Gravitational Wave emission mechanisms in accreting systems

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GWs from rotating neutron stars
- LMXBs and accretion models

Emission mechanisms
- Crustal and core mountains
- Magnetic mountains
- Unstable modes (r-modes)
  - Superfluid effects and dissipation

Conclusions
Neutron star mountains

\[ \epsilon = \frac{I_{xx} - I_{yy}}{I_{zz}} \]

Emission at \( \omega = 2\Omega \)

\[ \frac{dE}{dt} \approx \epsilon^2 \Omega^6 \]
r-mode instability

- r-mode generically unstable to GW emission

- Emission at $\omega \approx \frac{4}{3} \Omega$

- Viscosity damps the mode except in a narrow window of temperatures and frequencies
Simple accretion model

- Interaction at magnetospheric radius $R_0$
- Accretion torque $\dot{J} = \dot{M} \sqrt{GM R_o}$
- Propeller sets spin equilibrium
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The case for GWs

- Need extra spin-down torque
- Gravitational waves can do the job!

(Bildsten, 1998)
Mountain “size”

- Deformation needed $\epsilon \approx 10^{-7}$
- Can the star sustain such a deformation?
- What mechanisms can generate it?
- Do we really expect GW of such amplitude? (i.e. was the accretion model too simple?)
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Thick disk model

- Problems at high $\dot{M}$
- Radiation pressure important at high $\dot{M}$
- Leads to thick sub-Keplerian disk
- Use phenomenological model

(Andersson, Glampedakis, BH, Watts 2005)
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Thick disk model

![Graphs showing relationships between various parameters in LMXBs](image)
GW detection?
GW detection?

- Detection prospect bleak (Watts et al. 2008)
- What is needed? (the spin!)
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- What is needed? (the spin!)
- Understand external torque variability
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  - Understand neutron star response
GW detection?

- Detection prospect bleak (Watts et al. 2008)
- What is needed? (the spin!)
  - Understand external torque variability
  - Understand neutron star response
  - Model emission mechanisms
Neutron star structure

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http://www.astro.umd.edu/~miller/nstar.html
Mechanisms
Mechanisms

- Mountains
  - Crustal mountains
  - Core mountains
  - Magnetic mountains
Mechanisms

- Mountains
  - Crustal mountains
  - Core mountains
  - Magnetic mountains
- Unstable modes
  - r-modes
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Crustal mountains

- Elastic matter in the crust
- Perturb spherical background
  \[ x^a \rightarrow x^a + \xi^a \]
- \[ \tau_{ab} = -\rho g_{ab} + \mu \sigma_{ab} \]
- \( \mu \) depends on crustal composition (accreted or non-accreted)
- Solve \( \nabla^a \tau_{ab} = -\rho \nabla_b \phi \)
- Crust will crack \( \bar{\sigma} > \sigma_{max} \)
- \( \sigma_{max} \approx 10^{-2} - 10^{-1} \)
  
  (Horowitz & Kadau 2009)
Mountain results

- Maximum deformation for an accreted crust
  \[ \epsilon \approx 10^{-6} \]  
  (BH, Jones, Andersson, 2006)

- What can produce such a deformation?
  - Non uniform temperature distribution
  - Non uniform stratification
    (Ushomirsky, Cutler, Bildsten 2000)
  - Magnus force?

- Mountains in the core?
Core mountains

- **Fluid exterior (n=1)**
- **Elastic core of deconfined quarks (incompressible)**
- **Shear modulus** \( \mu = 3.96 \times 10^{33} \left( \frac{\Delta}{10\text{MeV}} \right)^2 \left( \frac{\mu_c}{400\text{MeV}} \right)^2 \text{erg/cm}^2 \)

(Mannarelli et al. 2007)
Core mountains

$\mu = 3.96 \times 10^{33} \left( \frac{\Delta}{10\text{MeV}} \right)^2 \left( \frac{\mu_c}{400\text{MeV}} \right)^2 \text{erg/cm}^2$

$350 \text{MeV} < \mu_c < 500 \text{MeV}$

$5 \text{MeV} < \Delta < 25 \text{MeV}$

(BH, Andersson, Jones, Samuelsson, 2007)

see also (Owen, 2005)
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Magnetic mountains

- The shape of a magnetic star is not spherical and an oblique rotator can be a source of GWs

Poloidal field

\[ \epsilon \approx 8 \times 10^{-11} \left( \frac{B}{10^{12} G} \right)^2 \]

Star is **oblate**

Toroidal field

\[ \epsilon \approx -5 \times 10^{-12} \left( \frac{B}{10^{12} G} \right)^2 \]

Star is **prolate**

- Stars with strong toroidal fields can “flip” and become orthogonal rotators

  (Cutler, 2000)

- Accretion can “compress” the field and lead to large polar mountains

  (Melatos & Payne 2005)
r-mode instability window
r-mode instability window
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r-mode instability window

- Duty cycle short (10% or less)
- Effects of EOS? (Hyperons..)
- Effects of superfluidity?
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Multifluid hydrodynamics

\[ \partial_t \rho_x + \nabla_i (\rho_x v^i_x) = 0 \]

\[ (\partial_t + v^j_x \nabla_j)(v^x_i + \varepsilon_x w^{yx}_i) + \nabla_i (\tilde{\mu}_x + \Phi) + \varepsilon_x w^j_{yx} \nabla_i v^x_j = \frac{f^x_i}{\rho_x} + \nabla_j D^j_i \]

\[ D^j_i \]

Dissipative terms (bulk viscosity, shear viscosity, etc.)

\[ f^x_i = 2 \rho_n B' \epsilon_{ijk} \Omega^j \omega^k_{xy} + 2 \rho_n B \epsilon_{ijk} \hat{\Omega}^j \epsilon^{klm} \Omega_l \omega^{xy}_m \]

Mutual Friction
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Mutual friction

- Superfluid rotates by forming quantised vortices
- In the core entrained protons give rise to a magnetic field along the vortex lines
- Electrons scatter dissipatively off vortices
- Vortices could be strongly pinned in the crust
Superfluid r-mode

- Frequency the same as barotropic r-mode to $O(\Omega^3)$
- Countermoving motion driven at higher order
- Leads to mutual friction damping and new dissipation coefficients
Hyperon bulk viscosity

- Consider a fluid of neutrons, protons, electrons, $\Sigma^-$
- Most likely to be superfluid
  - New bulk viscosity coefficients
- In most simple case (low T, charged components locked): 3 bulk, 1 shear
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Hyperon bulk viscosity

Single fluid: Nayyar & Owen 2006, Haensel et al. 2002
Multifluid: Haskell et al. (in preparation)
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Hyperon bulk viscosity

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Mutual friction

(BH, Andersson, Passamonti, 2009)
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Mutual friction

(BH, Andersson, Passamonti, 2009)
Conclusions

- More input needed for detection
- Observational input: spins (also theoretical)

Theoretical input:
- External torque variations
- Neutron star response
- Realistic mountain scenarios
- Dissipation mechanisms