Probing a magnetar's internal field and superfluidity using QPOs

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with Andrea Passamonti; see today's arXiv:1210.2969

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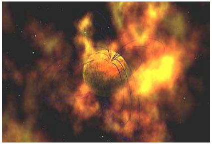
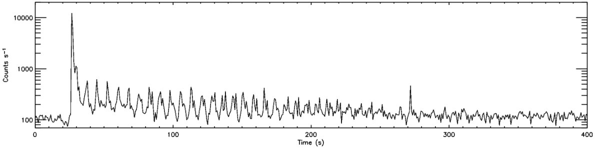
Magnetar QPOs





- Magnetars occasionally experience giant flares
- in the aftermath, see oscillations in rough range 10 – 1000 Hz
- origin first thought to be purely crustal elastic modes, later magnetic modes of interior or magneto-elastic modes of crust-core system

  (Review: Watts 2011)
- understanding the nature of these QPOs could give us a probe of the stellar interior: the EOS and magnetic field configuration!
- no simulations that account for multifluid interior of magnetar

Motivation and plan

A neutron star is not a single-fluid ball obeying a barotropic ($P = P(\rho)$) EOS:

- *multifluid interior*: contains superfluid neutrons and superconducting protons (Baym et al. 1969)
- at magnetar field strengths, superconductivity may be broken and protons normal (Glampedakis et al. 2011)

Also: indications that magnetic fields in barotropic stars are generically unstable (Reisenegger 2009, Lander & Jones 2012). If so, additional physics (like stratification) is essential for a 'realistic' model.

Plan of this talk

- construct stratified magnetic equilibria with superfluid neutrons
- time-evolve MHD perturbation equations
- first quantitative results for superfluid magnetar oscillations

Two-fluid equilibrium equations

We model a magnetar as a magnetised fluid body with stratification. We assume the whole star is multifluid (no crust) for simplicity, and find equilibrium models by solving the:

Two-fluid Euler equations

$$\frac{\nabla P_{\rm p}}{\rho_{\rm p}} + \nabla\Phi - \frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi\rho_{\rm p}} = 0,$$

$$\frac{\nabla P_{\rm n}}{\rho_{\rm n}} + \nabla\Phi = 0.$$

The two fluid species are (mildly) coupled through gravity:

$$\nabla^2\Phi = 4\pi G(\rho_{\rm n} + \rho_{\rm p}),$$

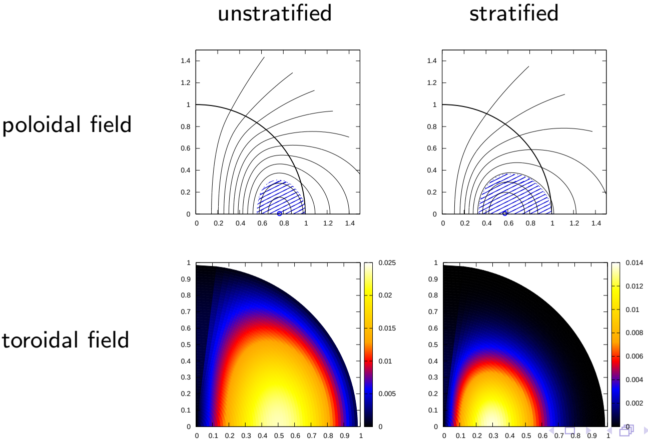
and we don't want any magnetic monopoles:

$$\nabla\cdot\mathbf{B} = 0.$$

Scheme also allows for rotation, but this is a small effect in magnetars.

Stratified NSs in normal MHD

We close the system with an equation of state. By choosing a two-fluid analogue of a barotrope, $P_{\rm p} = k_{\rm p}\rho_{\rm p}^{1+1/N_{\rm p}}$ and $P_{\rm n} = k_{\rm n}\rho_{\rm n}^{1+1/N_{\rm n}}$, we are able to introduce stratification but still re-use tricks from the barotropic case (Lander et al. 2012).



Magnetar oscillations with superfluidity

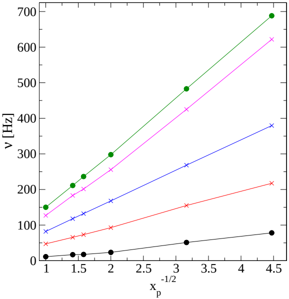
We solve the two-fluid perturbation equations using our multifluid equilibria as backgrounds. The perturbations are numerically time-evolved using a code that combines two previous ones (Passamonti et al. 2009, Lander et al. 2010). For now we're studying non-axisymmetric modes.

Two-fluid effects

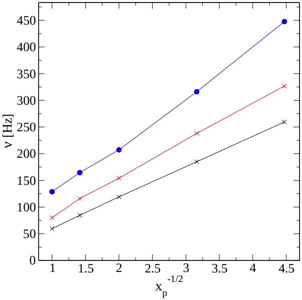
- Proton fraction: in a single-fluid magnetar model the whole star feels the magnetic field. With superfluid neutrons we have a two-fluid system and oscillations depend on $x_\mathrm{p} = \rho_\mathrm{p}/\rho$.
- Entrainment: coupling between the protons and superfluid neutrons. Large entrainment effectively returns the star to a single-fluid body. (Results in paper but not talk.)
- Stratification: caused by composition gradients. This is equivalent to a non-constant proton fraction.

Unstratified two-fluid models

Mode frequencies for a two-fluid star scale in the expected way (Andersson et al. 2009) with proton fraction. In the single-fluid limit $x_{\rm p} \to 1$ we recover earlier results. Polar-led modes, $B = 10^{16}$ G. We see that there is a possibility to infer details of the magnetar's field geometry from QPOs.

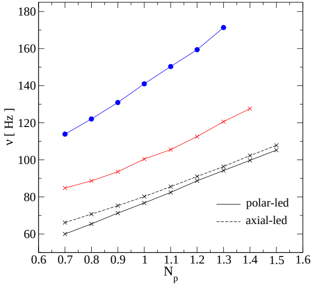


Poloidal field. For a 'typical' value of $x_{\rm p} = 0.1$ we find five widely spaced modes, between 50 and 500 Hz.



Toroidal field. The three modes we find in this case are far more closely spaced: $180 - 320$ Hz at $x_{\rm p} = 0.1$.

Stratification and two-fluid frequency scaling



Toroidal field, axial- and polar-led modes. We fix $N_\mathrm{n} = 1$ and vary N_p, so $N_\mathrm{p} = 1$ is an unstratified model. $B = 5 \times 10^{15}$ G here.
For $N_\mathrm{p} > N_\mathrm{n}$ mode frequencies are enhanced w.r.t. unstratified values.

We find that the expected scaling of Alfvén modes in the presence of superfluid physics is:

$$\sigma_{2f} \approx 6.3\, \sigma_{1f} \left[0.15 + 0.85\left(\frac{N_\mathrm{p}}{2.0}\right)\right]\left(\frac{\varepsilon_\star}{1.3}\right)^{1/2}\left(\frac{x_\mathrm{p}(0)}{0.1}\right)^{-1/2}.$$

Alfvén modes have far higher frequencies in a multifluid magnetar!

Implications for magnetar QPOs

These is clearly missing physics from our model (crust, superconductivity). Nonetheless, we can ask: according to our model, what modes do the different observed magnetar QPOs represent?

High-frequency QPOs: long-lived QPOs at 150 Hz and 625 Hz (SGR 1806-20) and at 155 Hz (SGR 1900+14). Within other models these are high — yet undamped — overtones of other modes. We suggest they could be 'fundamental' Alfven modes after two-fluid enhancement:

$$25 \to \mathbf{150}\ \mathrm{Hz}\ (m = 0?)\quad ;\quad 100 \to \mathbf{625}\ \mathrm{Hz}\ (m = 2?)$$

Low-frequency QPOs: QPOs below around 50 Hz cannot be explained in our fluid model. These could perhaps be magneto-elastic modes of the crust. We hope to add in this extra physics and check...

Next...

Hopefully a few more giant flares!