Hydrodynamic stability of neutron star cores

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Why study stability?

- What is the underlying state of a spinning-down neutron star?

- Turbulence may be connected with timing noise (random fluctuations in pulsar spin frequency)
  
  see e.g., Melatos & Peralta, Link (2012a,b), Melatos & Link (2014)

- Proposed as cause of glitches (impulsive increase in spin frequency)
  
  see e.g., Glampedakis & Anderson (2009)
Neutron star hydrodynamics

- 5% superconducting protons + electrons (MHD plasma)
- 95% superfluid neutrons
Superfluidity and superconductivity

- Vortices and flux tubes form to accommodate rotation and magnetic field
- Arrays pin due to magnetic forces

Proton-electron fluid (MHD fluid)

Mutual friction (pinning)

Neutron condensate (Inviscid fluid)
Rotational lag develops between neutrons and protons

Is this stable?
No magnetic field: two-stream instabilities

- Perfect pinning: Glampedakis & Andersson (2009)

- Inertial modes coupled by mutual friction produce two-stream instabilities

- What about magnetic fields?
Kelvin-Helmholtz instability

- Two-stream interfacial instability
Kelvin Helmholtz instability

- Add transverse field

- No Effect!
Kelvin Helmholtz instability

What about parallel field

Stabilized for Alfvén speed, $v_A > v_1 - v_2$
Magnetic field structure

- Pure dipole field is unstable (Flowers and Ruderman ‘77)

- Only known stable configuration is the twisted torus

- Toroidal field at least equal to dipole field for stability

Braithwaite and Spruit (2004)
Bulk two-stream instability

- Perfectly pinned flux tubes and vortices

- Growth time $\sim 1/(\Omega_n - \Omega_p) \sim s$ (Glampedakis and Andersson 2009)
What about magnetic fields?

Add poloidal (dipole field), what happens?

No effect!
What about magnetic fields?

What about toroidal field?

Stabilized for Alfven speed, $v_A > v_n - v_p$

Corresponds to $B=10^{10}$ G --> stable!
Imperfect pinning

- Vortices excited by thermal fluctuations overcome pinning barriers – vortex slippage (Link 2014)

- Additional class of instabilities arise

- Slower growth rates (days) - timing noise? (Link 2012, Andersson et al 2013)

- Also stabilized by the magnetic field
Other unstable modes?

- Unstable sound waves?
  - Relative flow for instability unrealistically high (e.g., Andersson et al. 2004)

- Entrainment (Fermi-liquid coupling)?
  - No instabilities in expected range of entrainment parameter (e.g., Andersson et al. 2004)

- Unstable g-modes (buoyancy), convective instability?
  - Weakly unstable thermal g-modes in young neutron stars (e.g., Gusakov and Kantor 2013, Passamonti et al. 2016)
Conclusions

- Outer core is stable in garden variety spinning down isolated neutron stars

- Turbulence unlikely to be responsible for timing irregularities in these objects

- Turbulence almost certainly relevant in freely precessing pulsars (Donnelly-Glaberson instability)