Chapter 1

NEUTRON STARQUAKES AND THE DYNAMIC CRUST

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1 Introduction

The most strongly magnetized neutron stars, the magnetars, have fields that can be as high as $\sim 10^{15}$ G [82][52]. Magnetars are highly active, with spectacular outbursts of gamma-ray flares powered by decay of the magnetic field. The rapidly changing field is strong enough that it should be able to stress and rupture the star’s crust (Figure 1), with potentially interesting seismic consequences [71][16]. The existence of a dynamical relationship was finally confirmed in dramatic fashion by the discovery of long-lived seismic vibrations excited by rare giant flares [32][67][79][68]. The starquakes associated with giant flares are, it seems, so catastrophic that they leave the whole star ringing.

These discoveries have opened up the possibility of using asteroseismology to study the extreme conditions of the neutron star interior. Early work showed how magnetar vibrations could in principle put extremely tight bounds on the composition of dense matter [68][58].

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Figure 1. Magnetic field lines (red, core field not shown) tangle as the field decays. The field is locked to the lattice of charged nuclei in the neutron star crust, putting it under stress. Stress can also build up in the magnetosphere, where low plasma density can hinder reconfiguration. Catastrophic stress release - a starquake - allows field lines to reconfigure, generating flares.

[41] [80] and interior magnetic field strength, which is very hard to measure directly [32]. This triggered a major theoretical effort to improve models of global seismic oscillations and include key physics. Much of this work has concentrated on the effects of the strong magnetic field, which couples the solid crust and fluid core together, complicating mode calculations. The presence of superfluid neutrons is now known to have a major impact, and we have uncovered serious uncertainties in our understanding of the composition of the lattice nuclei in the solid crust.

In Section 2 I review the main observational properties of the oscillations seen in the giant flares, and in Section 3 the state of the art in terms of theoretical models of global seismic vibrations in magnetars. In Section 4 I discuss efforts to extend oscillation searches to smaller flares (which are more frequent but less energetic). Finally, in Section 5 I discuss the role that crust rupturing might play in triggering magnetar flares and exciting global seismic oscillations.
2 Quasi-periodic oscillations in giant flares

2.1 Giant flares from SGR 1806–20 and SGR 1900+14

On December 27th 2004, the most energetic giant flare ever recorded was detected from the magnetar SGR 1806–20 [69, 54, 30]. Analysis of data from both the Rossi X-ray Timing Explorer (RXTE) Proportional Counter Array (PCA) and the Ramaty High Energy Solar Spectroscopic Imager (RHESSI) revealed a set of highly significant Quasi-Periodic Oscillations (QPOs) in the decaying tail of the giant flare [32, 79, 68]. Subsequent re-analysis of RXTE PCA data from the August 27th 1998 giant flare from the magnetar SGR 1900+14 [29, 19] revealed a similar set of QPOs [67]. Figure 2 shows the RXTE PCA lightcurves of both giant flares.

Figure 2. RXTE PCA (2-90 keV) 0.125s resolution lightcurves for the 2004 giant flare from SGR 1806-20 and the 1998 giant flare from SGR 1900+14. Note that there were data gaps in the highest time resolution data stream for the SGR 1900+14 event that reduced the amount of data available for high frequency QPO searches (shown here is the lower time resolution Standard1 data stream). The PCA is completely saturated in the peak of the flares, despite the fact that neither event is on-axis for the telescope. Thereafter strong pulsations can be seen at the spin period in both events (7.6s for SGR 1806–20 and 5.2s for SGR 1900+14). The rotational pulse profile is complex, with two main peaks for SGR 1806-20 and four main peaks for SGR 1900+14.
Table 1. Key properties of QPOs in giant flares.

| Frequency (Hz) | Width (Hz) | Amplitude (% rms) | Duration (s) | Satellite |
|----------------|------------|-------------------|--------------|-----------|
| SGR 1806–20 giant flare in 2004 [32, 79, 68] |
| 18             | 2          | 4                 | 60–230       | RXTE, RHESSI |
| 26             | 3          | 5                 | 60–230       | RXTE, RHESSI |
| 30             | 4          | 21                | 190–260      | RXTE       |
| 93†            | 2          | 10–20†            | 150–260      | RXTE, RHESSI |
| 150            | 17         | 7                 | 10–350       | RXTE       |
| 626            | 1–2†       | 10–20†            | 50–260†      | RXTE, RHESSI |
| 1837           | 5          | 18                | 230–245      | RXTE       |
| SGR 1900+14 giant flare in 1998 [67] |
| 28             | 2          | 4                 | 55–110       | RXTE       |
| 53             | 5          | 7                 | 55–110       | RXTE       |
| 84             | · · ·      | 10                | 55–60*       | RXTE       |
| 155            | 6          | 11                | 55–110       | RXTE       |

*The frequency is the centroid frequency from a Lorentzian fit; the quoted width is the associated full width at half maximum. All amplitudes are the values computed from rotational phase dependent power spectra. The duration is given with respect to the main flare at time zero (see Figure 2). The nominal energy band in which the QPOs are seen is < 100 keV except where noted.

†Appears to drift upwards in frequency and amplitude over time.

‡Seen at early times in 100 – 200 keV RHESSI data at high amplitude, then at later times in RXTE data with lower amplitude/coherence and at different rotational phase.

*Signal actually appears to be concentrated in an even shorter, ~ 1 s, time window.
The frequencies, and some other properties of the QPOs, are summarized in Table 1. There are several key characteristics that need to be explained by any theoretical model.

2.2 Frequencies

The frequencies of the observed QPOs lie in the range $\approx 18$–$1800$ Hz. Time resolution for both RXTE and RHESSI datasets was such that higher frequencies could easily have been detected. Sensitivity to lower frequencies, however, is affected by the presence of a strong pulsation at the spin period and its harmonics, as well as red noise from the overall decaying shape of the giant flare lightcurve.

It is also clear that the signals are genuinely quasi, rather than strictly, periodic. The coherence $Q$ (defined as the ratio of frequency to the width of the QPO) is however quite variable, see Table 1. One simple possibility that would explain the quasi-periodicity is an exponentially decaying amplitude (as might be expected for oscillations triggered by a starquake). An exponentially decaying signal gives rise to a QPO with a width that is related to the decay timescale. By measuring width from the power spectrum, one can therefore infer the decay timescale and hence calculate the time that would have been necessary for the signal amplitude to fall, for example, to 5% of its initial level. For all of the observed QPOs this time is very short, $\sim 1$ s, far shorter than the signal duration that has been inferred for most of the QPOs (see Section 2.3). One can therefore conclude that simple exponential decay models cannot explain all of the QPO widths. So what else might be causing the broadening of the signal? Options include frequency drift and splitting (with closely-separated frequencies being unresolved). Unfortunately existing data for the QPOs are not good enough to resolve this question, but there is tentative evidence from the strongest QPOs suggesting that both possibilities may be occurring [32, 68].

2.3 Amplitudes and duration

The QPOs are all found to be strongly rotational phase dependent – with amplitude apparently varying strongly over the rotational cycle. However the dominant rotational phase is not the same for all of the detected QPOs. The amplitudes of the QPOs, in the rotational phase where they are strongest, can be very high (see Table 1). Where it can be measured, amplitude seems to increase with photon energy. However some caution must be exercised with energy-dependent analysis since none of the events were on-axis for the detectors so there would have been substantial scattering of photons within the body of the spacecraft prior to their interaction with the detectors. For this reason the published analysis considers only very broad energy bands.

For the strongest QPOs, which can be detected in relatively short time windows, it is possible to measure duration reasonably precisely. For the weaker QPOs, where multiple cycles must be stacked to record a detection, duration can be estimated by analysing how signal strength varies once extra cycles are introduced to the analysis. From this we infer that many of the QPOs persist for much of the decaying tail, with some only becoming visible some time after the main peak of the flare. By contrast, other QPOs seem to be detectable in only very short time windows (Table 1). Pinpointing the precise point at which signals appear and disappear in the current data is however limited by both statistics and
the difficulty of tracking variable-amplitude signals that drift in frequency across rotational cycles.

2.4 Additional analysis

Since the initial QPO discovery papers [32, 67, 79, 68], some additional analysis of the QPOs in the giant flares has been published. A more thorough rotational-phase and photon energy-dependent search for QPOs in the tail of the giant flare from SGR 1900+14, motivated by a search for QPOs with a frequency $\sim 10$ Hz, revealed no additional significant signals [65]. However the upper limits that it was possible to set on amplitude were still higher than the amplitude of the lowest frequency (18 Hz) QPO detected in the tail of the giant flare from SGR 1806–20, due to the lower quality of the data available.

Recently [26] published the results of a new analysis of the RXTE data from the tail of the SGR 1806–20 giant flare. There were several differences in analysis technique compared to the earlier results of [32, 68]. Firstly the authors took more rigorous account of the effects of the background lightcurve variations in assessing the significances of the detections (see discussion in Section 4), confirming the existing detections. They used a Bayesian method to assess statistical significances rather than the more traditional methods used in the previous papers. They also conducted searches for shorter duration QPOs, finding several additional frequencies in the range 17–117 Hz. The previous analysis, by contrast, focused more on long duration signals (the duration of intervals to be searched is one of the choices that must be made during the analysis). It would be interesting to see whether these short duration signals are seen, with comparable significances, using the more traditional method – assuming that the choices made about the number of different time intervals to search can be properly factored into the numbers of trials.

Gravitational wave astronomers have also joined the hunt for QPOs in giant flares. The LIGO Hanford detector was taking science data at the time of the SGR 1806–20 giant flare in 2004. Analysis of the data stream for signals at the same frequencies as those seen in the X-ray and Gamma-ray data reported no significant detections, but were able to place upper limits on the strength of any associated gravitational wave emission at these frequencies [2]. Although the limits were not particularly constraining for models, this bodes well for future giant flares, as gravitational wave detector sensitivity continues to improve.

2.5 Impulsive phase variability

There is also some evidence for variability in the earlier, impulsive phase of the giant flares. In an analysis of Prognoz and Venera data from the first 200 ms of the 1979 giant flare from the magnetar SGR 0526-66 [49] (the only high time resolution data available for this event) [7] reported evidence for variability at a frequency of $\approx 43$ Hz. Geotail observations of the first 500 ms of the SGR 1806-20 giant flare indicated periodicity at $\approx 50$ Hz, but no similar periodicities are seen in the SGR 1900+14 giant flare [70]. Analysis of variability in the impulsive phase of giant flares is however complicated by effects such as dead time.
3 Theoretical models for global seismic oscillations

3.1 Early models

In 1998, well before the discovery of the QPOs, [16] had suggested that the starquakes associated with giant flares might excite global seismic oscillations (GSOs) of the neutron star. It was argued that the easiest modes to excite would be toroidal (or torsional) shear modes of the neutron star crust. These modes, which involve primarily horizontal displacements, are restored by the shear modulus of the ions in the solid crust. Toroidal modes, unlike modes that involve compression or vertical displacements, have much lower energies of excitation and longer damping times. Using earlier work by [27, 50] as a guide, and applying a correction for gravitational redshift, [16] estimated frequencies for the expected modes, finding a fundamental toroidal shear mode frequency of \( \approx 30 \) Hz.

The fact that frequencies in this range were discovered in both of the giant flares provided immediate support for the interpretation of the QPOs in terms of GSOs\(^1\) [32]. The GSO model seemed to provide a natural explanation for both the observed frequencies and the fact that similar phenomena were seen in giant flares from two different magnetars. It also opened up the possibility of using asteroseismology to constrain the interior properties of neutron stars.

The torsional shear mode models of [16] used a ‘free-slip’ boundary condition between the solid crust and the fluid core of the star. The earliest QPO papers showed that it was indeed possible to fit many (although not all) of the observed frequencies with sequences of such torsional shear modes, with the higher frequencies corresponding to higher harmonics [32, 67]. The discovery of the 625 Hz QPO in the SGR 1806-20 giant flare [79, 68], with a frequency in the range expected for the first radial overtone of the toroidal shear crust mode [57], caused particular excitement. Since fundamental and first radial overtone depend in different ways on stellar compactness, identification of both frequencies has the potential to put very tight constraints on the dense matter equation of state [68, 41, 58].

The lowest QPO frequencies, however, did not fit within the framework of the existing toroidal shear mode models, since their frequencies were lower than the estimates of the fundamental toroidal shear mode frequency. In their discovery paper, [32] suggested that these lower frequency QPOs might be torsional Alfvén modes of the fluid core. If this interpretation were correct, the mode frequencies could then be used to measure the interior magnetic field strength. Although it is possible to estimate the dipole field strength using spin-down measurements, the strength of the internal toroidal component has yet to be measured directly for any neutron star (although its magnitude can be estimated, for example, by the energy budget required to power repeated magnetar flares, [71]). Theorists have attempted to constrain the ratio of poloidal to toroidal components by considering the stability of magnetic equilibrium models [9, 36, 12, 13, 40, 48, 59]. However the models still permit a range of possibilities. The results are also rather sensitive to choices of boundary conditions, and as a consequence the models do not all agree. An independent measure of internal field strength is essential.

\(^1\)Other models, including purely magnetospheric oscillations or phenomena associated with a residual disk of fallback material from the supernova, were considered but discarded [81]. However see also the paper by [48] that considers the role of standing sausage mode oscillations in flux tubes in the magnetosphere.
Having established that GSOs were the most plausible model to explain the QPOs, and their potential to explore both the dense matter equation of state and the interior magnetic field, efforts then turned to improving the GSO models. The following sections summarize the main research directions.

### 3.2 Magnetic field effects

Most of the work on GSO models has concentrated on the effects of the strong magnetic field, which (as first pointed out by [44]) couples crust and core, thereby rendering the ‘free-slip’ boundary condition inappropriate. This means that one has to consider global magneto-elastic modes rather than treating the crust and core in isolation. A simple plane parallel slab model developed by [23] explored how this might work for a crust and core coupled with a uniform magnetic field.

A major complication in such a problem is that the Alfvén modes of a magnetized fluid core (for a realistic, non-uniform, field configuration) admit a continuum of solutions. These can lead to unusual time-dependent behaviours. Work by [45] illustrated that the presence of such a continuum could lead to the development of drifting QPOs that might amplify when they passed close to the ‘native’ (uncoupled) frequencies of the crust or core. This work also confirmed that a perturbation applied to the crust would quickly excite motion in the core.

A number of groups have explored the problem of a magnetized crust that remains decoupled from the fluid core, to understand how the native crust frequencies would be affected. Work by [57], using a simple slab model and a uniform magnetic field, showed that the radial overtones of the shear modes were particularly susceptible to magnetic modification for fields above $\sim 10^{15}$ G. Studies using a dipole field geometry in Newtonian gravity [42] and in GR [63] confirmed this result, which was also found to hold for more general field configurations [63]. These studies confirmed that strong magnetic fields, of the order that one might expect in magnetars, can indeed affect shear mode frequencies in the crust even before one considers coupling to the core. Another study explored the degree to which magnetic splitting might affect mode frequencies [60].

The nature of the Alfvén continuum was investigated initially using models that treated only the fluid core of the star, without considering the effect of the crust. A study by [62] of torsional (axial) Alfvén oscillations of a star with a dipole field, in GR, found two families of QPOs. These could be interpreted as the end points of different continua, one associated with closed field line regions near the equator, and one with the open field line regions near the magnetic pole. A study of polar oscillations for the same field geometry, by contrast, revealed only discrete modes [64]. The authors pointed out that unlike the axial oscillations, the polar oscillations (which are restored by pressure as well as magnetic forces in this problem) do not collapse to a zero-frequency spectrum in the zero-field limit. It is zero-frequency solutions which typically give rise to continua. They suggested that the presence of the crust in the coupled problem, which would provide an additional restoring force, might therefore remove the continua for the axial oscillations. Their work was then extended by [14], who computed torsional Alfvén modes of a fluid star for a background with a mixed poloidal/toroidal field configuration. This study also found two families of QPOs that seemed to be associated with the end points of a continuum. This result was confirmed...
by a fully non-linear study, also in GR [10]. Recent oscillation calculations in Newton- 
ian gravity by [37, 39] have not found evidence for a continuum for non-axisymmetric 
polar perturbations, for poloidal-only and toroidal-only background field configurations. 
Although the studies are not directly comparable, this result seems to support the conclu-
sions of [64] that continua may not affect polar perturbations. In summary, the presence 
of continua seems to depend on both perturbation type and background field configuration. 
Torsional perturbations are however likely to be in the affected category.

Armed with a better understanding of the continuum, several groups are now attempting 
the full magneto-elastic oscillation problem, taking into account the coupling of crust and 
core. Non-linear GR simulations by [21], of axisymmetric torsional oscillations of a star 
with a pure dipole field, continue to show two families of QPOs that seem to be associated 
with Alfvén continua. GR calculations by [15] for the same field geometry, however, find a 
more complicated situation. They recover discrete crust-dominated and Alfvén oscillations 
in addition to the continua. This picture is backed up by the work of [76], who employ 
a simpler model to explore the nature of the solutions to the coupled oscillator problem. 
These authors find gaps in the continuum frequency bands, with strong discrete gap modes 
developing if the ‘native’ crust frequencies happen to sit within these gaps. These may be 
the discrete modes found in an earlier Newtonian study of coupled crust-core oscillations 
by [43]. Drifting frequency behaviour, due to the effects of the continua, seems to be 
ubiquitous [76].

The studies that have been done on the effect of the magnetic field are diverse, employ-
ing many different analytical and numerical techniques. One can nevertheless draw several 
clear conclusions from this body of work. Firstly, it has been confirmed that torsional modes 
can indeed be easily excited by giant flares [46]. An initial perturbation applied to the crust 
will however excite motion in the core on a very rapid (< 0.1 s) timescale. Crust and core 
therefore cannot be considered in isolation, since the strong field couples the two together, 
so GSO models must consider the global magneto-elastic oscillations of the star. The nature 
of such oscillations is now much clearer. A realistic (non-uniform) magnetic field geometry 
admits continuum solutions in various frequency bands. The turning points (end-points) 
of the continua can give rise to a strong response at these frequencies (which can appear 
similar in a power spectrum to the more usual discrete modes). In addition, the presence 
of the continua can lead to unusual behaviour including frequency drifting and amplitude 
variability. Such dynamical responses are typical for continua (see for example [77, 78]). 
The system can also still admit discrete modes, in the gaps between the various continuum 
frequency bands.

The potential of the GSO technique is also still clear. The frequencies of the magneto-
elastic oscillations depend on both the dense matter equation of state and the interior field 
strength. Crust physics, in particular the shear properties, is still thought to be important 
in setting at least some of the observed frequencies. However no model can yet fit all of 
the observations. In addition, how GSOs modulate the X-ray emission and to give rise to 
properties such as the observed high QPO amplitudes remains an open question [73].
3.3 Superfluidity

The neutrons in the inner crust and core of the star are expected to be in a superfluid state. The superfluid in the inner core is expected to affect the dynamics of the crust by virtue of the interaction (entrainment) between the free neutrons and the lattice nuclei. The superfluid may also affect the dynamics of the core (and hence the frequencies of Alfvén modes). If the protons in the core are in the form of a Type II superconductor, the magnetic field will be carried in flux tubes, which can interact with the superfluid vortices (the means by which the superfluid supports rotation). Work by [75] has shown that the Alfvén modes of the core are not significantly mass-loaded by superfluid neutrons, even if the vortices are strongly pinned to the flux tubes. The interaction between superfluid neutrons and the lattice nuclei in the deep crust is more likely to be important. Analysis of the effect on global mode frequencies in the crust by [59], building on earlier local analysis by [6], suggests that there might be at least a 10% correction to the mode frequencies due to superfluid effects.

3.4 Crust composition

Current results from the magneto-elastic simulations indicate that the shear modulus of the crust is likely to set at least some of the observed frequencies (Section 3.2). There is however a substantial degree of uncertainty about these shear properties. Particularly problematic is the uncertainty in the density dependence of the symmetry energy (the energy cost of creating an isospin asymmetry in nucleonic matter - or in simpler terms, of creating matter with unequal numbers of neutrons and protons) [65]. To obtain a fundamental torsional shear mode frequency \( \approx 30 \text{ Hz} \), as computed by [16, 57], requires a nuclear symmetry energy that depends only very weakly on density. If the nuclear symmetry energy varies more strongly with density (a possibility well within the current bounds of uncertainty) then the fundamental shear mode frequency could be much lower, perhaps \( \sim 10 \text{ Hz} \). This is due to the effect on the composition of the nuclei in the crust lattice, which in turn sets the shear modulus [53, 66]. Lower crust frequencies would overlap the expected range of the Alfvén continua and their turning points, so could make identification of frequencies using coupled GSO models more complex.

GSO modelling may offer a way of testing strange star models. Strange stars are expected to have crusts with properties that are quite different to those of normal neutron stars. One possibility is for a strange star to have a thin crust of normal nuclear material extending only to neutron drip, suspended above a strange quark matter fluid core by a strong electric field [5]. Another model posits a crust in which nuggets of strange quark matter are embedded in a uniform electron background [33]. Both types of crust are much thinner than neutron star crusts, and have very different shear moduli. A study by [80] of the shear mode frequencies for such a crust has shown that they are very dissimilar to those of neutron star crusts. Fitting the observed QPO frequencies was very difficult. While that study did not consider crust-core coupling, it seems unlikely that coupling would change this conclusion since strange star crust shear mode frequencies could fit neither low nor high frequency QPOs (so magnetically-dominated oscillations would have to account for all of the observations, something that seems difficult, see Section 3.2). However this should be verified.
4 Oscillations in smaller bursts

During active phases magnetars emit numerous bright gamma-ray bursts spanning orders of magnitude in duration ($10^{-2} - 10^3$ s) and peak luminosity ($10^{39} - 10^{46}$ ergs/s), see for example [24, 25]. The longest and most energetic events (the giant flares) are extremely rare, only three having been observed since the advent of high-energy (X-ray or gamma-ray) telescopes. This has motivated searches for lower level oscillations in the far more numerous smaller bursts. Energetics of mode excitation suggest that this is not unreasonable, and the smaller flares clearly involve localized asymmetries that could be modulated by seismic motion.

A search for QPOs in a period of enhanced emission with multiple bursts (a ‘burst storm’), from the magnetar SGR J1550-5418, has been carried out using data recorded by the Fermi Gamma-ray Burst Monitor (GBM) [35]. The analysis considered the entire period of the enhancement, both during and between bursts. No significant signals were reported, with a $3\sigma$ upper limit on QPO amplitude $\sim 10\%$ rms for frequencies in the range 100–4096 Hz. Upper limits for frequencies below 100 Hz are even less constraining. Unpublished searches for QPOs from intermediate flares (such as the August 29 1998 event from SGR 1900+14, [31]) have also not revealed any significant signals. Techniques for this kind of search are however being refined (see discussion of the complications below) and further studies are ongoing. Gravitational wave searches for oscillations excited by regular magnetar bursts and burst storms have not made any detections, but have reported upper limits [3, 4, 1].

Recently, the detection of QPOs in some short bursts from the magnetar SGR 1806–20 has been claimed by [18]. There are however issues with the analysis carried out by these authors that render the conclusions doubtful. The standard analysis technique, when searching for periodic or quasi-periodic signals, is to use Fast Fourier Transforms to produce a power spectrum (see [74] for a comprehensive review). In the absence of any periodic signal, the Poisson statistics of photon counting yield powers that are distributed as $\chi^2$ with two degrees of freedom. When searching for quasi-periodic signals, it is often common to average powers from neighbouring frequency bins. In searches for weak signals one can also stack, or take an average, of power spectra from many independent data segments (time bins) or bursts. This affects the number of degrees of freedom in the theoretical $\chi^2$ distribution of noise powers, but the modified theoretical distribution is known.

Having obtained a high power in a particular frequency bin, one first computes the probability of obtaining such a high power through noise alone. By this we mean the chances of getting such a high value of the power, in the absence of a periodic signal, due to the natural fluctuations in powers that are a by-product of photon counting statistics. One does this using the known properties of the $\chi^2$ distribution with the appropriate number of degrees of freedom. One must then take into account the number of trials, which depends on the number of independent frequency bins, time bins, energy bands and bursts searched.

A complication then comes from the fact that the noise powers are not always in accor-
dance with the theoretical distribution. The reason for this is simple. What we are searching for is a periodic signal superimposed on the overall rise and decay of a burst lightcurve. This gives low-frequency power and adds side-bands to noise powers, boosting their level (for a nice discussion of these issues, see [20]). These problems are particularly acute in short bursts when the background lightcurve is changing rapidly and there are sharp edges that can lead to spurious high frequency variability.

Assessing the true distribution of noise powers, that is to say the values that they would take in the absence of a periodic signal, is most commonly assessed using Monte Carlo simulations. One makes a model of the burst lightcurve, and then uses this as a basis to generate a large sample of fake lightcurves with Poisson counting statistics but without any periodic signal. Taking power spectra from these fake lightcurves then yields the true, most likely frequency-dependent, distribution of noise powers. Taking into account the varying nature of the background lightcurve should make the significance of any claimed detection drop compared to the significance computed from the ideal $\chi^2$ distribution. Although [18] do carry out simulations, the significances that they quote rise substantially, indicating a problem in their Monte Carlo simulation method. Indeed their simulated power spectra show far fewer high noise powers than one would expect given the number of simulations carried out and the number of independent frequency bins (enhancing the significance of any tentative detection). We conclude that the quoted significances are not robust, and need to be revisited before the claimed detections can be verified.

5 The role of crust rupturing

The underlying cause of magnetar activity is decay of the ultra-strong magnetic field, which twists the field lines into an unstable configuration [8]. Once a tipping point is reached, the field lines undergo rapid reconfiguration (perhaps involving reconnection, the splicing of field lines). This creates currents whose dissipation generates gamma-rays. What is not understood at all, however, is what triggers the flares. For flaring to be sporadic, there has to be some barrier to magnetic reconfiguration that yields when a threshold is reached. The nature of this barrier - and the trigger for the starquakes - is not known [17].

One possibility is that reconfiguration is gated, or held up, by the crust of the star. The solid crust can in principle resist motion as it is stressed by the changing interior field, yielding only when magnetic force exceeds the breaking strain [71, 55]. The resulting crust rupture enables external field lines to move and reconfigure, generating the flare. Whether this is the case depends on the breaking strain of the crust, set by its composition, crystalline structure, and melting properties [28]. The strength of the deep crust, where the nuclei are expected to be highly deformed (the so-called pasta phase), is likely to be critical [56].

This is not the only option, however. Stress could also build up in the external magnetosphere, being released only when plasma conditions permit reconnection via various instabilities [47, 22]. If the crust yields plastically rather than resisting stress, then this may be more likely [34]. The excitation of GSOs then becomes an important issue, however. In addition it is now clear that flaring is not the only way of transferring magnetic stress from the interior of the star to the exterior. The level of twist in the magnetosphere changes even

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1 Ideally effects such as deadtime and pileup should also be taken into account, see [24].
when there is no flaring, suggesting that non-violent stress transfer is also possible [72, 51].

6 Conclusions

The initial excitement associated with the discovery of the magnetar QPOs was due in large part to the fact that they were thought to be torsional shear modes of the neutron star crust. The successful identification of a sequence of modes, including radial overtones, would have enabled a measurement of the thickness of the neutron star crust and placed a very strong constraint on the dense matter equation of state.

The picture is, it now appears, more complex. Crust physics remains, nonetheless, an important part of the equation. Global magneto-elastic seismic oscillations remain the most plausible explanation for the QPOs. In these models the shear properties of the crust and restoring force of the magnetic field couple together to create a complex oscillatory response to the giant flare. Mode identification in such a system will be more challenging (and will benefit hugely from better data), but will be far richer in terms of the revealed physics that initially imagined.

The role of the crust in gating magnetar flares also remains unclear. How the crust yields under the influence of magnetic stress, in particular whether this process is gradual or sudden, remains unresolved. Studies that are beginning to explore this issue are of critical importance to understanding how and why magnetars burst.

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