Shear Oscillations in Hadron-Quark Mixed Phase

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Hadron-Quark Mixed Phase

• Nonuniform structure between the crust and core (pasta).
• As increasing the density, hadronic matter could change to quark matter with the \textit{phase transition}.
• Similar to the pasta in crust region, the \textit{hadron-quark mixed phase} may become nonuniform structure, whose properties depend strongly on the \textit{surface tension}.
  – \(10 \text{ MeV fm}^{-2} < \sigma < 70 \text{ MeV fm}^{-2}\)
• \textit{How can we see such properties ??}
Asteroseismology

- Via the observations of stellar oscillations
  → One can get the interior information (asteroseismology) e.g., helioseismology for Sun
- With this technique, the possibilities to get the information of NSs have been suggested.

\[ \omega_f \approx 0.78 + 1.64 \left[ \frac{M}{1.4 M_\odot} \left( \frac{10 \text{km}}{R} \right) \right]^{3/2} \]

Andersson & Kokkotas (1998)

\[ L > 50 \text{ MeV} \]

18 Hz

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Shear Oscillations

- Shear oscillations can be characterized by $\mu$.
- We know the formula of $\mu$ only in bcc lattice.
  - considering the shear only in quark spherical droplet.
  - frequency of fundamental oscillation $\propto v_s (v_s^2 \sim \mu / \rho)$
  - calculated frequencies could be lower limit

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

$n_i$ : number density of quark droplet
Z : charge of quark droplet
a : spacing of quark droplet

strohmayer et al., 1991
Shear Modulus

- $\mu \sim 10^{-10}$-$10^{-9}$ in crust
- $\mu \sim 10^{-7}$-$10^{-6}$ in HQ mixed phase
  - number of “charge” is quite different

![Graph of shear modulus](image)

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Estimations

• Compared with crust properties,
  – $\mu$ becomes $\sim10^3$ times larger
  – $\rho$ becomes $\sim10$ times larger
  – $v_s = (\mu/\rho)^{1/2}$ could be $\sim10$ times larger

• Frequencies of shear oscillations $\propto v_s$
  – In HQ mixed phase, the frequencies of shear oscillations could become $\sim10$ times larger than that in crust.
Fundamental Oscillations 1

- Frequencies of fundamental shear oscillations as a function of stellar mass
  - those depend strongly on the surface tension

$c_f \ t_2$ in crust ~ 20 - 30 Hz
Fundamental Oscillations 2

- We find that the frequencies of fundamental shear oscillations are almost **proportional to** $\sigma$.
- With the help of the observation of stellar mass, it might be possible to obtain the value of $\sigma$. 
Fundamental Oscillations 2

- We find that the frequencies of fundamental shear oscillations are almost proportional to $\sigma$.
- With the help of the observation of stellar mass, it might be possible to obtain the value of $\sigma$. 
Conclusion

• We consider the shear oscillations in hadron-quark mixed phase, whose properties depends strongly on the surface tension.
• Frequencies of shear oscillations in HQ phase becomes ~10 times larger than those in crust.
• Frequencies of fundamental oscillations are proportional to surface tension.
• We show the possibility to determine the value of $\sigma$.
  – With the help of the observation of stellar mass, one might be possible to obtain the value of $\sigma$ via the observation of shear oscillations.
1st Overtones

- Frequencies of 1st overtone shear oscillation as a function of stellar mass
- We can not see the linearity with respect to $\sigma$. 
Comparison with QPO frequencies

- Comparison of frequencies of torsional oscillations with the QPO frequencies observed in SGR 1806-20

- less than 5% accuracy