ups might include correlation with environmental data channels and more refined estimates of significance.

We set model-dependent upper limits on *f*-mode ringdowns with circular and linear polarizations and frequencies sampling the range for *f*-modes (1–3 kHz, which accounts for plausible NS equations of states and magnetic fields), and with a decay time constant of $\tau = 200$ ms. We observed no more than 15%

[119] http://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/2008_05/00312582000
[120] http://heasarc.gsfc.nasa.gov/FTP/swift/data/obs/2008_05/00090056009

degradation in strain upper limits using ringdowns with τ in the range 100–300 ms as compared to the nominal value of 200 ms. We set additional limits on band- and time-limited white noise bursts with 11 ms and 100 ms durations (motivated by observed rise times and durations of magnetar burst light curves) spanning the 100–200 Hz and 100–1000 Hz search bands. While these frequencies are chosen principally to explore the detectors' most sensitive region below the *f*-mode frequencies, the observed range of QPO frequencies provides astrophysical motivation. Upper limits depend on the frequency sensitivity of the detectors (Figure 1).

Simulations are constructed using knowledge of the target magnetar's sky location and the EM burst time. Following Abbott et al. (2008b), $h^2_{\rm rss} = h^2_{\rm rss+} + h^2_{\rm rss\times}$, where $h^2_{\rm rss+,\times} = \int_{-\infty}^{\infty} h^2_{+,\times} dt$ and $h_{+,\times}(t)$ are the two GW polarizations. The relationship between the GW polarizations and the detector response $h(t)$ to GW signals arriving from an altitude and azimuth (θ, ϕ) and with polarization angle ψ is

$$h(t) = F^+(\theta, \phi, \psi) h_+(t) + F^\times(\theta, \phi, \psi) h_\times(t), \quad (1)$$

where $F^+(\theta, \phi, \psi)$ and $F^\times(\theta, \phi, \psi)$ are the antenna functions for the source at (θ, ϕ). The polarization angle for each simulation was randomly chosen from a flat distribution between 0 and 2π. The GW emission energy (if the integrand is averaged over inclination angle) is

$$E_{\rm GW} = 4\pi d^2 \frac{c^3}{16\pi G} \int_{-\infty}^{\infty} \left(\dot{h}_+^2 + \dot{h}_\times^2\right) dt. \quad (2)$$

We estimate model-dependent upper limits on $E_{\rm GW}$ or $h_{\rm rss}$ for a given signal region as follows.

1. We determine the loudest event in the signal region.
2. For a specific simulated signal type, we inject a simulation at a specific $E_{\rm GW}$ and $h_{\rm rss}$ in a randomly selected 4 s interval of the background data and find events in that region. We compare the loudest signal region event to the loudest event with a cluster centroid time near the known injection time (within 100 ms for ringdowns and within 50 ms for white noise bursts).
3. We repeat step (2) for a range of $E_{\rm GW}$ and $h_{\rm rss}$ values, and at each value we determine the fraction of injections with associated events louder than the loudest signal region event.
4. We repeat step (3) using different simulated signal types. For each signal type, we estimate the 90% detection efficiency loudest event upper limit, $E^{90\%}_{\rm GW}$ or $h^{90\%}_{\rm rss}$, at which 90% of injection events would be louder than the loudest signal region event.

3. RESULTS AND DISCUSSION

We find no evidence of a GW signal in any of the signal regions analyzed. The loudest event of the search occurred at 2009 January 22 05:48:43.2 UTC and was the only event with a false-alarm rate below our predetermined follow-up threshold of $1/(3 \times 4808\ {\rm s}) = 6.9 \times 10^{-5}$ Hz as estimated via extrapolation from the 2000 s local background region. This event cannot be considered a GW candidate because it was found when only the Hanford 2 km detector was observing and was coincident with a strong glitch caused by fluctuations in the AC power picked up by a magnetometer, and thus is highly likely to be an instrumental artifact.

We estimate $h^{90\%}_{\rm rss}$ and $E^{90\%}_{\rm GW}$ for each signal region, which depend on detector sensitivities and antenna factors, the loudest signal region event, and the simulation waveform type. $E^{90\%}_{\rm GW}$ upper limits also depend on nominal source distance d_N and can be scaled to any source distance d via the factor $(d/d_N)^2$.

Figure 3 shows $E_{\rm GW}$ upper limits for each of the EM triggers from the six magnetar candidates, for each waveform type. The complete table of upper limits is available online.[121] We spotlight bright bursts from SGR 0501+4516 and AXP 1E 1547.0−5408; however, it is unknown whether $E_{\rm EM}$ and $E_{\rm GW}$ are correlated. Table 2 presents $E_{\rm GW}$ and $h_{\rm rss}$ upper limits for three exceptional EM triggers, and for a burst from SGR 0501+4516 occurring in the signal region centered at 2008 August 23 16:31:22 UTC which yielded the lowest limits of the search. Each was analyzed with a network of the LIGO 2 km and GEO600 detectors. The SGR 0501+4516 burst with the largest EM fluence (2.21×10^{-5} erg cm^{-2}; Aptekar et al. 2009, which corresponds to a 1 kpc isotropic energy of 2.7×10^{39} erg) occurred in the signal region centered at 2008 August 24 01:17:58 UTC. The two candidate progenitor bursts for the expanding X-ray rings around AXP 1E 1547.0−5408 occurred at 2009 January 22 6:45:14 UTC and 6:48:04 UTC, with estimated isotropic $E_{\rm EM}$ of 10^{44}–10^{45} erg (Tiengo et al. 2010). Table 2 also gives upper limits on the ratio $\gamma \equiv E^{90\%}_{\rm GW}/E_{\rm EM}$ for the three bursts with $E_{\rm EM}$ estimates. The γ upper limits for the two ring bursts were estimated using $E_{\rm EM} = 10^{45}$ erg, and beat the best previous upper limits on γ, set for the SGR 1806−20 GF (Abbott et al. 2008b), by a factor of a few.

Superscripts in Table 2 give uncertainties at 90% confidence. The first is uncertainty in detector amplitude calibrations. The second is the statistical uncertainty (via the bootstrap method) from using a finite number of injected simulations. Both are added linearly to final $h_{\rm rss}$ upper limit estimates; corresponding uncertainties are added to $E_{\rm GW}$ upper limit estimates.

Our best $E_{\rm GW}$ *f*-mode upper limits are an order of magnitude lower (better) than the best *f*-mode limits from previous searches and approach the range of EM energies seen in SGR GFs for the first time. The best SGR 0501+4516 *f*-mode limit of 1.4×10^{47} erg (at 1090 Hz and a nominal distance of 1 kpc) probes below the available energy predicted in a fraction of the parameter space explored in Ioka (2001) and Corsi & Owen (2011), the predicted maximum being $\sim 10^{48}$–10^{49} erg. The best 100–200 Hz white noise burst limit of 3.5×10^{44} erg is—for the first time—comparable to the $E_{\rm EM}$ seen in "normal" GFs.

Improved upper limits and perhaps detection will come in the future via the following routes.

1. Additional GFs could push down upper limits on $\gamma \equiv E^{90\%}_{\rm GW}/E_{\rm EM}$.
2. An analysis which stacks isolated bursts (from, e.g., SGR 0501+4516 and AXP 1E 1547.0−5408) using the method of Abbott et al. (2009b). Stacking 100 or more bursts observed with a constant detector sensitivity, as in Abbott et al. (2009b), might yield up to an additional order of magnitude improvement in $E^{90\%}_{\rm GW}$.
3. The GW detectors will become more sensitive. Second generation detectors (Advanced LIGO and Advanced Virgo) are expected to begin observing by 2015, promising more than two orders of magnitude improvement in $E_{\rm GW}$ sensitivity over the LIGO 2 km + GEO600 network which observed SGR 0501+4516 (Abbott et al. 2009a). Recently,

[121] https://dcc.ligo.org/cgi-bin/DocDB/ShowDocument?docid=25737

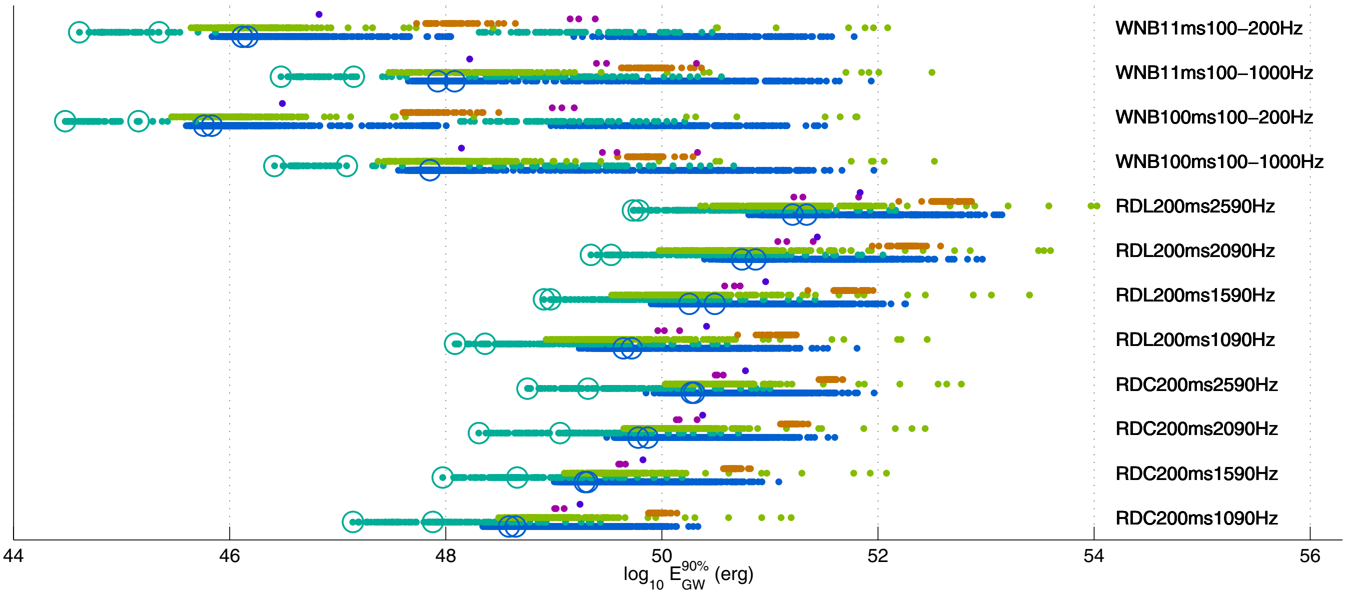

Figure 3. $E_{\rm GW}^{90\%}$ upper limits for the entire SGR burst sample for various circularly/linearly polarized ringdowns (RDC/RDL) and white noise burst (WNB) signals (see Section 2). For each of 12 waveform types, we show six rows of dots marking upper limits for the sources (from top to bottom): SGR 1900+14 (violet), SGR 0418+5729 (purple), SGR 1627−41 (orange), SGR 1806−20 (green), SGR 0501+4516 (teal), and AXP 1E 1547.0−4508 (blue) for that waveform type. The limits shown in Table 2 for SGR 0501+4516 and AXP 1E 1547.0−4508 are indicated in the figure by circles.

(A color version of this figure is available in the online journal.)

Table 2

GW Strain and Energy Upper Limit Estimates at 90% Confidence ($h_{\rm rss}^{90\%}$ and $E_{\rm GW}^{90\%}$), for the Burst Trigger Yielding the Lowest $E_{\rm GW}^{90\%}$ Upper Limits (Top Left), the Brightest SGR 0501+4516 Burst (Top Right), and the Two "Ring" Events from AXP 1E 1547.0−5408 (Bottom)

Simulation Type	SGR 0501+4516 Best Limits			SGR 0501+4516 Brightest Burst		
	$h_{\rm rss}^{90\%}(10^{-22}{\rm Hz}^{-\frac{1}{2}})$	$E_{\rm GW}^{90\%}$ (erg)	γ	$h_{\rm rss}^{90\%}(10^{-22}{\rm Hz}^{-\frac{1}{2}})$	$E_{\rm GW}^{90\%}$ (erg)	γ
WNB 11 ms 100–200 Hz	$7.0^{+1.0+0.89} = 8.9$	6.8×10^{44}	…	$13^{+1.9+1.3} = 16$	2.2×10^{45}	8×10^{5}
WNB 100 ms 100–200 Hz	$5.1^{+0.76+0.26} = 6.1$	3.1×10^{44}	…	$11^{+1.6+0.69} = 13$	1.4×10^{45}	5×10^{5}
WNB 11 ms 100–1000 Hz	$13^{+3.6+0.62} = 17$	3.5×10^{46}	…	$25^{+7.3+1.6} = 34$	1.4×10^{47}	5×10^{7}
WNB 100 ms 100–1000 Hz	$13^{+3.7+0.56} = 17$	3.2×10^{46}	…	$26^{+7.3+1.4} = 34$	1.2×10^{47}	4×10^{7}
RDC 200 ms 1090 Hz	$15^{+2.4+1.3} = 18$	1.4×10^{47}	…	$35^{+5.8+1.7} = 42$	7.6×10^{47}	3×10^{8}
RDC 200 ms 1590 Hz	$30^{+4.9+2.1} = 37$	1.2×10^{48}	…	$59^{+9.7+2.9} = 71$	4.6×10^{48}	2×10^{9}
RDC 200 ms 2090 Hz	$32^{+5.3+1.6} = 39$	2.4×10^{48}	…	$69^{+11+4.7} = 85$	1.1×10^{49}	4×10^{9}
RDC 200 ms 2590 Hz	$40^{+6.7+2.9} = 50$	6.1×10^{48}	…	$77^{+13+5.2} = 96$	2.1×10^{49}	8×10^{9}
RDL 200 ms 1090 Hz	$40^{+6.6+8.1} = 54$	1.3×10^{48}	…	$58^{+9.6+5.0} = 73$	2.3×10^{48}	9×10^{8}
RDL 200 ms 1590 Hz	$86^{+14+9.8} = 110$	1.1×10^{49}	…	$80^{+13+6.5} = 100$	9.3×10^{48}	3×10^{9}
RDL 200 ms 2090 Hz	$96^{+16+20} = 130$	2.7×10^{49}	…	$110^{+19+12} = 140$	3.4×10^{49}	1×10^{10}
RDL 200 ms 2590 Hz	$110^{+19+17} = 150$	5.5×10^{49}	…	$120^{+21+10} = 160$	6.1×10^{49}	2×10^{10}
	AXP 1E 1547.0−5408 2009 Jan 22 6:45:14 UTC			AXP 1E 1547.0−5408 2009 Jan 22 6:48:04 UTC		
WNB 11 ms 100–200 Hz	$7.9^{+1.2+1.3} = 10$	1.5×10^{46}	10	$7.6^{+1.1+1.0} = 9.8$	1.3×10^{46}	10
WNB 100 ms 100–200 Hz	$5.3^{+0.80+0.41} = 6.6$	5.8×10^{45}	6	$5.8^{+0.86+0.47} = 7.1$	6.8×10^{45}	7
WNB 11 ms 100–1000 Hz	$16^{+4.5+1.0} = 21$	8.4×10^{47}	8×10^{2}	$18^{+5.2+0.91} = 24$	1.2×10^{48}	1×10^{3}
WNB 100 ms 100–1000 Hz	$15^{+4.5+0.73} = 21$	7.1×10^{47}	7×10^{2}	$16^{+4.5+0.80} = 21$	7.2×10^{47}	7×10^{2}
RDC 200 ms 1090 Hz	$19^{+3.2+1.4} = 24$	3.8×10^{48}	4×10^{3}	$21^{+3.5+1.0} = 25$	4.4×10^{48}	4×10^{3}
RDC 200 ms 1590 Hz	$30^{+4.9+2.5} = 37$	1.9×10^{49}	2×10^{4}	$31^{+5.1+1.6} = 37$	2.1×10^{49}	2×10^{4}
RDC 200 ms 2090 Hz	$39^{+6.6+2.8} = 49$	6.0×10^{49}	6×10^{4}	$44^{+7.4+3.8} = 56$	7.4×10^{49}	7×10^{4}
RDC 200 ms 2590 Hz	$57^{+9.4+3.9} = 70$	1.9×10^{50}	2×10^{5}	$60^{+1.00+3.3} = 73$	2.0×10^{50}	2×10^{5}
RDL 200 ms 1090 Hz	$60^{+1.00+9.9} = 80$	4.4×10^{49}	4×10^{4}	$66^{+11+10} = 87$	5.3×10^{49}	5×10^{4}
RDL 200 ms 1590 Hz	$84^{+14+13} = 110$	1.8×10^{50}	2×10^{5}	$110^{+18+22} = 150$	3.1×10^{50}	3×10^{5}
RDL 200 ms 2090 Hz	$110^{+19+16} = 150$	5.5×10^{50}	6×10^{5}	$130^{+22+18} = 170$	7.4×10^{50}	7×10^{5}
RDL 200 ms 2590 Hz	$150^{+25+33} = 210$	1.6×10^{51}	2×10^{6}	$180^{+30+29} = 240$	2.2×10^{51}	2×10^{6}

Notes. Upper limits on the ratio $\gamma \equiv E_{\rm GW}^{90\%}/E_{\rm EM}$ are given when estimates for $E_{\rm EM}$ are available; for the ring events, $\gamma = E_{\rm GW}^{90\%}/10^{45}$ erg. Upper limits were estimated using the circularly and linearly polarized ringdowns (RDC/RDL) and white noise burst (WNB) waveforms (see Section 2). Uncertainties, from detector calibration and using a finite number of injected simulations, are added to the final upper limit estimates. These are given for the $h_{\rm rss}$ limits as superscripts, with the first showing detector calibration uncertainty and the second showing statistical uncertainty from finite injected simulations.

Levin & van Hoven (2011) made semi-quantitative predictions on *f*-mode excitations in GFs. Their predictions are pessimistic as to whether an *f*-mode signal from a GF at 1 kpc would be detectable in the second generation, though they do not consider crustal cracking. Third generation detectors could yield two additional orders of magnitude in energy sensitivity.

We look forward to further predictions on GW emission amplitudes from these enigmatic sources.

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