Neutron star oscillations, crustal fractures, and LOFT

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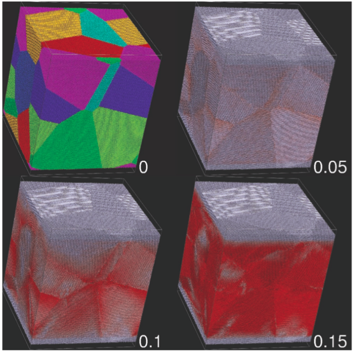
Overview

- Crustal strength plays a key role in several aspects of neutron star physics.
  - Determines maximum possible sizes of departures from axisymmetry.
  - Sets maximum amplitude of torsional modes of elastic oscillation.
  - Failure of crust plays key role in starquakes and magnetar flares.
- Overlap with X-ray astronomy considerable, and has impact on Graviational wave (GW) searches.
- **Aim of this talk is to describe how oscillations, breaking strain, GWs & LOFT fit together.**
- Will focus on LMXBs, CCOs & magnetars.

Just how strong is the crust?

- Shear modulus has long been known to be $\lesssim 10^{29}$ erg cm^{-3}.
- Breaking strain $\theta_{\rm max}$ more difficult to estimate.
- Recent large-scale molecular dynamics of Horowitz & Kadau (2009) indicate very high breaking strain, $\theta_{\rm max} \sim 0.1$:



Of course, plastic flow may relax crust on longer timescales (Chugunov & Horowitz 2010).

LMXBs: Gravitational wave emission mechanisms

- LMXBs are potential targets for Advanced GW detectors.
- They may be at a spin equilibrium between GW spin-down and accretion spin-up:

$$h_0 \approx 5 \times 10^{-27} \left(\frac{300\,\mathrm{Hz}}{f_{\mathrm{spin}}} \right)^{1/2} \left(\frac{F_{\mathrm{X}}}{10^{-8}\,\mathrm{erg\,cm^{-2}\,s^{-1}}} \right)^{1/2} .$$

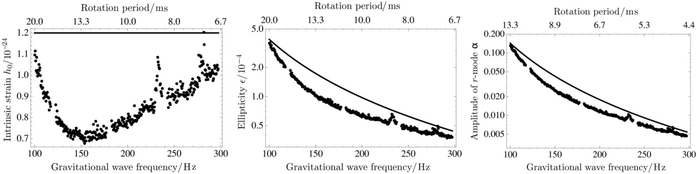
- Both ‘mountains’ and r-modes are possible GW emission mechanisms.
  - For mountains, $f_{\mathrm{GW}} = 2 f_{\mathrm{spin}}$.
  - For quadrupolar r-modes, $f_{\mathrm{GW}} = 4/3 f_{\mathrm{spin}}$, with $\sim 20\%$ ‘uncertainty’, related to stellar compactness M/R (Lockitch et al 2003).
- $\Rightarrow$ **If LOFT can supply f_{spin}, can distinguish the two mechanisms, and, in case of r-modes, measure compactness.**

LMXBs: Gravitational wave searches thus far

- Two GW searches carried out so far, both targeting Sco X-1:
- Abbott et al (2007):
  - Analysed coherently about 6 hours of data.
  - Upper limit $h \lesssim 1.3 \times 10^{-21}$ over band $604 - 624$ Hz.
  - Can be recast as an upper limit on ellipticity $\epsilon \lesssim 4 \times 10^{-4}$.
- Abadie et al (2011):
  - Analysed about 330 days of data using cross-correlation.
  - Obtained upper limits, stronger by factor of 5, over wide frequency band.
- Weakness of coherent search due to uncertainties in orbital parameters (Watts et al 2008).
- **Connection to LOFT: Need better fix on orbital parameters to carry out proper coherent search.**

Central Compact Objects

- CCOs *may* be rapidly spinning down due to GW emission.
- Abadie et al. (2010) targeted Cas A.
- Searched 12 days of data, over interval 100 Hz–300 Hz, allowing for non-zero $\dot{f}_{\rm GW}$ and $\ddot{f}_{\rm GW}$, beating 'indirect' bound $h_0 \lesssim 1.2 \times 10^{-24}$:



Abadie et al., Ap.J. **722** 1504 (2010)

- **Connection with LOFT: fix on $f_{\rm GW}(t)$ would allow much deeper search, and distinguish emission mechanism.**

Magnetars: the basic picture

- Magnetar flares extremely energetic–possible sources of GW bursts.
- According to canonical Thompson-Duncan model, decay δB in magentic field induces strain θ in crust of shear modulus μ.
- Fracture occurs when breaking strain reaches critical value $\theta_{\rm max}$:

$$B\delta B \sim \mu\theta_{\rm max} \Rightarrow \frac{\delta B}{B} \sim 10^{-2}\left(\frac{\mu}{10^{29}\,{\rm erg\,cm^{-3}}}\right)\left(\frac{\theta_{\rm max}}{0.1}\right)\left(\frac{10^{15}\,{\rm G}}{B}\right)^2 .$$

- These fractures power axial oscillations of elasto-magentic character [Cedra-Duran's talk], as well as the relativistic fireball.

Magnetars: Gravitational wave searches thus far

- Have been four GW papers on magnetar flares:
  - Abbott et al (2007) targeted QPO frequencies of Dec 27th 2004 hyperflare of SGR 1801-20.
  - For 92.5 Hz QPO, got bound on GW energy $\sim$ EM energy.
- More recent papers looked at other flares, and targeted mainly f-modes; bounds on $E_{\mathrm{GW}}/E_{\mathrm{EM}}$ weaker.
- **Connection with LOFT: accurate QPO frequencies and durations to guide GW searches.**

Magnetar flares: why search for GWs from f-modes?

- There exist selection effects that favour seeing QPOs in the electromagnetic domain, but favour f-modes in the gravitational wave domain.
  - F-mode decays on timescale $\lesssim 0.5$ s, QPOs live $\gtrsim 10^2$ s.
  - F-mode is a perfectly efficient GW emitter; torsional elastic/Alfve'n modes aren't.
  - If a significant fraction of E_{mag} dumped into GWs, should be detectable by aLIGO (Ioka 2001; Corsi & Owen 2011).
  - For given excitation energy, surface displacement for QPO-modes greater than that for f-mode—see next slide.
- Putting all this together, search for GWs from f-mode seems well motivated. However ...

Magnetar flares: a simple scaling argument for amplitudes

- If an energy E is deposited in a mode of frequency ω, a typical fluid element will undergo a displacement δr:

$$E \sim M_{\rm mode}\omega^2(\delta r)^2,$$

  where $M_{\rm mode}$ is the portion of the stellar mass that participates in mode.

- For f-mode, $M_{\rm mode} \sim M$, $f \sim$ kHz.
- For torsional modes, $M_{\rm mode}$ may lie in interval $(M_{\rm crust}, M)$, depending upon strength of coupling of crust to core, while observed QPOs span interval $(\sim 30, \sim 600)$ Hz.
- Parameterising:

$$\frac{\delta r_{\rm f-mode}}{\delta r_{\rm torsional}} \sim 5\times 10^{-3} \left(\frac{f_{\rm elastic}}{30{\rm Hz}}\right) \left(\frac{2\,{\rm kHz}}{f_{\rm f-mode}}\right) \left(\frac{M_{\rm torsional}/M}{0.1}\right)^{1/2} \left(\frac{E_{\rm f-mode}}{E_{\rm torsional}}\right)^{1/2}$$

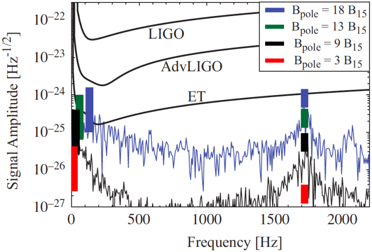
Magnetar flares: more detailed modelling

More detailed modelling seems to indicated that elastic/magnetic QPOs are more likely to be detectable than f-modes:

- Levin & van Hoven (2011) used simple analytic argument to show that, in fact, only a small fraction of total burst energy deposited in f-mode:

$$\Delta E_{\mathrm{f-mode}} \lesssim \frac{E_{\mathrm{mag}}}{E_{\mathrm{grav}}} E_{\mathrm{mag}} \sim 10^{-6} E_{\mathrm{mag}}.$$

- Numerical simulation of global magnetic instability of Zink et al. (2012) also pessimistic for f-modes, but torsional modes more easily detectable (see also Ciolfi & Rezzolla 2012):



Magnetar flares

- So, in terms of GWs, torsional modes seem more promising than f-modes.
- Further searches for both types may nevertheless be carried out.
- **Challenge for X-ray astronomy/LOFT: could f-mode excitation be seen, or at least constrained?**

Decay of modes

- Decay time of f-modes well constrained by theory ($\tau_{\rm f} \lesssim 0.5$ s).
- But what is decay time for torsional modes? Presumably *at least as long* as the observed lifetimes of $\sim 10^2$ s, as this reflects lifetime of fireball, not of mode.
- **Connection with LOFT: search to see if actual stellar oscillation lives longer than the previously observed (fireball) QPOs.**

Decay of modes cont . . .

In collaboration with Kostas Glampedakis, am looking at mechanisms that damp torsional modes. These include:

- Internal dissipation; cutting of vortices through flux tubes seems leading mechanism, with $\tau \sim 10^2$ s for Alfveń modes in core.
- External dissipation: shaking of surface can launch waves into magnetosphere, where energy is then dissipated. Find $\tau \sim 10^2$ s for crustal elastic mode.
- Investigated other mechanisms, and obtained variety of longer timescales; there are several possibilities, no one of which we are confident can be excluded.
- Decay rate may even undergo abrupt changes, as nature of dominant dissipation mechanism can depend upon amplitude.
- **Connection with LOFT: Measurement of decay times can shed light on dominant damping mechanism, giving insight into nature of stellar core and magnetosphere.**

Summary

In the context of stellar oscillation/rotation, LOFT can potentially:

- Measure spin frequency/orbital parameters of LMXBs, to guide GW search and distinguish between rival emission mechanisms.
- Measure spin evolution of CCOs, to guide GW search and distinguish between rival emission mechanisms.
- Measure magnetar QPO frequencies, amplitudes, and decay times, and look for additional mode excitation, to guide GW searches, and give insight into physics of stellar crust, core and magnetosphere.