Neutron star oscillations and neutron rich matter

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Context

- Compact objects support a complex zoo of oscillation modes.
- Oscillations can depend sensitively on the equation of state and other stellar properties.
- Some may play a crucial role in astronomical systems, e.g.
    - Setting the upper spin frequency in accreting systems.
    - Determining the spins of newly born neutron stars.
    - Fixing the frequency of magnetar oscillations.

Overview

Will concentrate on some possible *instabilities*:

- Gravitational wave instability.
- Superfluid instability.

Gravitational wave instability

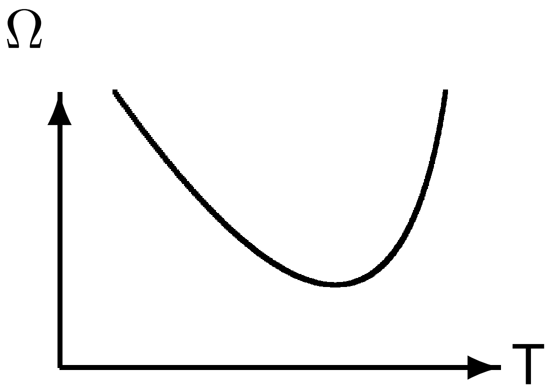
- Oscillation modes affected by *gravitational radiation reaction*.
- In non-rotating stars, always damps the mode.
- In rotating stars, CFS (Chandrasekhar-Friedman-Schutz) instability can set in.
- Is an example of a 2-steam instability, in this case between the stellar fluid and the spacetime.

Gravitational wave instability of the r-mode

- A type of inertial mode; restoring force is the Coriolis force.
- Consists of a ‘twisting’ or toroidal motion of the fluid.
- Of great CFS interest as, in absence of viscosity, mode is CFS unstable in all rotating stars.

Astrophysical manifestation of the r-mode

- Useful to think in terms of an *instability curve* in the spin frequency (Ω) verses temperature (T) plane:



- Trajectories computed using coupled ODEs containing the important physics.
- Qualitative outcome depends upon high density EoS (Wagoner 2002; Nayyar & Owen 2006; Andersson, DIJ & Kokkotas 2002).

R-mode: some crucial ingredients

Both the instability curve and the (Ω, T) trajectory sensitive to many physical inputs, including:

- **Physics of the crust-core boundary layer:** A viscous boundary layer forms, so dissipation depends on viscosity and crust stiffness.
  - Larger viscosity $\Rightarrow$ larger spin frequencies.
- **Cooling mechanism:** Trajectory depends upon fraction of star where direct Urca occurs (Bondarescu, Teukolsky & Wasserman, 2007):
  - Lower direct Urca fraction favours runaway.
  - Higher direct Urca fraction favours cyclic solutions.
- Still an important candidate for gravitational wave detection.

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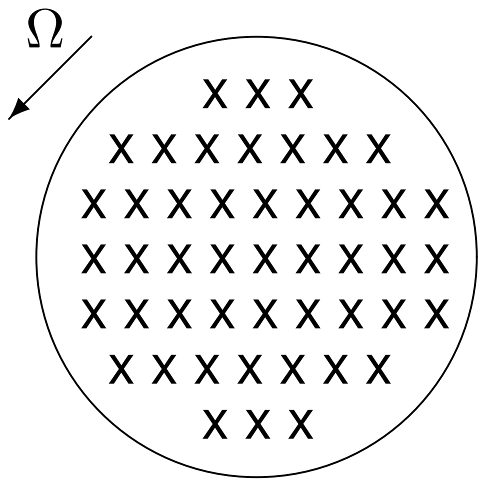
- **Superfluid instability.**

Superfluid neutron stars

- Can model star as a mixture of
  1. Superfluid neutrons
  2. Charged particles (protons & electrons)
- The superfluid neutrons rotate by forming an array of vortices:



Evidence for vorticity: glitches

- Some spinning neutron stars undergo occasional glitches.
- Leading theory relies on *pinned vorticity*: some of the superfluid vortices are rigidly attached to the solid phase, preventing them from undergoing smooth spindown.
- When a sufficiently large angular velocity lag has built up catastrophic unpinning occurs, corotation is established, spinning up the charged part of the star.

Free precession

- Free precession is the most general motion of a rigid body.
- Classically, determined by moment of inertia tensor I_{ab}.
- Characteristic timescale of order

$$P_{\rm fp} \sim \frac{P}{\epsilon},$$

where ϵ is dimensionless asymmetry in I_{ab}.

- $\Rightarrow P_{fp} \sim$ months–years for a typical pulsar.

Free precession plus superfluidity

- A pinned superfluid component changes the picture radically.
- Angular momentum now given by

$$J_a = I_{ab}\Omega^b + J_a^{\mathrm{SF}}.$$

- The pinned superfluid acts like a gyroscope, ‘sewn’ into the star (Shaham 1977).
- Find $P_{\mathrm{fp}} \sim$ minutes or less!

The free precession ‘conundrum’

- Best evidence for precession comes from PSR B1828-11, with $P_{\rm fp} \sim 500$ days! (Stairs, Shemar & Lyne 2000).
- What is going on? Do we need to redraw our picture of neutron star interiors? (Link 2006)

Vortex dynamics

- Vortices are acted upon by two forces:
  1. A Magnus force, sourced by $v_a^{\text{vortex}} - v_a^{\text{n}}$ difference
  2. A drag force, $-R(v_a^{\text{vortex}} - v_a^{\text{p}})$, caused by charged/magnetic component scattering off the vortex core.
- This results in a *mutual friction* force, f_a^{MF}, coupling the neutrons and protons:

$$\begin{aligned} \frac{dv_a^n}{dt} &= -\nabla_a(\mu^n + \Phi) + f_a^{\text{MF}}, \\ \frac{dv_a^p}{dt} &= -\nabla_a(\mu^p + \Phi) - f_a^{\text{MF}}/x_p \end{aligned}$$

We therefore have a two-component *coupled* system.

An instability

- Consider a rotating star, and allow the protons to have some velocity $w_{||}$ along the neutron vortices.
- Find an short wavelength instability for sufficiently fast relative flow, e.g. in weak drag limit (Sidery, Andersson & Comer, 2008):

$$|w_{||}| > \frac{2\Omega^n}{k_{||}}$$

- This corresponds to perturbation having a speed intermediate between the neutron and proton fluids; analogue of Donnelly-Glaberson instability in helium.
- Will this instability occur in neutron stars?

Free precession and the instability

- Free precession automatically generates a flow $w_{||}$ along the vortices.
- Find that, for sufficiently strong drag, precession triggers the instability, (probably) destroying the pinning (Glampedakis, Andersson & DIJ, 2008).
- So, premature to conclude that conventional view of neutron star core is wrong!

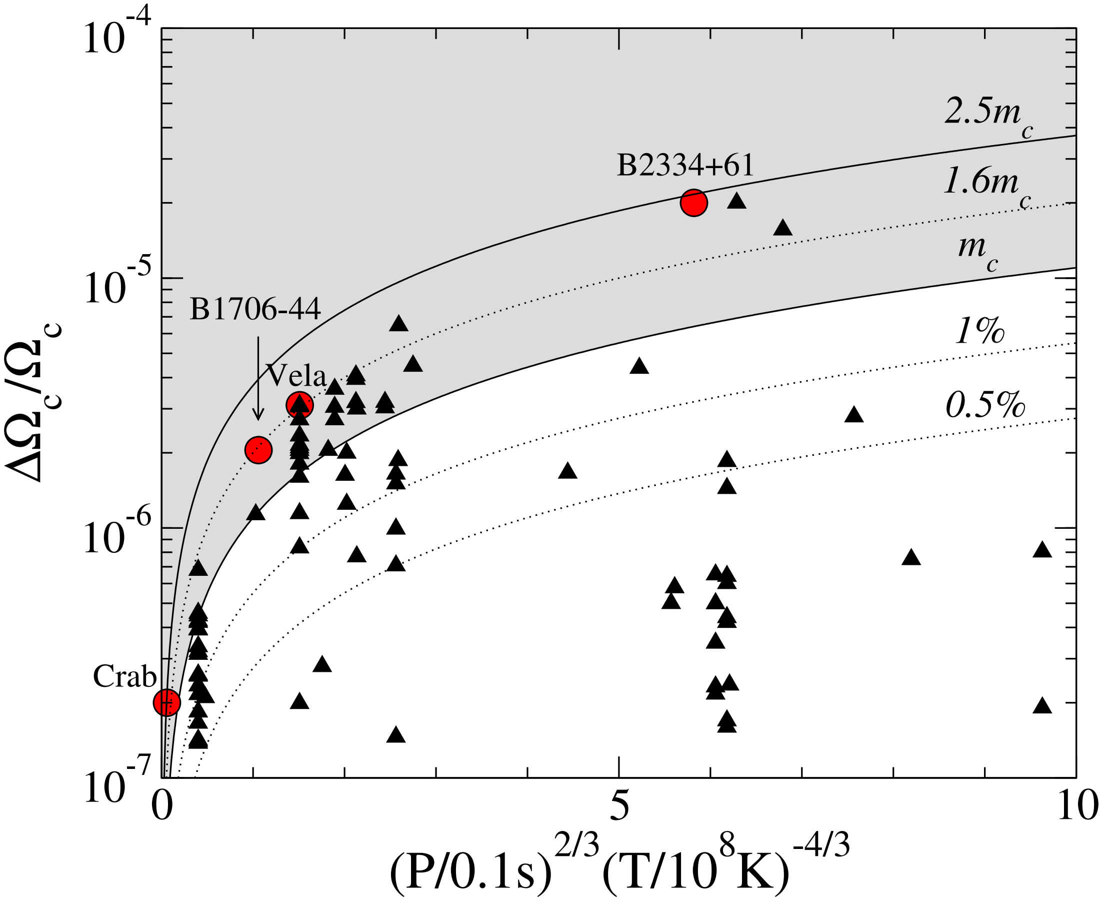
Another application: glitches revisited

- Glitches seems to occur when a sufficiently large angular velocity lag has build up in star.
- But what exactly triggers the glitch?
- Apply 2-fluid model to a star with mismatched Ω^n and Ω^p.
- Find that, in strong vortex drag regime, an r-mode instability is triggered if (Glampedakis & Andersson 2009)

$$\frac{\Omega^n - \Omega^p}{\Omega^p} > 6 \times 10^{-5} \left(\frac{P}{0.1\,\mathrm{s}} \right)^{2/3} \left(\frac{10^8\,\mathrm{K}}{T} \right)$$

- Not of gravitational wave interest, as mode number very high ($m > 320$).

Comparison with glitch data



(From Glampedakis & Andersson, 2009)

Summary

Instabilities play a crucial role in neutron star oscillations. Of particular interest are:

- Gravitational wave instability in r-modes,
- Superfluid instability in precessing and glitching stars.

The instabilities are sensitive to lots of the things that we are interested in, including:

> Crust shear modulus, physics of crust-core boundary, shear viscosity, bulk viscosity, presence of exotic phases, cooling mechanism, superfluidity, superconductivity, vortex drag, . . .

⇒ **instabilities are an excellent probe of neutron star matter!**