Modulating magnetar emission by magneto-elastic oscillations

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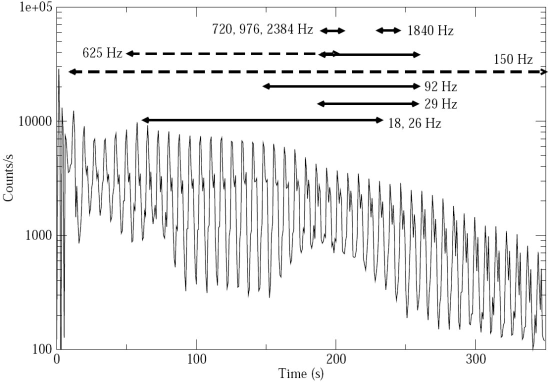
QPOs (quasi-periodic oscillations) in magnetar giant flares

Giant flares

- SGR 0526-66 (1978), SGR 1900+14(1998), SGR 1806-20 (2004)
- Peak luminosity $10^{44} \ldots 10^{46}$ erg/s
- Low frequency modulation $\Rightarrow$ rotation period $(5 \ldots 10\text{s})$
- High frequency quasi periodic oscillations QPOs

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



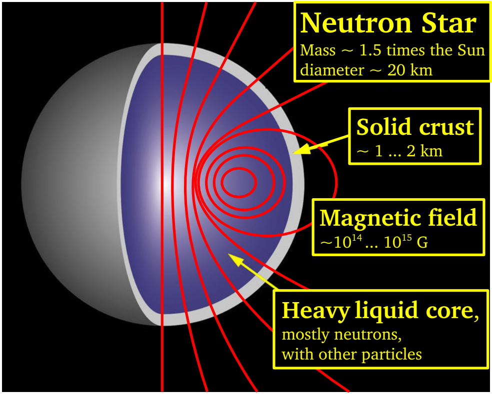
Strohmayer & Watts 2006

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?



Possible origin of the observed frequencies

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

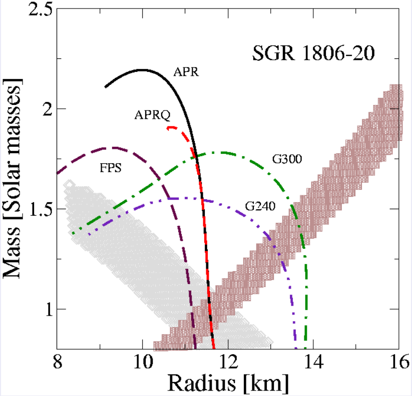
Coupled Crust-Core oscillations

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

What can we learn from magnetar QPOs?

Constraints by crustal modes

Samuelsson & Andersson 2007



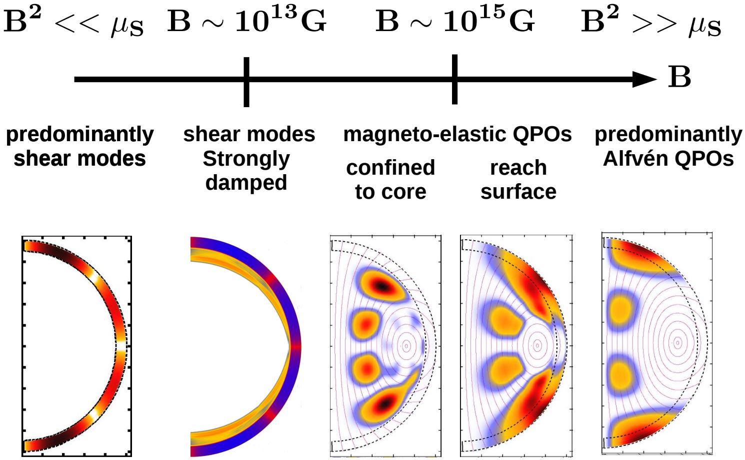
$f_{n=0} \sim 1/R$; $f_{n=1} \sim 1/\Delta$

Constraints by Alfvén oscillations

- Magnetic field strength: $f \sim B$
- Topology of magnetic field inside neutron star
  - Field penetrating the core ?
  - Field confined to crust ?
  - Poloidal vs. toroidal ?
- Probing physics of core
  - Superconductivity ?
  - Superfluidity ?
  - ...

$\Rightarrow$ constrain the EOS and/or magnetic field

Magneto-elastic QPOs inside the magnetar



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

Superfluid neutron star core

- Complete entrainment in crust

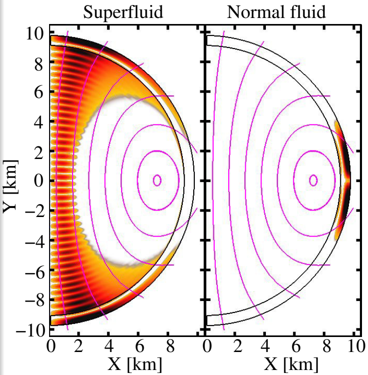
$\Rightarrow$ like normal fluid

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

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

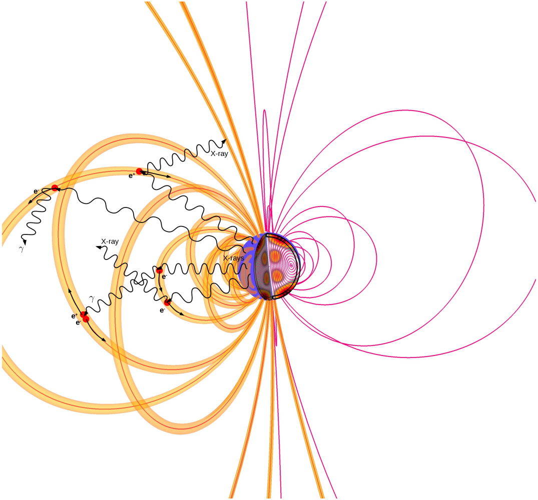
$\Rightarrow$ QPOs at $f \lesssim 150\,\mathrm{Hz}$ at $B \lesssim 10^{15}\,\mathrm{G}$

- High frequency QPOs ($f > 500Hz$): Resonance between $n = 1$ shear mode in crust and Alfvén overtone in core
- Normal fluid case:
  - $B \lesssim 10^{15}$ G: strong reflection of QPO at crust-core interface
  - $B > 10^{15}$: $B^2 \gtrsim \mu_S$ in crust $\rightarrow$ no $n = 1$ crustal mode



$\Rightarrow$ Superfluidity seems to be a key ingredient (Gabler et al. 2013)

The exterior - modulating the magnetar emission



Interior

- Magneto-elastic QPOs

Exterior field

- Force-free configuration
- Obtained from surface magnetic field

Modulation mechanism

- Twisted magnetic field maintained by currents
- Photons interact with charge carriers

⇒ Resonant cyclotron scattering (Timokhin et al. '08)

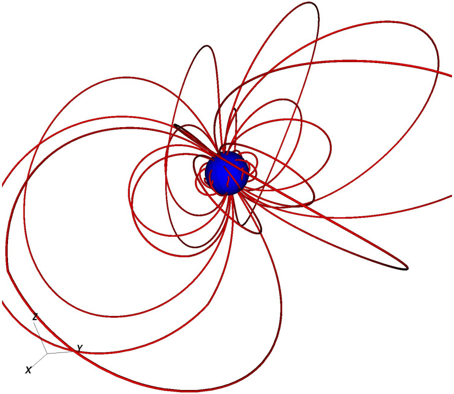
Twisted magnetospheric field

- Caused by motion of foot points
- Quasi-static sequence of linearized force-free equilibria with:

$$
\begin{aligned}
(J \times B)_\varphi &= 0 \\
\frac{B_{pol} \cdot \nabla(\alpha r \sin\theta B_\varphi)}{\alpha r \sin\theta} &= 0
\end{aligned}
$$

- B_φ antisymmetric
- Very different from self-similar solutions

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

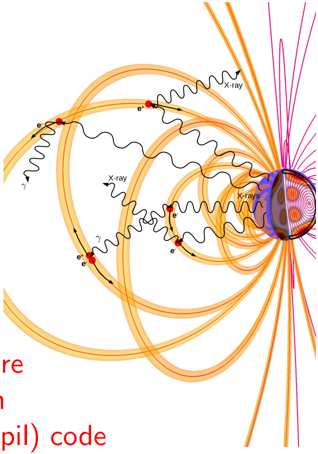


MCMaMa - Monte-Carlo MAgnetar MAgnetospheres

- Currents ($e^{\pm}$) induced by the twisted magnetic field
- $e^{\pm}$ scatter photons resonantly (RCS)

$\Rightarrow$ Changes spectrum

- Physical ingredients:
  - Scattering cross sections (Klein-Nishina)
  - Distribution of seed photons (black body)
  - Spatial distribution of charge carriers (determined by force-free magnetic field)
  - Momentum distribution of charge carriers (determined by magnetic field and interaction with photon field)



- MCMaMa: Monte-Carlo Magnetar Magnetosphere scattering code coupling a Monte-Carlo radiation transport for the photons to a particle-in-a-line (pil) code for the charge carriers

(Beloborodov 2012, Timokhin et al. 2008)

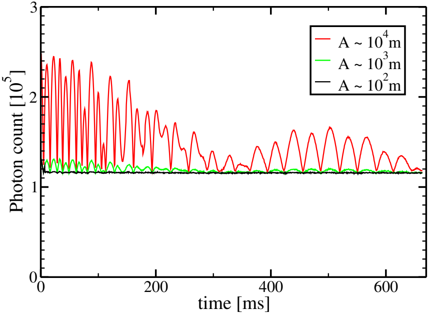
Modulating the EM emission

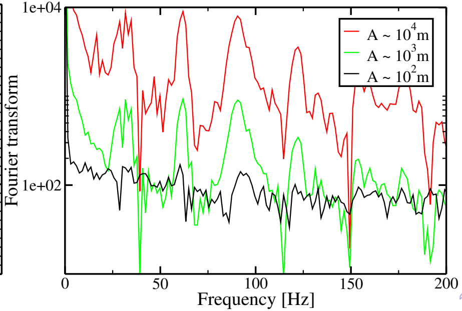
- Maxwellian momentum distribution of mildly relativistic electrons ($\beta = 0.3c$) for the quiescent emission at kT$\sim$ 0.5keV
- Integrated light curve (E=[2keV, 8keV]) for high QPO amplitude

$\Rightarrow$ strong modulation at the expected frequencies

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

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





Conclusions

- Purely crustal shear modes do not exist at $B \gtrsim 10^{14}$ G
- Normal fluid magneto-elastic QPOs can explain observed low frequencies in SGR QPOs for $8 \times 10^{14} \lesssim B \lesssim 4 \times 10^{15}$ G
- Superfluid magneto-elastic QPOs can explain low and high frequencies for $2 \times 10^{14} \lesssim B \lesssim 10^{15}$ G
- Force-free exterior field favours antisymmetric QPOs
- Modulation mechanism: resonant cyclotron scattering (RCS)
- Constructed new code for RCS: MCMaMa

Preliminary result

Superfluid magneto-elastic QPOs with odd equatorial symmetry can modulate the emission significantly for realistic surface amplitudes < 1 km
$\Rightarrow$Fully self-consistent model that explains the origin of the QPO and the modulation of the signal