Resonant Shattering of Neutron Star Crusts: Probing Crust Properties with Coincident Multimessenger Observations

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Short-Hard Gamma Ray Bursts

- Short GRBs: $E \sim 10^{50} - 10^{51}$ ergs
- $T_{90} < 2s$
- Leading progenitor: NS-NS or NS-BH merger
- Swift/BAT, Fermi/GBM, Suzaku
Precursor Mechanisms

- **Magnetic Field Interaction?**
  
  \[ L \simeq 7 \times 10^{45} \text{ erg s}^{-1} \left( \frac{B}{10^{15} \text{ G}} \right)^2 \left( \frac{a}{10^7 \text{ cm}} \right)^{-7} \]

- B-field needs to be > Magnetar Strength

- **Early Central Engine?**

- **Hyper-massive NS/Magnetar?**

- **What about crust cracking?**


Kochanek (1992), APJ, 398, 234
For tidal crust cracking we need $\frac{\delta R}{R} \sim \epsilon_{\text{break}} \sim 0.1$
Direct Tidal Crust Cracking

How much energy can you get out of the crust?

Energy stored in crust:

\[ \mu \sim \frac{(Ze)^2}{a} n_i \sim 10^{30} \text{ ergs cm}^{-3} \]

\[ E_c \sim 4\pi R^2 H \mu \sim 10^{48} \text{ ergs} \]

Fracture when \( \frac{dR}{R} \sim 0.1 \):

\[ \frac{\delta R}{R} \sim \frac{M_1}{M_2} \left( \frac{R}{d} \right)^3 \sim 0.1 \Rightarrow d \sim \text{few } \times R \]

Releasing energy:

\[ E_{\text{tide}} \sim 4\pi (\delta R)^2 H \mu \sim 10^{46} - 10^{47} \text{ ergs} \]

When does this happen?
Direct Tidal Crust Cracking

Surface deformation in inspiral

Frequency at time before merger

\[ \tau_{gw} \sim \frac{c^5}{G^3} \frac{d^4}{M_{tot} M_1 M_2} \sim \text{few} \times 10^{-3} \text{ s} \]

Direct crust cracking doesn’t happen until just before merger (if at all). What else?
Tidal Resonance

• NSs have normal modes

• Tidal resonance can transfer huge amounts of energy

• Need a mode that:
  • strains the crust
  • couples to the tidal field (l=2, spheroidal)
  • hits a resonance well before merger (f < 1 kHz)

• We treat perturbations with McDermott et al (1988) and Reisenegger & Goldreich (1994), using modern backgrounds

Tsang et al, PRL 108, 011102 (2012)
Tidal Resonance

- Need a mode that:
  - strains the crust  \( \times \)
  - couples to the tidal field (\( l=2 \), spheroidal)  \( \checkmark \)
  - hits a resonance well before merger (\( f < 1 \text{ kHz} \))  \( \checkmark \)

Tidal Resonance

- Need a mode that:
  - strains the crust ✓
  - couples to the tidal field (l=2, spheroidal) ✗
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Tidal Resonance

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Tsang et al, PRL 108, 011102 (2012)
□ How does the i-mode couple to the tidal field?

\[ Q \equiv \frac{1}{MR^2} \int d^3x \rho \, \xi^* \cdot \nabla [r^2 Y_{2, \pm 2}(\theta, \phi)] \approx 0.025 \]

□ How much energy can be transferred tidally?

\[ E_{\text{max}} \simeq 3 \times 10^{50} \text{ erg} \, f_{185}^{-1/3} Q_{0.03}^2 M_{1.4}^{-2/3} R_{12}^2 \, q \left( \frac{2}{1 + q} \right)^{5/3} \]

□ How much energy does it take to break the crust?

\[ E_b = (2\pi f_{\text{mode}})^2 \int d^3x \rho \, \xi_b^* \cdot \xi_b \approx 5 \times 10^{46} \text{ erg} \, \epsilon_{0.1}^2 \]

□ What happens next?
When the total seismic energy in the NS crust exceeds the elastic limit of the fractures occur, more energy is deposited into seismic energy in the crust.

\[ E_{\text{crack}} \approx \epsilon_b^2 \mu \Delta r_{\text{crust}}^3 \]

\[ \approx 10^{43} \text{erg} \]

Seismic energy \( E_{\text{crack}} \) is given by

\[ E_{\text{crack}} = \int dV \epsilon_b^2 \mu \approx 10^{46} \text{erg} \]

\[ E_{\text{tidal}} \approx 10^{50} \text{erg s}^{-1} \]

\[ E_b \approx 10^{47} \text{erg} \]

\[ L_{\text{max}} = \int_{\text{surf}} (v \times B) \times B \cdot dA \]

\[ \approx 10^{47} \text{erg s}^{-1} (v/c)(B_{\text{surf}}/10^{13} \text{G})^2 (R/10 \text{km})^2. \]
What can we tell from shattering?
Nuclear Symmetry Energy

\[ E(\rho_n, \rho_p) = E_o(\rho) + S(\rho) \left( \frac{\rho_n - \rho_p}{\rho} \right)^2 + ... \]

\[ A = 16 \]

Experimental constraints on \( S(\rho), L(\rho) \) at nuclear saturation density
Astronomical Observations

J. M. Lattimer

Have We Converged on an Understanding of the Dense Matter Equation of State?

(Courtesy Jim Lattimer)
Magnetar Flares and Shear Modes

Steiner & Watts (2009) constrained equation of state based using QPOs from 2004 giant flare

See also e.g. Fantina et al. (2016)

TABLE I. Resonant mode properties for the $l = 2 \, i$ mode. The background star is taken to be a $1.4M_\odot$ NS, with various equations of state given in [15]. The crust-core transition baryon density is fixed to be $n_t = 0.065$ fm$^{-3}$ for each model.

<table>
<thead>
<tr>
<th>EOS</th>
<th>$f_{\text{mode}}$ [Hz]</th>
<th>$Q$</th>
<th>$\Delta E_{\text{max}}$ [erg]</th>
<th>$E_b$ [erg]</th>
<th>$\dot{E}_{\text{tidal}}$ [erg/s]</th>
</tr>
</thead>
<tbody>
<tr>
<td>SLy4</td>
<td>188</td>
<td>0.041</td>
<td>$5 \times 10^{50}$</td>
<td>$5 \times 10^{46}$</td>
<td>$1 \times 10^{50}$</td>
</tr>
<tr>
<td>APR</td>
<td>170</td>
<td>0.061</td>
<td>$1 \times 10^{51}$</td>
<td>$2 \times 10^{46}$</td>
<td>$9 \times 10^{49}$</td>
</tr>
<tr>
<td>SkI6</td>
<td>67.3</td>
<td>0.017</td>
<td>$8 \times 10^{49}$</td>
<td>$3 \times 10^{45}$</td>
<td>$1 \times 10^{48}$</td>
</tr>
<tr>
<td>SkO</td>
<td>69.1</td>
<td>0.053</td>
<td>$7 \times 10^{50}$</td>
<td>$1 \times 10^{46}$</td>
<td>$1 \times 10^{49}$</td>
</tr>
<tr>
<td>Rs</td>
<td>32.0</td>
<td>0.059</td>
<td>$7 \times 10^{50}$</td>
<td>$1 \times 10^{46}$</td>
<td>$3 \times 10^{48}$</td>
</tr>
<tr>
<td>Gs</td>
<td>28.8</td>
<td>0.060</td>
<td>$8 \times 10^{50}$</td>
<td>$1 \times 10^{46}$</td>
<td>$3 \times 10^{48}$</td>
</tr>
</tbody>
</table>

DT et al (2012)
GW phase change too small to measure

\[ \Delta \phi \sim \frac{t_{rr} E_b}{t_{orbit} E_{orbit}} \sim 10^{-3} \text{rad} \]
Tsang et al. (2012)
Optical/Radio “Afterglow”

- 1 cm$^{-3}$
- 10$^{-3}$ cm$^{-3}$
- 200 Mpc
- 10$^{48}$ erg isotropic shattering flare
- 10$^{51}$ erg (E$_{\text{ISO}}$) GRB

Based on Morsony et al. 2016 (arXiv:1602.05529)
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Parabolic/Eccentric Encounters

- If encounter is close enough shattering flare can occur
- Emission similar to circular case
- Eccentric captures may lead to multiple bursts
- Possible EM/GW signal!
- Rates are not very good... (~100x less than Lee et al, 2010; O'Leary, Kocsis & Loeb, 2009)
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Summary

- Precursor flares are seen before some SGRBs
- Shattering flare caused by tidal resonant excitation of the i-mode
- Coincident timing of precursor w/ GW inspiral determine mode freq.
- Can provide constraints on shear speed/nuclear physics/EOS at base of crust
- Total fluence can constrain breaking strain

- We will know source w/ coincident detection/timing
- **Isotropic** emission mech w/ Optical/Radio Afterglow
- Parabolic/Eccentric Encounters in Globular/Nuclear Clusters
- Need $10^{12} < \text{surf. B-field} < 10^{15}$
- Possible weak “GRB”, even for off-axis or low spin/high mass BH/NS merger
The End