Superfluid magneto-elastic oscillations of magnetars

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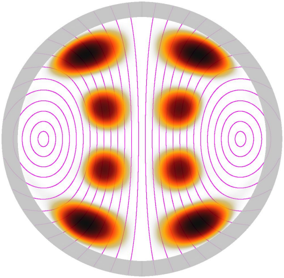

MNRAS, 443, 2014
PRL, 111, 2013
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MNRAS, 421, 2012
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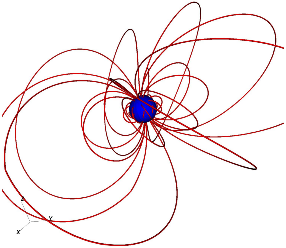

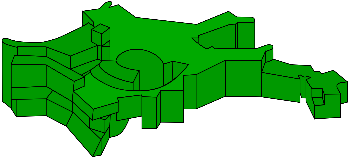

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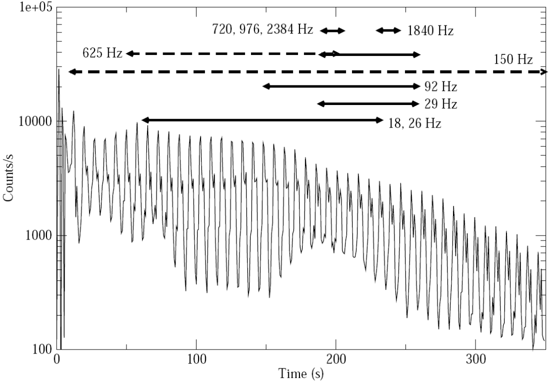
QPOs in giant flares of magnetars

Giant flares

- SGR 0526-66 (1978), SGR 1900+14(1998), SGR 1806-20 (2004)
- Strong modulation ⇒ rotation period (5 . . . 10s)
- Additional quasi periodic oscillations (QPOs)

(Israel et al. 2005, Strohmayer & Watts 2006, El-Mezeini & Ibrahim 2010, Hambaryan et al. 2011)

- QPOs in normal bursts: 93, 127 and 260Hz (Huppenkothen et al. 2014)



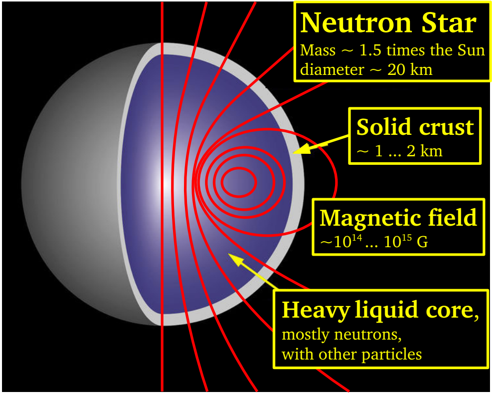
Strohmayer & Watts 2006

Confirmed QPO frequencies

SGR 1806-20: 18, 26, 30, 92, 150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84, 155 Hz

Where do the QPOs come from? Are they Starquakes?



Possible origin of the observed frequencies

- Discrete Shear modes (crust)?
- Alfvén oscillations at the turning points of a continuum (core+crust)?

Coupled Crust-Core oscillations

(Glampedakis et al. '06; Levin '07; Van Hoven & Levin '11 & '12; Colaiuda et al. '10 & '11 & '12; Gabler et al. '11 & '12)

Torsional shear modes

Samuelsson & Andersson 2007

Observed frequency in Hz		Shear mode	
SGR 1806-20	SGR 1900+14	n	l
18		???	???
26		???	???
30	28	0	2
	53	0	4
92	84	0	6
150		0	10
	155	0	11
625		1	
1840		3	

(Schomaker & Thorne 1983, Piro 2005, Samuelsson & Andersson 2007)

- No magnetic field
- Free slip / zero traction at crust core interface
- Relativistic estimates for f:

$\Rightarrow$ $n = 0$:

$$f^2 \sim \frac{(l-1)(l+2)}{RR_c}$$

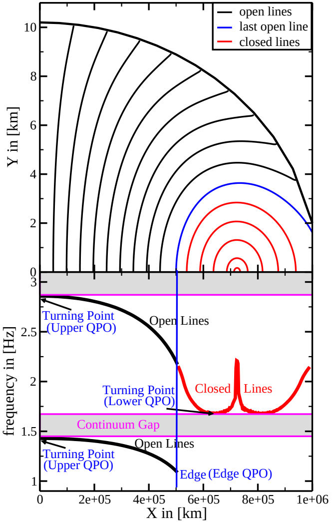
R_c - radius of crust

$\Rightarrow$ $n > 1$:

$$f \sim \frac{n}{\Delta}$$

Δ - crust thickness

The Alfvén continuum



- Each field line has proper eigenfrequency (purely poloidal magnetic field + torsional oscillations)
- Field lines are coupled through: (i) surface boundary conditions (ii) the crust (iii) numerics
- Long-lived QPOs exist at the turning-points or edges of the continuum
- Gaps between successive Alfvén overtones
- $f_1 : f_2 : f_3 : ... = 1 : 2 : 3 : ...$

(Levin '06 & '07, Sotani et al.'07, Cerdá-Durán et al. '09)

MCoCoA - 2D GRMHD simulations

MCoCoA

- Ideal MHD code in dynamical space-time (Godunov type schemes + flux CT)
- Spherical polar coordinates in axisymmetry (2D)
- Zero temperature, tabulated EOS
- Including elastic crust
- Spherically symmetric background
- Small-amplitude oscillations
- Cowling approximation
- In linear regime and axisymmetry poloidal and toroidal perturbations decouple

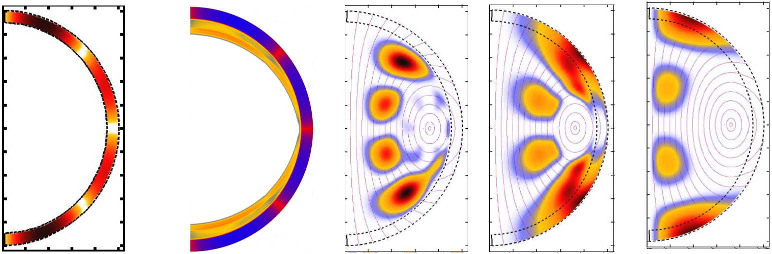
$\Rightarrow$ only consider torsional oscillations

Results - magneto-elastic oscillations inside the magnetar

$\mathbf{B^2 << \mu_S}$ $\mathbf{B \sim 10^{13} G}$ $\mathbf{B \sim 10^{15} G}$ $\mathbf{B^2 >> \mu_S}$

$\longrightarrow$ $\mathbf{B}$

predominantly shear modes | **shear modes strongly damped** | **magneto-elastic QPOs** (**confined to core** / **reach surface**) | **predominantly Alfvén QPOs**



Identifying observed frequencies

- Frequency ratio of low frequency magneto-elastic oscillations (antisymmetric, symmetric) is roughly

$$1 : 2 : 3 : 4 : 5 : \ldots$$

- Different magnetic field configurations give more than one fundamental

SGR 1806-20: (18), 26, 30, 92, 150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84, 155 Hz
or 28, 53, 84, 155 Hz

Superfluid neutron star core - one-fluid approximation

Effective one fluid model (decoupling n from p):
$\rho \to \rho_p \sim 0.05\rho$

$$v_A^2 = \frac{B^2}{\rho} \to \frac{B^2}{\rho_p}$$

Fundamental oscillations

Exist as before but with:

$$f_{\rm sf} \sim \frac{1}{t_A} \sim \frac{v_A}{R} \sim \frac{B}{R\sqrt{\rho_p}} \sim \frac{B}{R\sqrt{0.05\rho}} \sim 5 \times f_{\rm n}$$

To match observed QPOs:

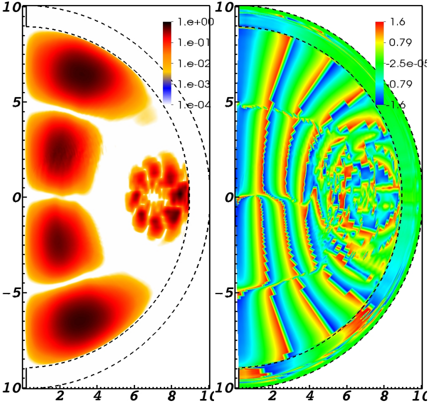
$$2 \times 10^{14} \lesssim B \lesssim 10^{15}\,\mathrm{G}$$

Andersson et al. '09, Glampedakis et al. '11, vanHoven & Levin '11 & 12, Passamonti & Lander '13

Constant Phase Oscillations

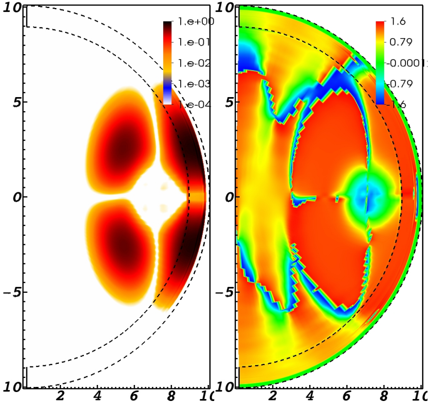
- Alfvén dominated oscillations confined to the core
- Continuous phase change

5×10^{13} G



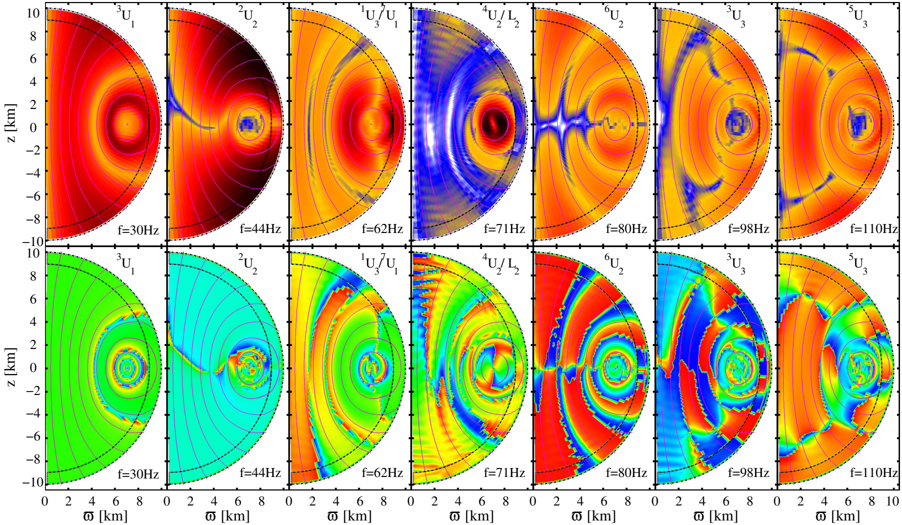
- Magneto-elastic oscillations penetrating the crust
- Constant phase

2×10^{15} G



Lowest frequency oscillations ${}^{l}U_n$ at $B = 2 \times 10^{15}$ G

- l maxima in θ direction
- n maxima in r direction



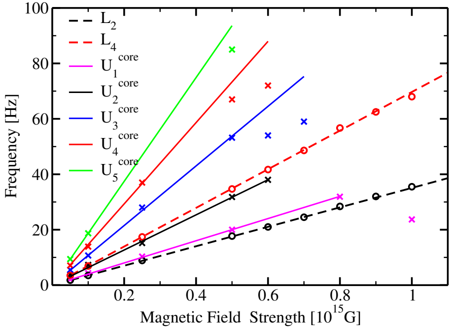
Scaling of the frequencies with B

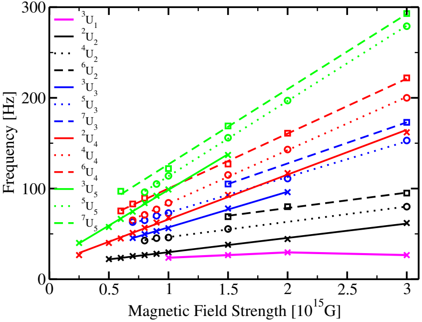
Alfvén oscillations (in the core)

- Continuous phase
- Scale linearly with B
- $f \to 0$ for $B \to 0$
- Exist for $B \to 0$

Magneto-elastic oscillations

- Constant phase
- Scale linearly with B
- $f \to f_0$ for $B \to 0$
- Disappear $B \lesssim \text{few} \times 10^{14}$ G





Scaling of the frequencies with $\varepsilon_\star X_c$ at $B = 5 \times 10^{14}$ G

Fitting function: $f\,[\mathrm{Hz}] = d_0 \times (\varepsilon_\star X_c)^d$

Alfvén oscillations (in the core)

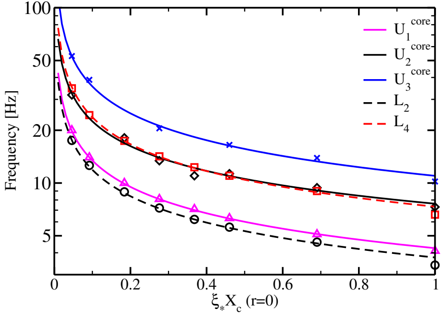
$d \sim -0.5$

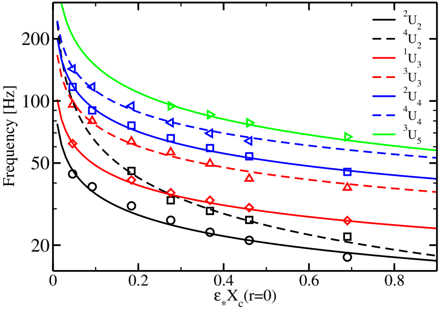
$$f \sim \frac{v_A}{R} \sim \frac{B}{R\sqrt{\varepsilon_\star X_c \rho}}$$

Magneto-elastic oscillations

$d \sim -0.33$

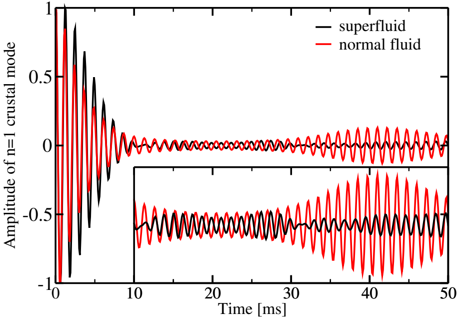
crust is important

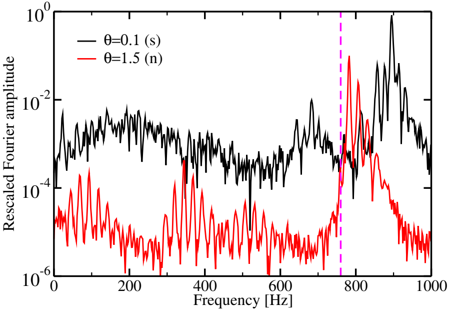




High frequency QPOs

- Rapid initial damping
- Long-lived QPOs at $f \sim f_{\rm crust}^{n=1}$





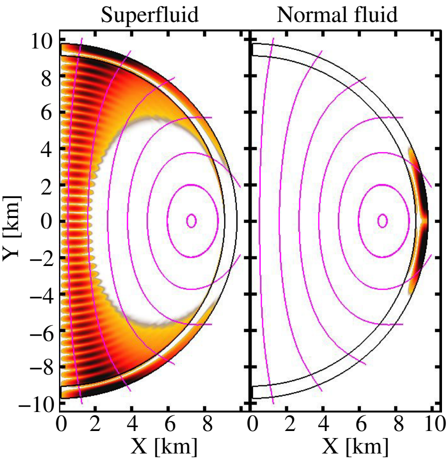
Superfluid neutron star core - High frequency QPOs

Normal fluid

- $n = 1$ radial shear mode structure
- Localized close to equatorial plane
- $\hat{B} \perp \hat{r} \Rightarrow$predominantly shear mode only in crust

Superfluid

- $n = 1$ radial shear mode structure
- Close to pole
- Resonance with Alfvén overtone of core



Identifying observed frequencies

- Frequency ratio of low frequency magneto-elastic oscillations (antisymmetric, symmetric) is roughly

$$1 : 2 : 3 : 4 : 5 : \ldots$$

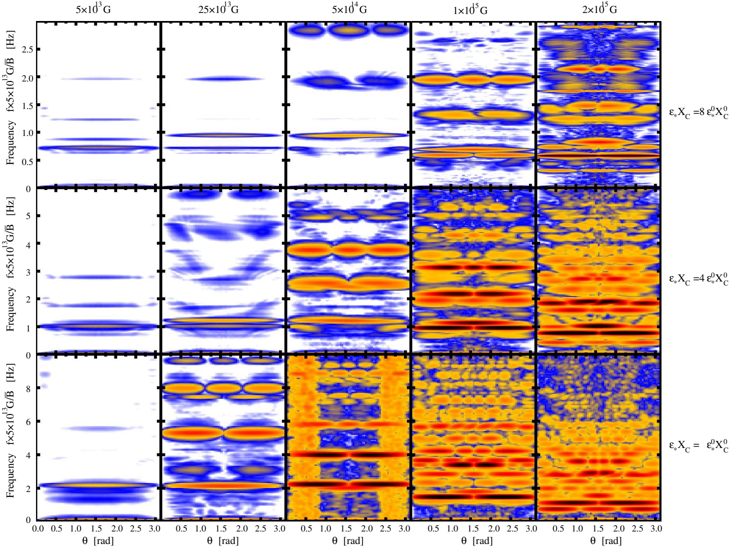
- Different magnetic field configurations give more than one fundamental
- More constant phase oscillations, because different l dependence
- High frequency QPO as resonance of higher Alfvén overtone in core with $n > 0$ crustal mode if core is superfluid

SGR 1806-20: (18), 26, 30, 92, 150, 625, 1840 Hz

SGR 1900+14: 28, 53, 84, 155 Hz
or 28, 53, 84, 155 Hz

Magneto-elastic oscillations break out of crust($B \sim 10^{15}$ G)

Magnitude of the FFT at different B



$\varepsilon_\star X_c =$

$8 \times \varepsilon_\star^0 X_c^0$

$4 \times \varepsilon_\star^0 X_c^0$

$\varepsilon_\star^0 X_c^0$

Conclusions

- Antisymmetric (v_φ) fundamental magneto-elastic oscillations can explain low frequency QPOs
- Inclusion of superfluid effects:

$\Rightarrow$ Low and high frequency QPOs

$\Rightarrow$ B estimates in agreement with spin down observations

$\Rightarrow$ Constant phase oscillations (no crustal modes in gaps!)

- Break out of oscillations sensitive to magnetic field strength and superfluid properties

QPOs of SGRs are probably superfluid magneto-elastic oscillations

Caveats:

- Different field configurations give same QPO frequency for different field strength
- Degeneracy between EOS and magnetic field configuration/strength