Effect of Temperature on Oscillations in Young Neutron Stars

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Final Aim

Calculate linear oscillations on a neutron star model and

- take temperature, composition, crust, superfluids etc. into account
- use realistic, modern equation of state
- everything in *General Relativity*!

Ingredients

- Take non-rotating neutron star as background
- Modelled as perfect fluid
- Temperature profiles for different time points
- Calculate first-order perturbations on this background

APR Equation of State

- allows for $2\,M_\odot$ neutron stars
- constructed from realistic quantum many-body calculations
- we know how to extend for superfluidity and two-fluid systems
- one-parameter EoS $\rightarrow$ add thermal pressure manually
- *Douchin-Haensel* EoS for the crust is manually matched at the crust-core interface

Mode classification

A non-rotating neutron star exhibits the following mode classes:

mode class	cause	affected by temperature
f-mode	surface of the star	no
p-mode	pressure	slightly
w-mode	spacetime	no
g-mode	gravity/buoyancy	yes
i-mode	density jump	no
elasticity modes	elasticity of crust	slightly
superfluid modes	superfluidity	"yes"

f-modes are due to surface of the star

p-modes are due to variation in pressure

w-modes are due to spacetime curvature

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Composition g-modes

- slow reaction
- nature of moving fluid element does not change $\rightarrow$ frozen composition
- enters through adiabatic index

$$\Gamma_f = \frac{\rho + p}{p} \left(\frac{\partial p}{\partial \rho} \right)_{n,\, T}$$

- differs from background which is assumed to be in β-equilibrium

$$\Gamma_\beta = \frac{\rho + p}{p} \left(\frac{\partial p}{\partial \rho} \right)_{\beta}$$

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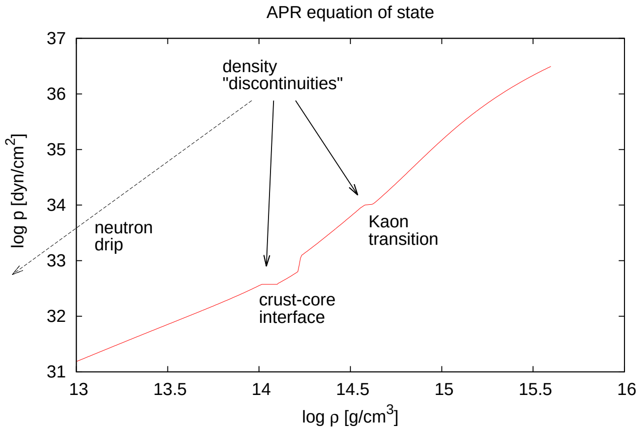
g-modes due to a temperature gradient

Thermal pressure is added on top of cold EOS:

$$p = p_0(\rho) + p_{th}(n, T)$$

- $p_0(\rho) =$ APR equation of state (cold)
- $p_{th}(n, T) = \frac{\pi^2}{6} nkT \frac{kT}{E_F}$
- effect on background negligible, but important for perturbations
- separate thermal pressure for different particles

i-modes due to density discontinuities



Neutron Star Model

Calculate mode evolution for a particular neutron star:

- Star #1 with $M = 1.4\,M_{\odot}$, $R = 11.47\,km$, $\rho_c = 1.0 \cdot 10^{15}\,\frac{g}{cm^3}$
- Use temperature profiles for $t \in [10^{-6}\,yr, 10^{6}\,yr]$ (provided by W. Ho)

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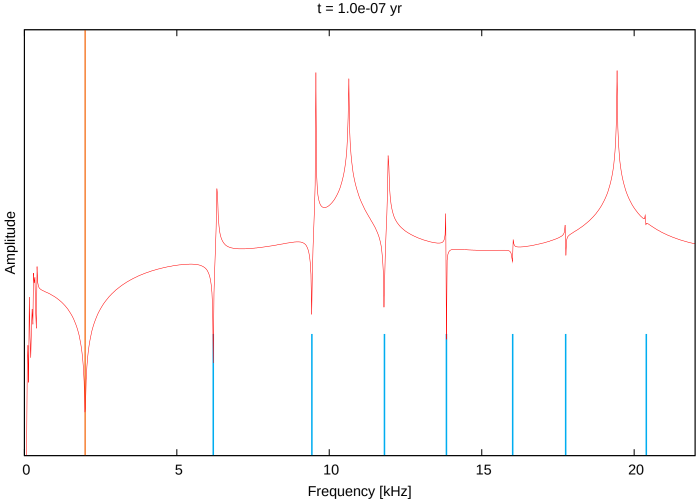
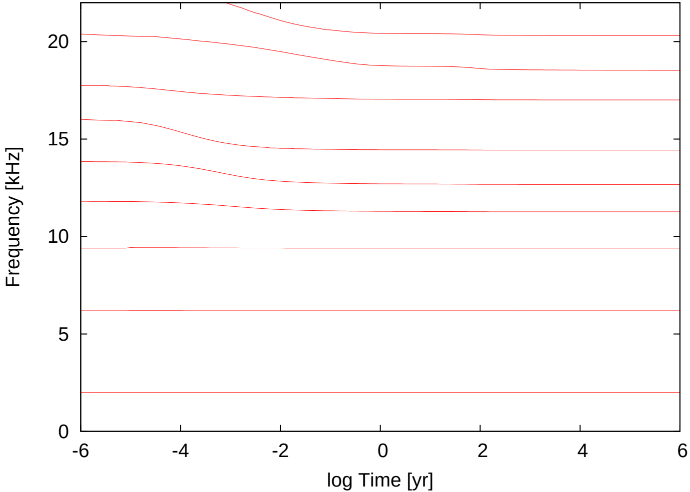
Work on cooling code for higher mass neutron stars (needs dURCA) is in progress...

High Frequency Domain



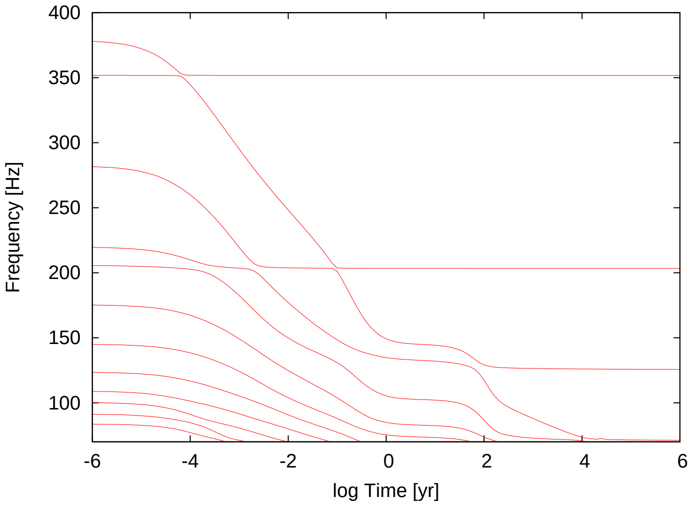
Movie: High Frequency

High Frequency Domain in Time



Movie: Low Frequency

Low Frequency Domain in Time



Summary

- Calculated time evolution of several classes of modes as the star cools down $\rightarrow$ main effect (as expected) on g-modes
- The neutron star model as well as the temperature profiles are calculated using modern equation of state and cooling codes
- Calculations are done in *General Relativity*
- Kaon transition as well as neutron drip give rise to i-modes.

Next steps:

- implement equations for elasticity
- account for superfluidity