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Recent searches for gravitational-wave bursts associated with magnetar flares with LIGO, GEO, and Virgo

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Abstract. Energetic electromagnetic flares from magnetars – highly magnetized neutron stars – are associated with sudden rearrangements of the mechanical and/or magnetic configurations of the star, which can give rise to mechanical oscillations, some of which may be strong radiators of gravitational waves. General arguments have indicated that gravitational-wave bursts associated temporally with (giant) flares from galactic magnetars may be observable with ground-based gravitational wave detectors. After discussing the expectations based on the astrophysical models, we present results from several campaigns to search for such bursts using the first generation of LIGO, GEO, and Virgo detectors over the period 2005-2009, emphasizing the most recent results. No detections have been made, and we present astrophysically informed limits. Finally, we discuss prospects for progress.

1. Introduction

Understanding neutron star structure is an important astrophysical objective. Perturbations of isolated neutron stars followed by their mechanical relaxation have provided some insights. The electromagnetic emissions associated with such events have provided valuable insights into neutron star astrophysics. However, the observations in the electromagnetic spectrum have so far been unable to provide decisive information to address questions of neutron star structure. Gravitational-wave observations, on the other hand, can potentially probe the large-scale structure of neutron stars and hence may play an important role in the advancement of neutron-star astrophysics.

The astrophysical sequence considered here involves magnetars — neutron stars with magnetic fields $\sim 10^{15}$ G — which undergo a rapid reconfiguration heralded by the emission of (giant) x-ray flares. The perturbation of the star is likely to excite mechanical modes, some of which may couple strongly to gravitational-wave (GW) emission. In the searches presented here, we assume the modes which are relevant to GW emission are damped in times of ~ 1 s or less [1]. Because the potential mechanisms for GW emission are uncertain, we do not assume any specific GW waveform in the search. An additional element of the GW search we employ relies on the expectation that the x-ray flare is nearly coincident with the GW emission. Hence, we use a triggered search strategy, as described below. The knowledge of the event time and position on the sky allows an improvement in sensitivity relative to an untriggered, all-sky search. Finally, the vast majority of detected flares associated with magnetars are galactic. The relative proximity of the magnetars, combined with the associated energetics of their rearrangements, make them viable targets in a search for a first GW detection.

The searches discussed here were performed using data from the LIGO [2], GEO [3], and Virgo [4] gravitational-wave detectors from 2004 to 2009. During this period, the detectors were operating at or near the sensitivity associated with their "initial" (or first-generation) configurations. The searches are reported in Refs. [5], [6], and [7].

1.1. Astrophysical context

Models for x-ray flares from galactic magnetars are based on a handful of well-measured episodes. The objects associated with these magnetar emissions may be termed soft gamma-ray repeaters (SGRs) or anomalous x-ray pulsars (AXPs). (The typical energy of the burst photons of ~ 100 KeV can be alternatively described as (hard) x-rays or (soft) gamma rays.) The prevailing scenario [8] posits that a neutron star crust cracking event is associated with the rearrangement of the magnetic field, which gives rise to the flare. Two classes of field rearrangement have been considered: internal mechanisms based on the large-scale rearrangement of the interior magnetic field, and external mechanisms which likely involve magnetic reconnections in the crust and magnetosphere. The total luminosity of giant flares and the time structure of their subsequent quasi-periodic oscillations are consistent with this picture. The energetics of these episodes can be used to estimate the possible energy content of associated gravitational-wave bursts. Such calculations were recently performed [9] for several models, resulting in available energies in the range 10^{45} to 10^{48} erg for neutron stars of conventional composition and about 10^{48} to 10^{50} erg for neutron stars which include quark matter or baryon-meson matter.

While the energetics are promising, efficient gravitational-wave production requires the excitation of quadrupolar mechanical modes. Much attention has thus been given to the quadrupolar f-modes. In fact, such modes are thought to damp primarily via GW radiation with a damping time ~ 200 ms [10]. Low-order f-modes in neutron stars have frequencies in the range 1-3 kHz. The excitation of f-modes from the standard giant flare mechanisms involving internal [11] and external [12] magnetic field rearrangement has recently been considered. Both calculations give poor f-mode coupling, indicating that even advanced GW detectors will be unlikely to detect gravitational waves via this mechanism. On the other hand, lower frequency modes are also likely to be excited, perhaps more strongly. For example, torsional modes (~ 100 Hz) are found [12] to couple well to flares. The viability of low-frequency modes for potential gravitational-wave observations is very uncertain and a topic of ongoing investigations.

Given the astrophysical uncertainties, with few observational constraints, we have elected to perform searches which do not assume a GW waveform. If no significant signal is observed, we evaluate upper limits using the available astrophysical guidance. In particular, we consider generic white noise bursts with frequencies ~ 100 Hz to evaluate the sensitivity to low-frequency modes and damped sinusoids with frequencies > 1 kHz to evaluate the sensitivity to f-modes.

1.2. Flare triggers

Figure 1 indicates the magnetars and their x-ray bursts. Most bursts trigger a GW search, as described in the next section. The six galactic magnetars shown represent those which produced significant flare activity during the LIGO/GEO/Virgo running periods discussed here. All detections were made by satellites of the IPN network [13]. Especially notable events are indicated. The SGR 1806−20 giant flare [14] was the most luminous of these emissions. In fact, with an energy estimated [15] to be $(3.7\pm0.9)\times10^{46}$ erg, it is the most luminous transient galactic event recorded. The corresponding GW search is described in [5]. (For complete citations for the flare detections and other astrophysical data relevant to the present analyses, see Refs. [5], [6], and [7].) SGR 1900+14 released a "storm" of flares over a 30 s period. The GW search is described in Refs. [5] and [6]. The emission from AXP 1547−5409 was discovered as

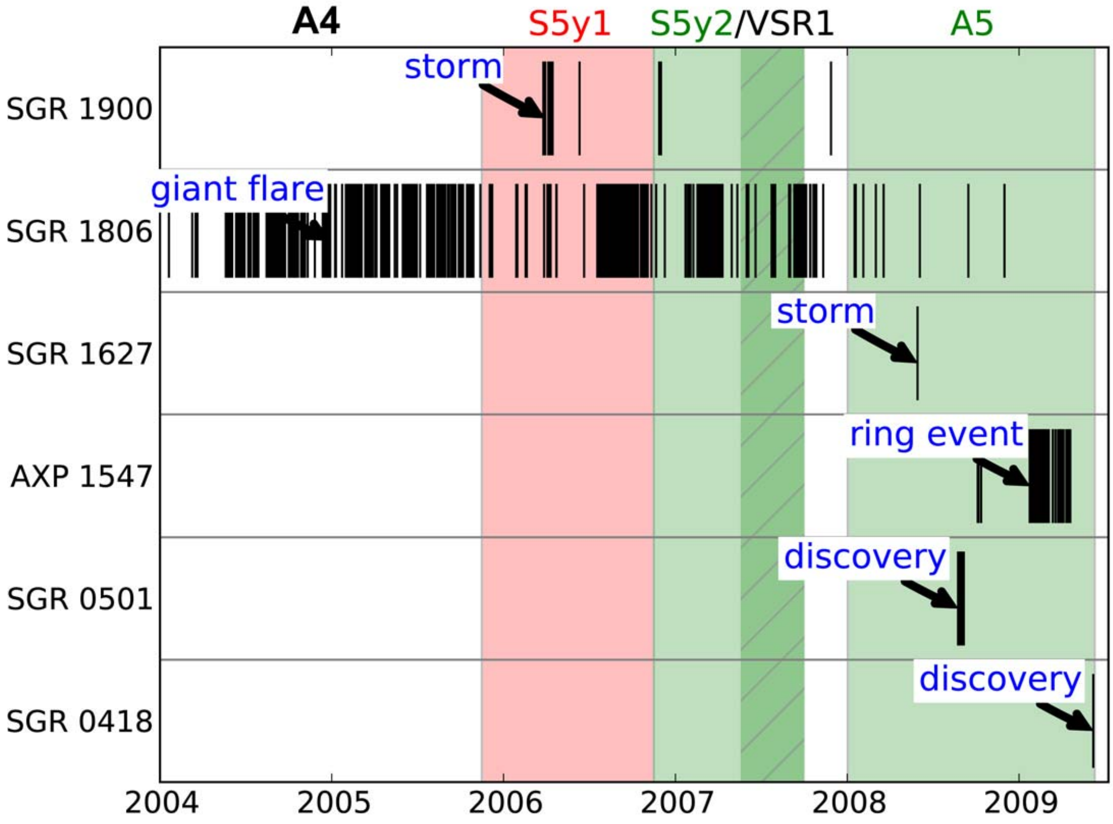

Figure 1. History of the x-ray bursts used as triggers in the GW burst searches. Each vertical black line represents an x-ray burst. The LIGO and GEO running periods A4, S5, and A5, and Virgo running period VSR1, are indicated.

expanding rings of x-rays scattered from dust sheets surrounding the magnetar. Its estimated energy [16] of 10^{44} to 10^{45} erg is comparable to a giant flare. The magnetars SGR 0501+4516 and SGR 0418+5729 were first revealed by flare activity in 2008 and 2009, respectively. SGR 0501+4516, at a distance of about 1 kpc, is also notable for being the nearest of these objects. Besides the flares associated with the SGR 1900+14 storm and giant flare episodes, the GW searches corresponding to the remaining flares are described in Ref. [7]. In all, roughly 1.5×10^3 electromagnetic bursts have been analyzed for associated GW bursts.

2. Methodology

2.1. Detectors and data

All three initial LIGO detectors were employed at various periods for the searches described here: the 4 km Hanford (H1) and Livingston (L1) interferometers, and the 2 km Hanford (H2) interferometer. The 3 km Virgo interferometer was employed for much of 2007. The GEO 600 interferometer was also crucial for many of the analysis epochs. Power spectral density curves are shown for all of these detectors in Figure 2. These represent a snapshot of the typical detector noise, in units of gravitational wave strain per $\sqrt{Hz}$, during the magnetar searches. It is worth noting that, although the LIGO detectors have better sensitivity at lower frequency ($\sim$ 100 Hz), all detectors are comparable in the f-mode regime ($>$ 1 kHz).

Data taking epochs are categorized by detector sensitivity and other factors. The LIGO

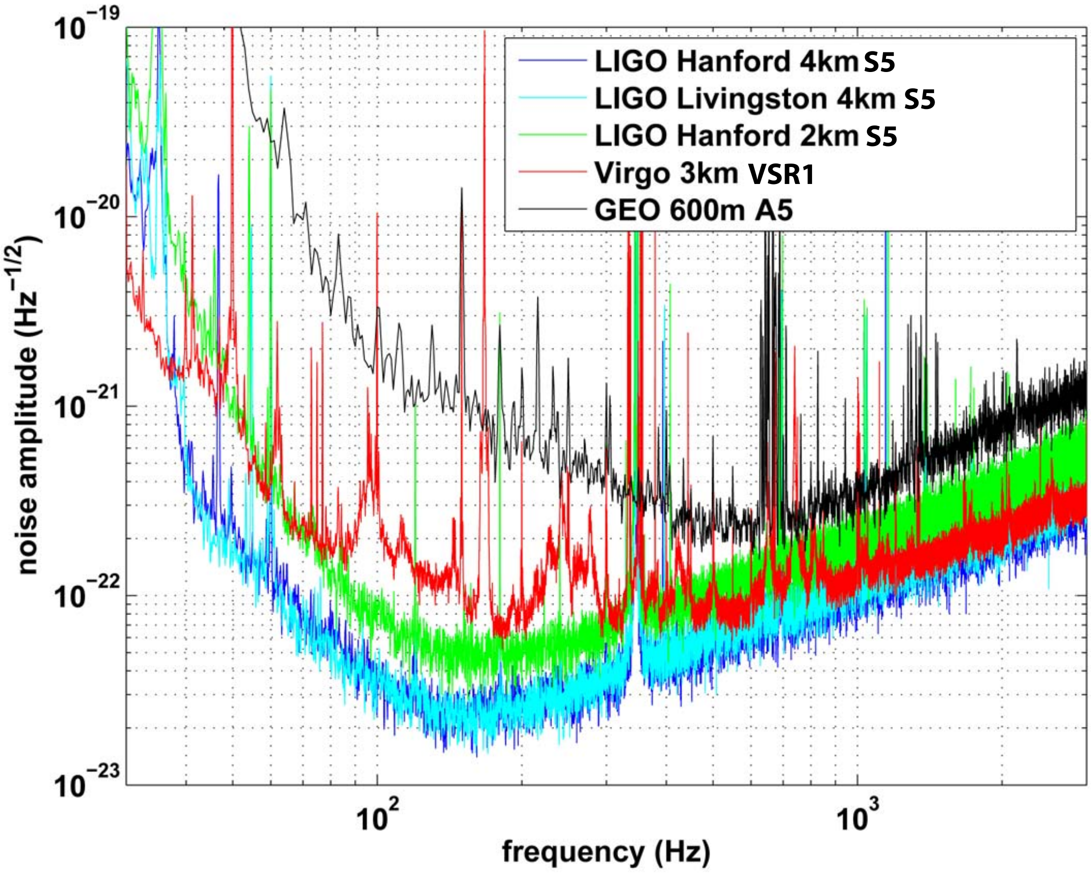

Figure 2. Power spectral density of detector noise in units of strain/$\sqrt{\text{Hz}}$. The curves represent typical performance of the detectors used for the magnetar searches. Curves from top to bottom at 100 Hz are GEO, Virgo, LIGO H2, LIGO H1, and LIGO L1.

two-year S5 science run took place after the detectors reached their design sensitivity in the initial-LIGO configuration. GEO also took data throughout S5. The first Virgo science run VSR1 began in 2007, and this data was used in the search for the S5/VSR1 period. Virgo approached design sensitivity in its initial configuration subsequent to the periods used for this search. A unique feature of the magnetar searches is that data was also analyzed outside of the designated science running periods. During these periods, termed *astrowatch*, data taking, typically at night, is interleaved with detector development and commissioning work. Because of the short stretches of data required for an externally triggered search like that employed here, the astrowatch searches are viable. These are labeled A4 and A5 in Figure 1. The typical LIGO amplitude sensitivity for A4 was roughly three times worse than for S5. GEO was operating with good uptime for the A5 period, and was joined only by the LIGO H2 interferometer. For most of this search, at least two interferometers were operating.

2.2. Analysis overview

The data segments used to search for gravitational-wave bursts are defined by the times of the detected magnetar x-ray bursts. The electromagnetic and GW bursts are expected to arrive nearly simultaneously. We also assume, as discussed above, that the GW signals should damp in less than 1 s. Hence, an "on-source" window of 4 s centered on the x-ray burst trigger is chosen. This should be large enough to include most of the GW signal energy and also not be sensitive to systematic errors in the burst timing measurement. The background is determined from 1000 s of off-source data on both sides of the trigger. When a different x-ray burst falls in the off-source, that 4 s segment is masked out.

The data are analyzed [17] using an excess power statistic applied to time-frequency pixels. We have checked that the excess power algorithm is insensitive to waveform, provided that the GW energy mostly falls within the on-source window. After pixel clustering, a list of significant "events" is formed. The algorithm has been constructed to properly weight excess power for general multi-detector networks. The off-source data is analyzed identically to the on-source, and a false-alarm rate (FAR) is determined. Signal candidates are identified when a loudest on-source event has FAR smaller than a predetermined threshold. Candidates are then scrutinized to determine if they were subject to any known instrumental problems or significant environmental disturbances.

For every electromagnetic burst considered, if no viable candidate results, then an upper limit is formed in the following way. GW waveforms are injected into 4 s off-source data segments and analyzed for excess power, as above. For a given injected GW strain amplitude, the loudest event in each 4 s segment is found and the fraction of injections louder than the loudest on-source event is determined. When this fraction is 90%, the strain upper limit is determined. The confidence level in strain is related to the isotropic GW energy release by

$$E_{\rm GW} = 4\pi d^2 \frac{c^3}{16\pi G} \int_{-\infty}^{\infty} \left(\dot{h}_+^2 + \dot{h}_\times^2 \right) dt. \tag{1}$$

where h_+ and $h_\times$ are the strain amplitudes and d is the magnetar distance. A 90% confidence level upper limit calculated in this way is written $E_{\rm GW}^{90\%}$.

Unlike the search algorithm, which does not presume a GW waveform morphology, the determination of upper limits, outlined above, must assume something for the signal injections. We have chosen two classes of injected waveforms which are informed by the astrophysics:

(i) f-modes. We use damped sinusoids (ring-downs) with frequency in the range 1-3 kHz and damping time 200 ms. We consider both linearly and circularly polarized cases.

(ii) low-frequency modes. We use white-noise bursts (WNB) of duration 10-100 ms and bands ranging from 100-200 Hz to 100-1000 Hz.

As can be seen from Figure 2, because of the better sensitivity of the LIGO detectors at lower frequency, we expect the WNB injections to produce better limits for a given x-ray burst.

3. Search results

One event survived as a GW signal candidate. It was the loudest event in the S5+S5/VSR1+A5 search [7] and the only event with FAR below the predetermined threshold of 6.9×10^{-5} Hz. It corresponds to an a x-ray burst which occurred when the H2 detector was operating in the A5 astrowatch period. However, the follow-up of this candidate revealed that it coincided with a large glitch recorded in a magnetometer. Its origin was an AC electrical power disturbance. Having discarded this candidate, upper limits were calculated for this and all other bursts.

It is interesting to note that a refinement of the search procedure was applied for the SGR 1900+14 "storm" episode (see Figure 1). Because of their proximity in time, the x-ray burst on-source times were "stacked" [18,6] together. This resulted in an upper limit approximately an order of magnitude better than the previous result [5].

The full set of upper limits are given in Refs. [5], [6], and [7]. Table 1 provides a few representative examples of the best limits. As discussed above, two classes of waveforms were used. The column labeled "1090 Hz" results from circularly polarized, damped sinusoidal

Table 1. Best upper limits for selected magnetar events. The "1090 Hz" column represents f-mode inspired limits. The "100-200 Hz" column is for white-noise bursts, representing unspecified low-frequency modes.

	distance (kpc)	event	$E_{\rm GW}^{90\%}$ (erg), 1090 Hz	$E_{\rm GW}^{90\%}$ (erg), 100-200 Hz
SGR 0501+4516 [7]	1	2008 discovery	1×10^{47}	3×10^{44}
AXP 1547−5408 [7]	4	2009 bright flare	4×10^{48}	6×10^{45}
SGR 1806−20 [5]	10	2004 giant flare	3×10^{50}	5×10^{47}
SGR 1900+14 [6]	10	2006 storm	1×10^{48}	2×10^{45}

waveforms, inspired by f-modes. The damping time is 200 ms. The central frequency of 1090 Hz is the lowest chosen frequency for this class of waveforms. It is expected that this would produce the best f-mode limit since the detector sensitivities worsen for higher frequencies. As discussed above, there remains much uncertainty for low-frequency modes. However, it is interesting to gauge the sensitivity to such modes using white-noise bursts. The column labeled "100-200 Hz" is for such bursts in the 100-200 Hz band and with duration 100 ms. Again, this band corresponds to the best LIGO sensitivity.

The nominal magnetar distances given in Table 1 are those used to form the energy upper limits using Equation (1). The measured distances are typically not precise and in some cases different measurements disagree. Rivising the limits to other distances is easily accomplished using d^2 scaling.

4. Discussion

While the search for GW bursts in association with energetic electromagnetic bursts from magnetars using data from initial GW detectors has yielded no detections, it is interesting to consider the astrophysical relevance of the calculated upper limits, as represented by the examples given in Table 1. As discussed above, current magnetar models imply that f-modes are unlikely to be excited by (giant) flares to the extent that they would result in detectable GWs. Nevertheless, one sees that the best limits of $\sim 10^{47}$ erg are comparable to the estimates [9] based on energy available to GW bursts.

Excitations resulting in GW bursts with frequency content $\sim$ 100 Hz are possible, but astrophysical expectations are currently uncertain. Nevertheless, we note that our best limits $\sim 10^{45}$ erg are comparable to the electromagnetic energy of the giant flares. Improved astrophysical understanding of potential lower-frequency modes would be welcome, as this represents a promising avenue for GW detection.

GW detections would likely provide a huge advance in the astrophysical understanding of magnetars and neutron stars. The biggest factors available for improving the likelihood of detections using the types of searches discussed here are (1) discovery of a very nearby ($<$ 1 kpc) magnetar; and (2) the realization of advanced GW detectors: The factor ~ 10 improvement in sensitivity for Advanced LIGO and Virgo gives a factor 10^2 in energy sensitivity.

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