Effect of Temperature on Oscillations in Young Neutron Stars

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Final Aim

- Construct neutron star based on realistic, modern equation of state
- Take temperature, composition, crust, superfluids, etc. into account
- Calculate oscillations on this model
- Finally do successful asteroseismology

Equations to solve

- Einstein equations

$$G_{\mu\nu} = 8\pi T_{\mu\nu} \,, \qquad \nabla_\mu T^{\mu\nu} = 0$$

- Schwarzschild-type metric
- Neutron star modelled as perfect fluid

$$T^{\mu\nu} = (\rho + p) u^\mu u^\nu + p g^{\mu\nu}$$

- Then derive equations for first-order perturbations on a static background (lengthy & messy)

APR Equation of State

- allows for $2\,M_\odot$ neutron stars
- constructed from realistic quantum many-body calculations
- can be obtained from analytical expressions
- we know how to extend for superfluidity and two-fluid systems

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

f-modes are due to surface of the star

p-modes are due to variation in pressure

w-modes are due to spacetime curvature

$$\tilde{g}_{\mu\nu} = g_{\mu\nu} + h_{\mu\nu}$$

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Composition g-modes

- slow reaction
- composition of moving fluid element does not change
  $\rightarrow$ frozen composition
- 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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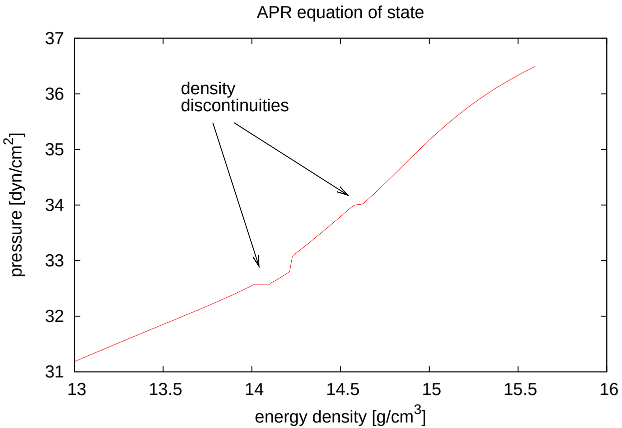
g-modes due to a temperature gradient

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)
- $p_{th}(n, T) = \frac{\pi^2}{6} nkT \frac{kT}{E_F}$
- separate thermal pressure for different particles

i-modes due to density discontinuities



Neutron Star Models

Calculate mode evolution for two different neutron stars:

- Star #1 with $M = 1.4\, M_\odot$, $R = 11.47\, km$, $\rho_c = 1.0 \cdot 10^{15}\ \frac{g}{cm^3}$
- Star #2 with $M = 2.0\, M_\odot$, $R = 10.96\, km$, $\rho_c = 1.6 \cdot 10^{15}\ \frac{g}{cm^3}$

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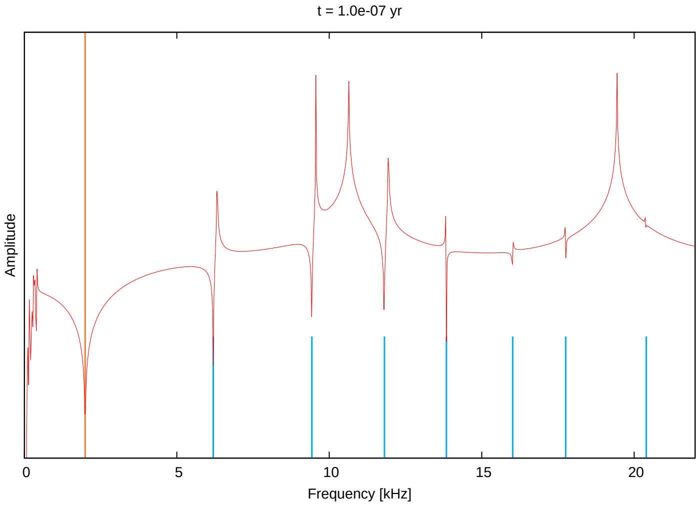
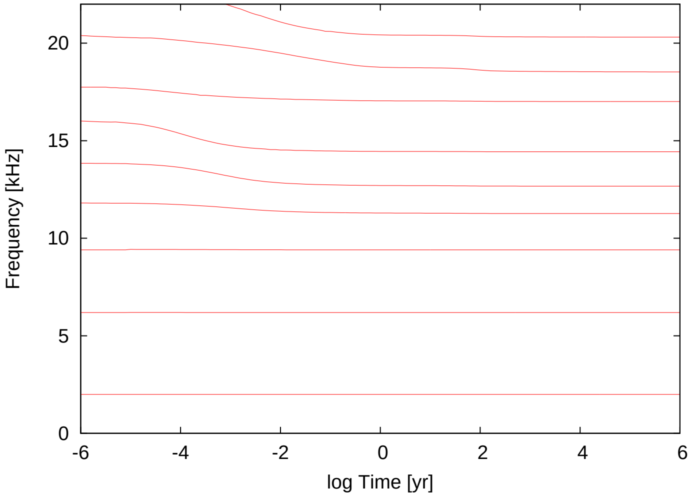
Supercomputer crashed last week... calculation for star # 2 not possible at the moment

High Frequency Domain



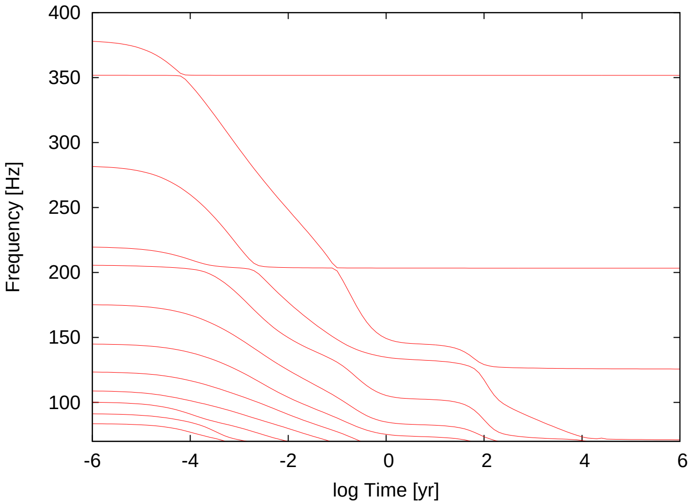
Movie: High Frequency

High Frequency Domain in Time



Movie: Low Frequency

Low Frequency Domain in Time



Summary

- Investigated effect of temperature on different mode classes
  $\rightarrow$ main effect on g-modes
- Neutron star model as well as temperature profiles are calculated using modern equation of state and cooling codes
- Next steps: Take crust and superfluidity into account