Effect of Pasta Phase on Oscillations in Neutron Stars

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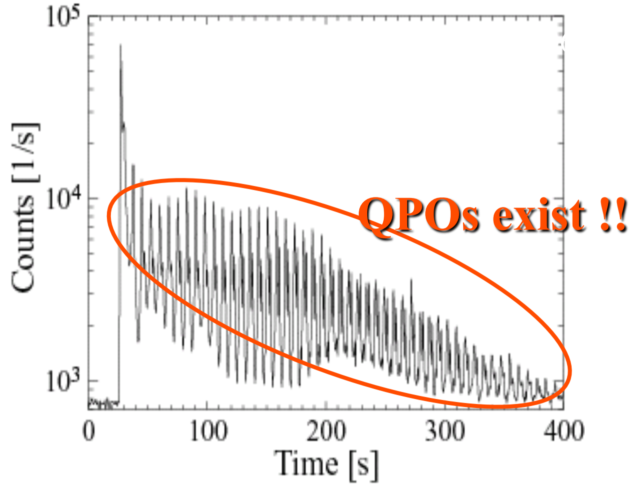
Introduction ~SGRs & QPOs~

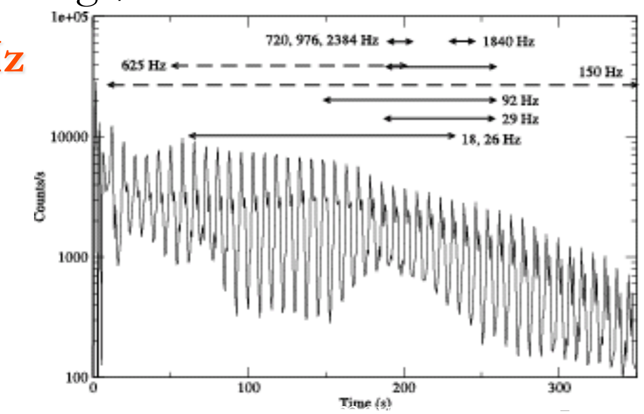
- **Soft gamma Repeaters** (SGRs) : objects that arise the gamma-ray flare activity.
  - Source…**Magnetar** ?? (neutron stars with strong magnetic fields > 10^{14} G)
- **Scenario for outbreak of gamma-ray burst** (Duncan & Thompson (1992))
  → During the evolution of magnetars, the magnetic stress accumulates in the crust.
  → When this stress is released, the gamma-ray could emit !
- **Giant Flare from SGRs (10^{44}-10^{46} ergs/s)**
  - SGR 0526–66 in March.5.1979
  - SGR 1900+14 in August.27.1998
  - **SGR 1806–20** in December.27.2004
- In the decaying tail after the flare, QPOs are found !!
  → Barat et.al. (1983); Israel et.al. 2005;
  Watts & Strohmayer 2005, 2006



– SGR 0526-66 : **23ms (43Hz)**, $B \sim 4 \times 10^{14}$G, $L \sim 10^{44}$ ergs/s

– SGR 1900+14 : $B > 4 \times 10^{14}$G, **28, 54, 84, and 155 Hz**

– SGR 1806–20 : $B \sim 8 \times 10^{14}$G, $L \sim 10^{46}$ ergs/s
18, 26, 30, 92.5, 150, 626.5, and 1837 Hz
(also 720Hz ?? and 2384 Hz ??)



Crustal Oscillations vs QPO frequencies

- SGR 1900+14

f [Hz]	28	54	84	155
torsional	${}_3t_0$	${}_6t_0$	${}_9t_0$	${}_{17}t_0$

- SGR 1806-20

f [Hz]	18	26	30	92.5	150	626.5	1837
torsional	${}_2t_0$	???	${}_3t_0$	${}_9t_0$	${}_{15}t_0$	${}_lt_1$	${}_lt_4$

- Missing frequencies exist
  - Difficulty to explain two QPO frequencies 26 and 30 Hz with a stellar model
  - Due to the magnetic oscillations in fluid core region ??

Alfven Oscillations

- There exist two types of oscillations
  - upper QPO and lower QPO
- Ratio between upper and lower QPO frequencies ~ 0.6
- Frequencies of overtones are nearly integer multiplies of the fundamental one;
- Frequencies are proportional to the magnetic strength.

$$f_{L_n}/f_{U_n} \sim 0.6$$
$$f_{L_n} \simeq (n+1) f_{L_0}, \;\; f_{U_n} \simeq (n+1) f_{U_0}$$

Alfven Oscillations vs QPO frequencies

- SGR 1900+14

f [Hz]	28	54	84	155
Alfven	U_0	U_1	U_2	???
		×2	×3	

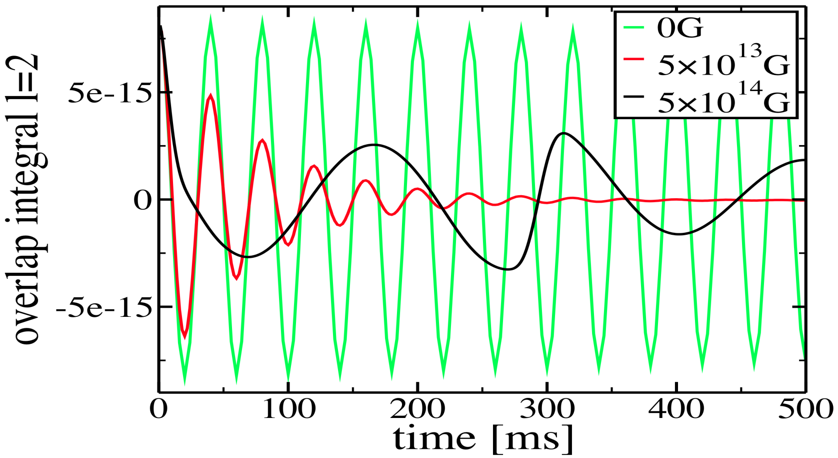
- SGR 1806-20

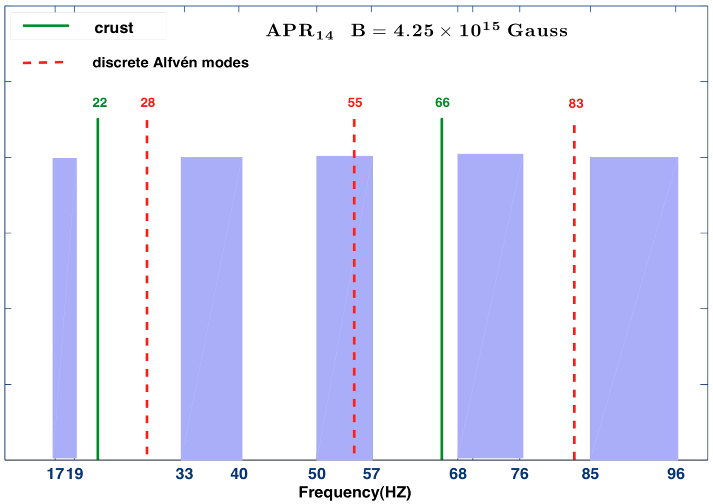
f [Hz]	18	26	30	92.5	150	626.5	1837
Alfven	L_0	???	U_0	U_2	U_4	???	???
	0.6 (L_0 – U_0)			×3	×5		

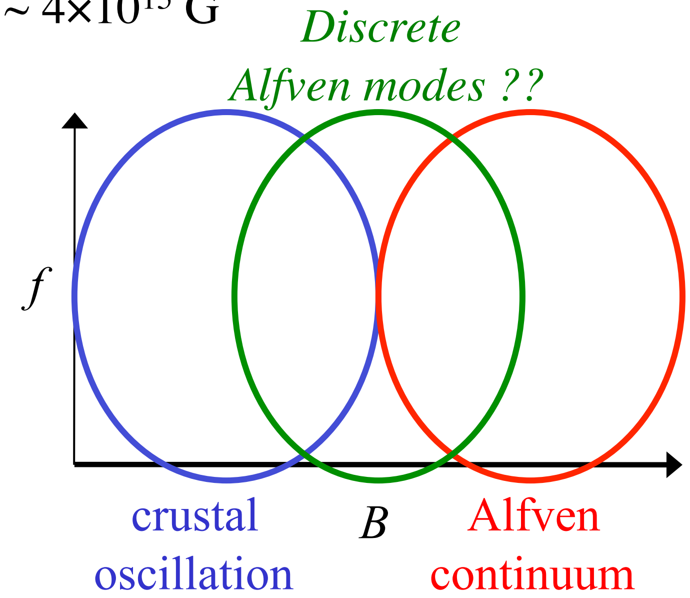
- Still, missing frequencies exist
  - Crust torsional oscillations ??
  - Dependence of magnetic field structure ??

<u>Crust coupling</u>

- *Gabler et al. (2010)*
  - Weak field：only crustal oscillations
  - Strong field：only Alfven oscillations
- *Claiuda & Kokkotas(2011)*
  - Similar results to Gabler et al (2010)
  - Discover *"Discrete Alfven modes"* for B ~ 4×10^{15} G







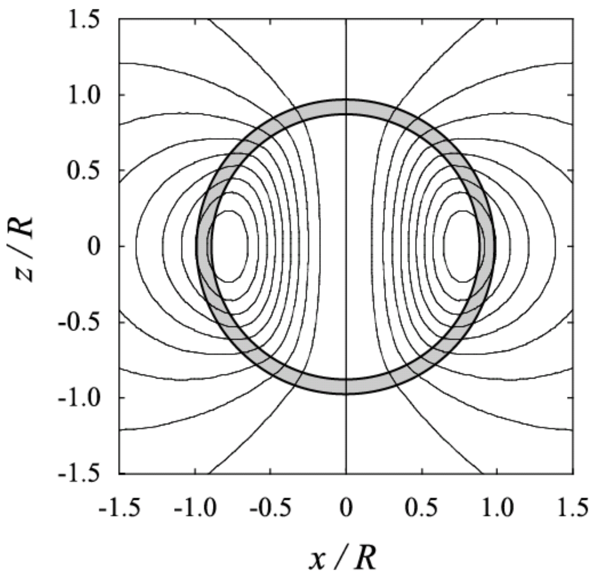
Shear modulus in crust region

- isotropic shear modulus : μ
- Body center cubic (bcc) is assumed

$$\mu = 0.1194 \frac{n_i (Ze)^2}{a}$$

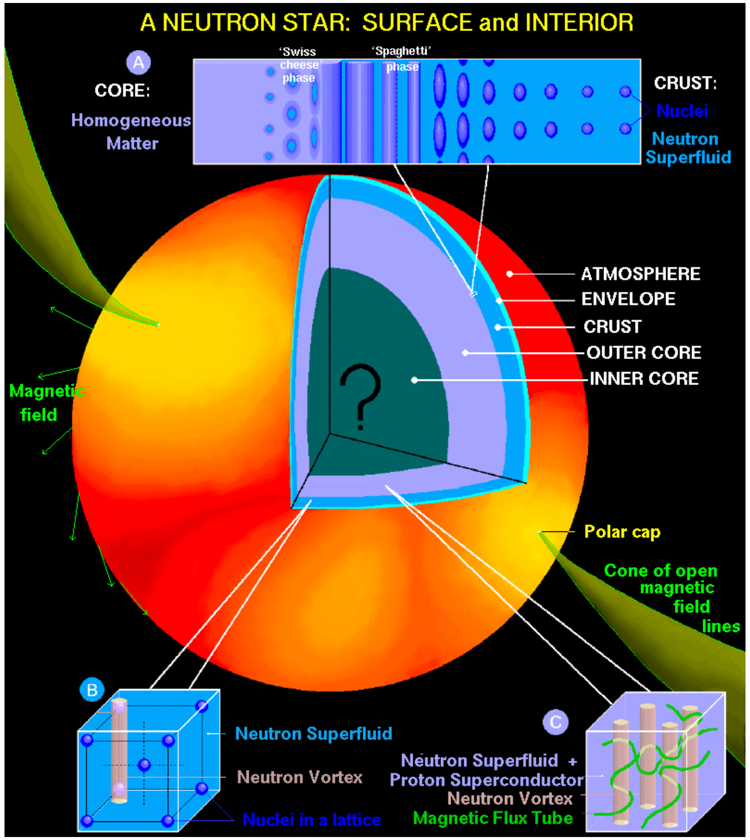
n_i : number density of ions
$+Ze$: average charge of ions
$a^3 = 3/4\pi n_i$: average space between ions

Strohmayer, et al. (1991)



Shear modulus in Pasta phase 1

- Nonuniform structure "pasta" exists
  - shear modulus in pasta could be different from that with bcc structure.
- Pethick & Potekhin (1998)
  - behavior like "liquid crystal"
  - smaller shear modulus
- Density that pasta structure appears
  - ~ 10^{13} g/cc (ex. Lorenz et al. (1993))
- Realistic shear modulus in pasta phase is still unknown…



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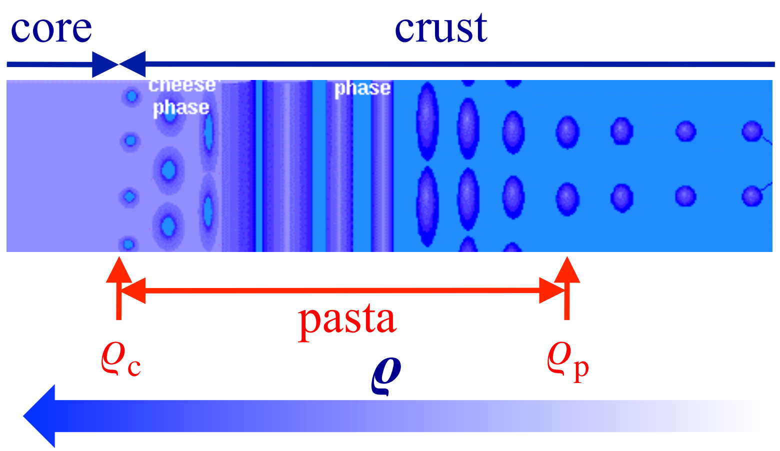
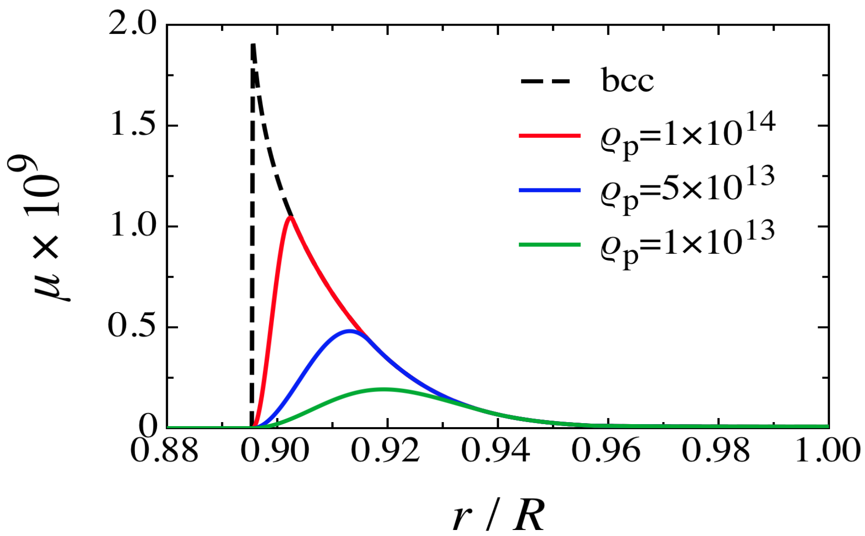
Shear modulus in Pasta phase 2

- We assume toy model for the shear modulus in pasta phase
  - ϱ_p : density that non-uniform nuclear structure appears
  - $\varrho_p = 10^{13} - 10^{14}$ g/cm^3
  - ϱ_c : density between the crust and core region ($\varrho_c = 1.24 \times 10^{14}$ g/cm^3)
  - $\varrho < \varrho_p$: nuclear structure forms bcc lattice
  - $\varrho_p < \varrho < \varrho_c$: non-uniform nuclear structure (pasta phase)
  - $\varrho > \varrho_c$: core fluid region

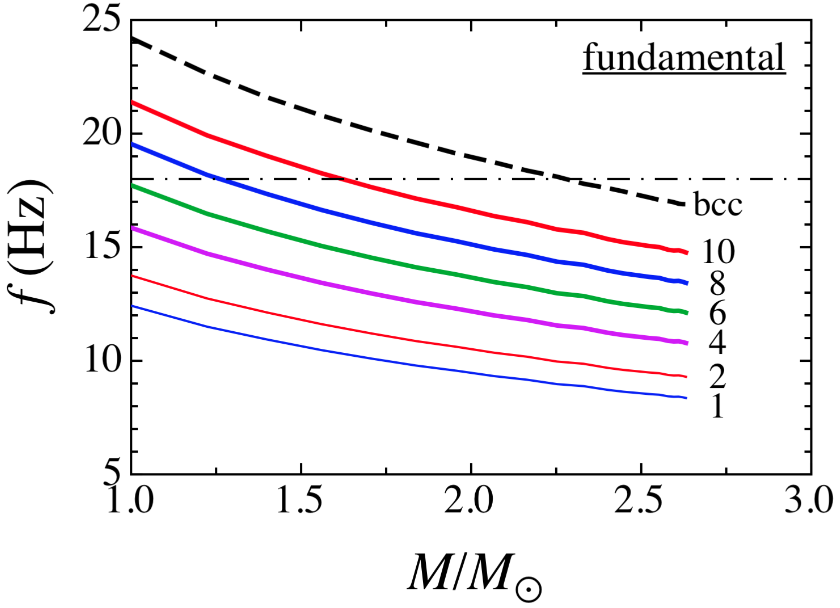


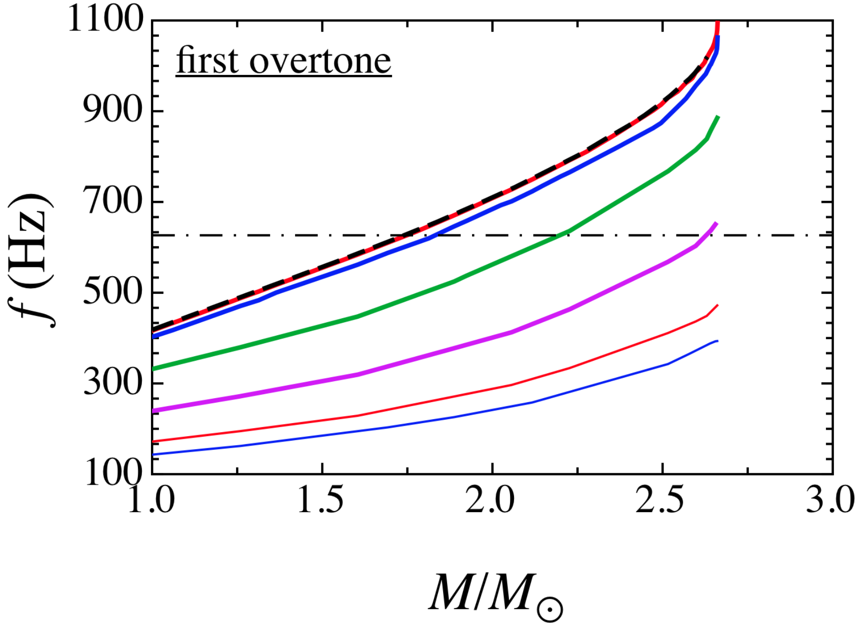


Dependence of pasta pahse

- Decreasing the shear modulus

  → $v_s = (\mu/\varrho)^{1/2}$ also decrease → frequencies become smaller

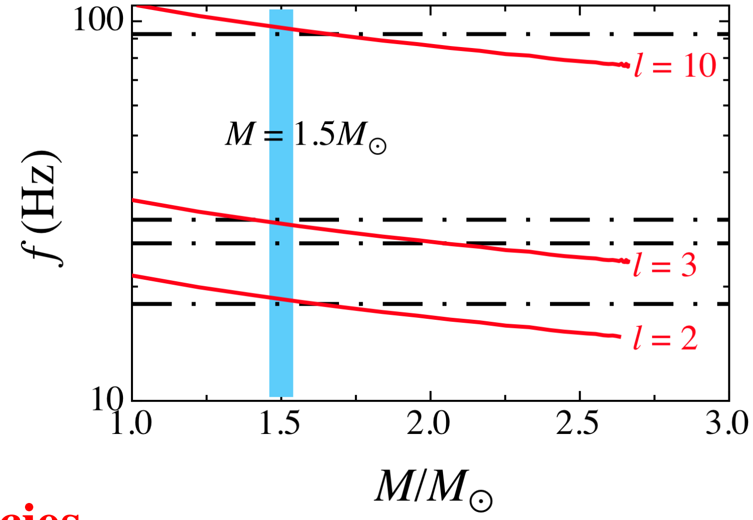


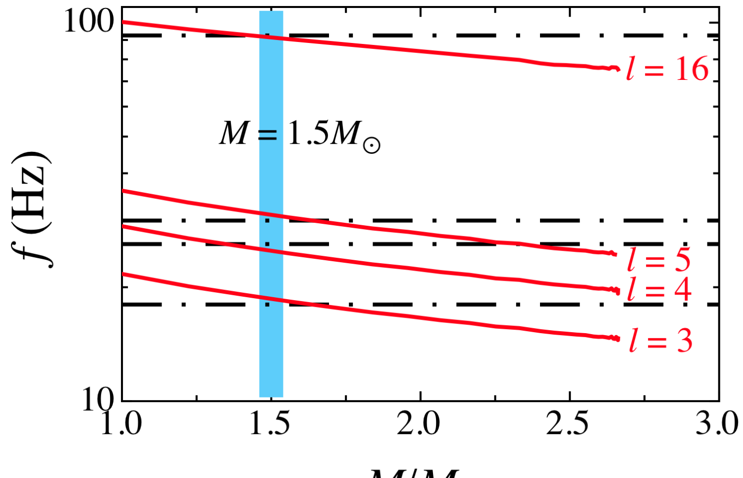


Comparison with QPO frequencies

- For $\varrho_p = 1 \times 10^{14}$ g/cm^3
  - some of QPOs are impossible to explain
  - similar difficulty to the previous study without pasta structure

- For $\varrho_p = 2 \times 10^{13}$ g/cm^3
  - **possible to explain the all QPO frequencies**





- **One needs to consider the effect of pasta**
- **Do more systematic analysis**

Summary

- In the giant flares, the QPO frequencies are discovered.
- It is impossible to explain theoretically by using only crustal oscillations or only Alfven oscillations
- In realistic stellar oscillations, there exists either crustal or Alfven oscillations
- We show the possibility to explain the all observed QPO frequencies with considering the pasta structure.

Future works

- Effect of magnetic field
- Consideration of realistic shear modulus μ
- Mechanism of gamma-ray burst
- Explain the time variability of QPO frequencies
- Possibility to detect gravitational waves from magnetars