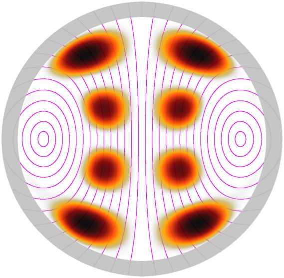
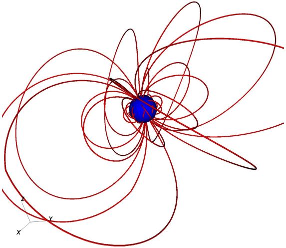
Shaking the magnetosphere of magnetars with magneto-elastic oscillations

Michael Gabler



Gabler et al. 2014,
MNRAS, 443

A. Mate, E. Müller,
P. Cerdá-Durán, T. Font,
N. Stergioulas



NewCompStar meeting 14.09.2016

SGR - Magnetar - QPO

SGR

- Repeated γ activity (normal burst)
- $P = 5 \ldots 10\text{s}$
- $\dot{P} \sim 3\,\text{ms/year}$
- Giant flares observed in 3 SGR ($1000\times$ energy flux)

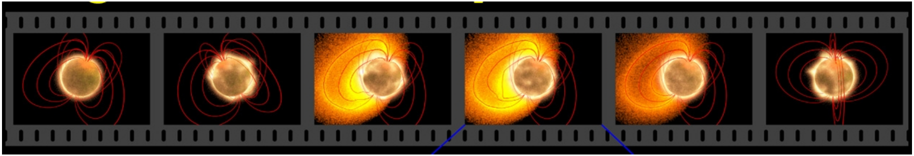
Confirmed QPO frequencies in Giant flares

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

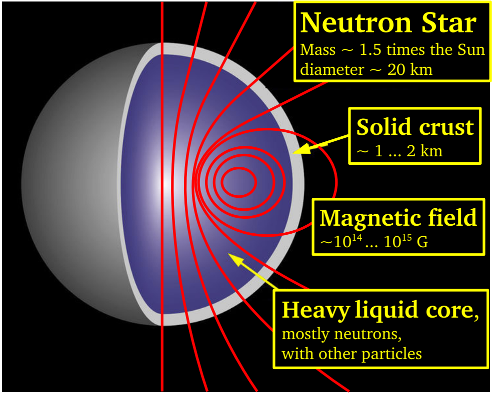
SGR 1900+14: 28, 53, 84, 155 Hz

(Israel et al. '05, Strohmayer & Watts '06, Hambaryan et al. '11)

R. Mallozzi, UAH/NASA MSFC



Where do the QPOs come from?



Possible origin of the observed frequencies

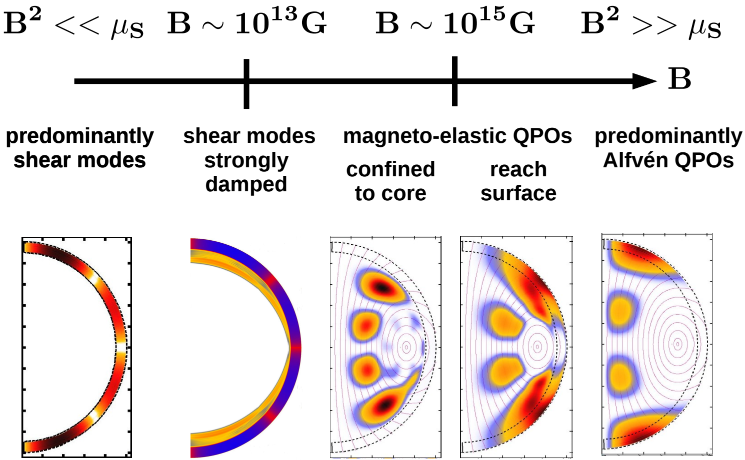
- Discrete Shear modes (crust)?
- Alfvén oscillations at the turning points of a continuum (core+crust)?
- Magnetospheric oscillations?

Coupled Crust-Core oscillations

With or without superfluid effects, pasta phases, ...

(Glampedakis et al. '06; Levin '07; Van Hoven & Levin '11 & '12;
Colaiuda et al. '10 & '11 & '12; Gabler et al. '11, '12, '13, & '16, Passamonti '12, '13, '14 & '16, Sotani et al. '07, '08, '13, '14, '15, ...)

Magneto-elastic QPOs inside the magnetar



$\Rightarrow$ QPOs at low frequencies $f \lesssim 150\,\mathrm{Hz}$ at $B \sim 0.8 \ldots 4 \times 10^{15}$ G

Superfluid neutron star core

- Complete entrainment in crust

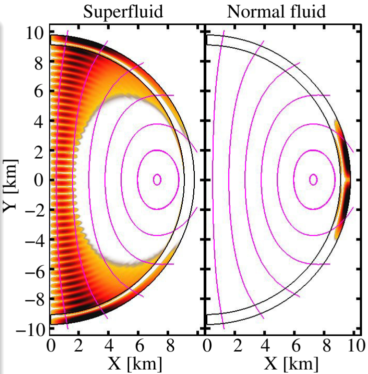
$\Rightarrow$ like normal fluid

- No entrainment in core: $\rho \rightarrow \rho_p \sim 0.05\rho$

$\Rightarrow$ $v_A^s = B/\sqrt{\rho_p} \sim 4 \times v_A$

$\Rightarrow$ QPOs at $f \lesssim 150\,\mathrm{Hz}$ at $B \lesssim 10^{15}\,\mathrm{G}$

- Constant phase QPOs
- High frequency QPOs ($f > 500Hz$): Resonance between $n = 1$ shear mode in crust and Alfvén overtone in core



$\Rightarrow$ Superfluidity seems to be a key ingredient (Gabler et al. 2013 & 2016, Passamonti 2014)

Identifying observed frequencies

- Frequency ratio of low frequency magneto-elastic QPOs (odd, even) is roughly

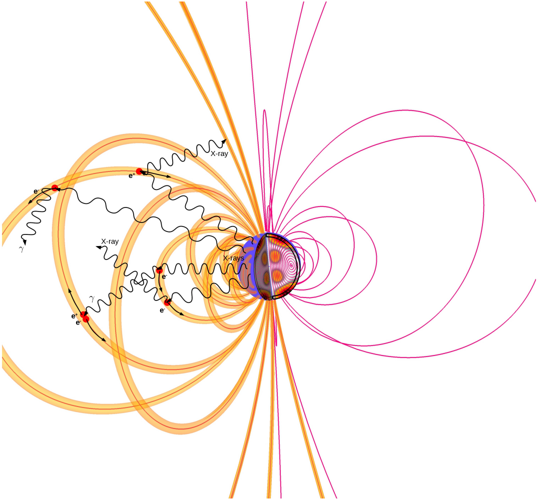
$$1 : 2 : 3 : 4 : 5 : ...$$

- Different magnetic field configurations gives more than one fundamental
- 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

The exterior - shaking the magnetar magnetosphere



Interior

- Magneto-elastic QPOs dynamically uneffected by exterior
- Exterior provides boundary condition (zero traction)

Exterior field

- Force-free configuration
- Maintained by currents (Assumption: there are sufficient charge carriers)
- Obtained from surface magnetic field

Timescales - quasi static field

- Highest oscillation frequency (low frequency QPOs) 150Hz
- Shortest field line that can resonate at this frequency has $\lambda_f \sim \frac{c}{f} \gtrsim 2000\mathrm{km}$
- Opening angle $\theta > 0.19$ rad (for dipolar configuration)

$\Rightarrow$ No oscillations excited along these field lines, but shearing/twisting allowed

- External magnetic field adjusts to new boundary condition

$\Rightarrow$ quasi-static evolution

Self-similar field

- Force-free: $\mathbf{J} \times \mathbf{B} = 0$
- Ansatz: $\mathbf{J} = \mathcal{P}(\Gamma)\mathbf{B}$ with $\Gamma = \Gamma_0 \left(\frac{r}{r_S}\right)^{-q} F(\cos\theta)$
- Particular choice of the flux parameter $\Gamma = r \sin\theta A_\varphi$ leads to:

$$B_r = -\frac{B_{\rm pole}}{2}\left(\frac{r_S}{r}\right)^{q+2}\frac{\partial}{\partial x}F(x)$$

$$B_r = \frac{B_{\rm pole}}{2}\left(\frac{r_S}{r}\right)^{q+2}\frac{qF(x)}{\sin\theta}$$

$$B_r = \sqrt{\frac{Cq}{q+1}}\frac{B_{\rm pole}}{2}\left(\frac{r_S}{r}\right)^{q+2}\frac{F(x)|F(x)|^{1/q}}{\sin\theta}$$

Global twist $\Delta\Phi$

$$\Delta\Phi = 2\int_\theta^{\pi/2}\frac{B_\varphi(\theta)}{B_\theta(\theta)}\frac{d\theta}{\sin\theta}$$

(Vigano et al. '11, Pavan et al. '09)

Force-free axisymmtetric equilibria in Schwarzschild geometry

- For poloidal background fields the linearized force-free equations are:

$$\begin{aligned} 0 &= \mathbf{J} \times \mathbf{B} \\ 0 &= (\mathbf{J} \times \mathbf{B})_\varphi \\ &= \frac{1}{r}\left[\frac{B_\theta}{\sin\theta}(\sin\theta\delta B_\varphi)_{,\theta} + B_r(r\alpha\delta B_\varphi)_{,r}\right] \\ &= \frac{1}{\alpha r\sin\theta}(\mathbf{B_0}\cdot\nabla)(\alpha r\sin\theta\delta B_\varphi) \end{aligned}$$

- $\alpha r \sin\theta\delta B_\varphi$ is flux function like $A_{\tilde{\varphi}}$

$$\delta B(\mathbf{x}) = \frac{\alpha_s r_s \sin\theta_s}{\alpha_x r_x \sin\theta_x}\delta B(\mathbf{r_s})$$

- valid for $\delta B_\varphi / B_0 \lesssim 0.1$

No anti-symmetric perturbations

$$0 = \frac{1}{\alpha r \sin\theta}(\mathbf{B_0} \cdot \nabla)(\alpha r \sin\theta \delta B_\varphi)$$

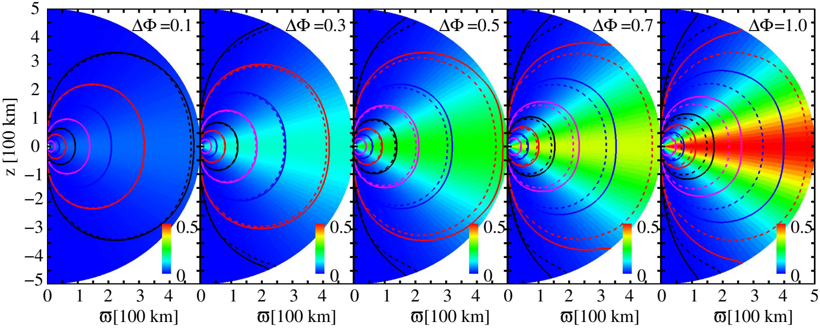
- $\alpha r \sin\theta \delta B_\varphi$ is a flux function

$\Rightarrow$ for symmetric B-fields, δB_φ has to be symmetric ($\alpha, r, \sin\theta$ are symmetric)

- Not all oscillation can 'shake' the magnetosphere
- Only symmetric (antisymmetric) perturbations in δB_φ (v_φ): These have approximately the frequency spacing like $1 : 3 : 5 : \ldots$ ($30, 92, 150$ Hz SGR 1806 or $28, 82, 155$ Hz SGR 1900)

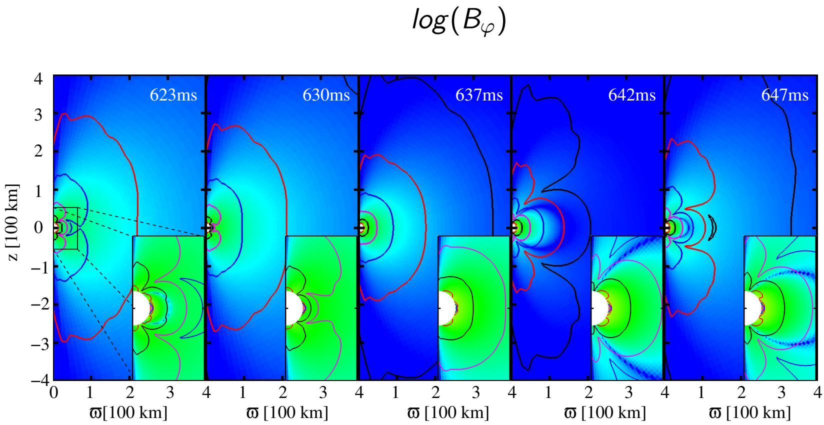
Comparison to self-similar model

B_φ / B_0



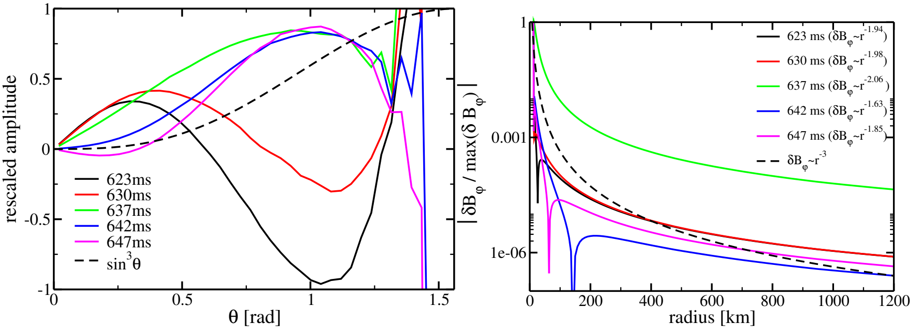
Approximation good up to $\Delta\Phi \lesssim 0.5$ ($\delta B_\varphi / B_0 < 0.25$)
Our models have $\delta B_\varphi / B_0 < 0.1$

Example evolution



Surface magnetic field from simulations of interior ($B_{\rm pole} = 3 \times 10^{15}$ G)
Complicated field geometries, with nodal lines.

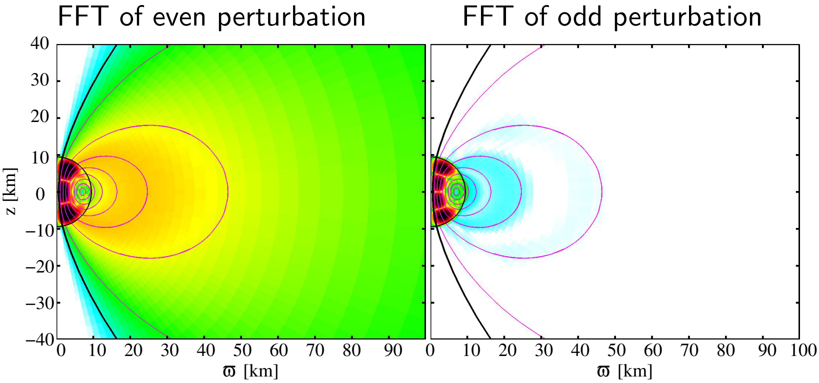
Example evolution - $B_\varphi(\theta, r = r_S)$ and $B_\varphi(\theta = \pi/2, r)$



- Dashed line = self-similar model: decays fast close to pole
- During evolution significantly stronger fields close to pole
- Nodal lines
- Slower (faster) decay of B_φ with r for large (small) radii

Confirmation with simulations

- MHD simulation with low density atmosphere ($\rho_{\rm surf} = 10^{-10}\rho_{\rm center}$ and $\rho \sim r^{-4}$)



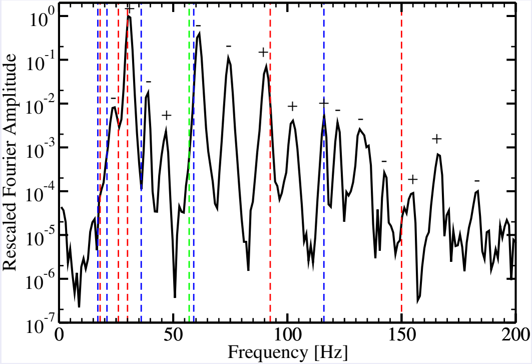
- Travelling waves only for $\theta < 0.19$
- Constant $\alpha \delta B^{\tilde{\varphi}} = \alpha r \sin\theta \delta B_{\varphi}$

Shaking the magnetosphere

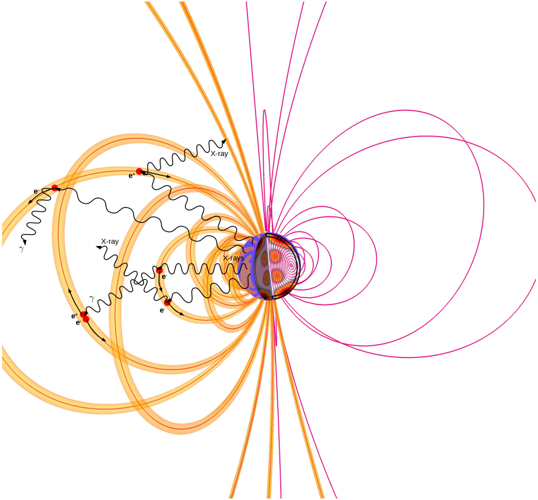
Conclusions

- Superfluid magneto-elastic QPOs can explain the observed frequencies of magnetar QPOs
- They can 'shake' the exterior magnetic field which is assumed to be force-free but with sufficient charge carriers

Only symmetric (in B_φ) oscillations can twist the exterior field and thus potentially modulate the emission



Outlook



Modulation mechanism

- Exterior magnetic field is twisted
- Twisted magnetic field maintained by currents
- Charge density $\gg \rho_{GJ}$
- Photons interact with charge carriers

$\Rightarrow$ Resonant cyclotron scattering:

  - $e^{\pm}$ move along B
  - $\perp$ momentum quantized
  - Excitation of Landau levels
  - $\omega_B = \frac{eB}{mc}$

Outlook - Monte Carlo radiation transfer with prescribed momentum distribtion of charge carriers

- Integrated light curve (E=[2keV, 8keV]) for high QPO amplitude

$\Rightarrow$ strong modulation at the expected frequencies

- Fourier transformation allows to detect the QPOs up to surface amplitudes of $A \leq 1$km

Lightcurve in energy band E=[2keV, 8keV]