Burst Oscillations and Nonradial Modes of Neutron Stars

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Piro & Bildsten 2004, 2005a, 2005b, 2005c (submitted)
Burst Oscillations from LMXBs

- Frequency and amplitude during rise are consistent with a hot spot spreading on a rotating star (Strohmayer et al. ‘97)

- Angular momentum conservation of surface layers (Strohmayer et al. ‘97) underpredicts late time drift (Cumming et al. ‘02)

- Ignition hot spot should have already spread over star (Bildsten ‘95; Spitkovsky et al. ‘02), so what creates late time asymmetry?!
The asymptotic frequency is characteristic to each object

- Frequency stable over many observations (within 1 part in 1000 over years; Muno et al. ‘02)

It must be the spin…right?

<table>
<thead>
<tr>
<th>Source</th>
<th>Asymptotic Freq. (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4U 1608-522</td>
<td>620</td>
</tr>
<tr>
<td>SAX J1750-2900</td>
<td>600</td>
</tr>
<tr>
<td>MXB 1743-29</td>
<td>589</td>
</tr>
<tr>
<td>4U 1636-536</td>
<td>581</td>
</tr>
<tr>
<td>MXB 1659-298</td>
<td>567</td>
</tr>
<tr>
<td>549 Aql X-1</td>
<td>549</td>
</tr>
<tr>
<td>KS 1731-260</td>
<td>524</td>
</tr>
<tr>
<td>SAX J1748.9-2901</td>
<td>410</td>
</tr>
<tr>
<td>SAX J1808.4-3658</td>
<td>401</td>
</tr>
<tr>
<td>4U 1728-34</td>
<td>363</td>
</tr>
<tr>
<td>4U 1702-429</td>
<td>329</td>
</tr>
<tr>
<td>XTE J1814-338</td>
<td>314</td>
</tr>
<tr>
<td>4U 1926-053</td>
<td>270</td>
</tr>
<tr>
<td>EXO 0748-676</td>
<td>45</td>
</tr>
</tbody>
</table>
Burst Oscillations from Pulsars

SAX J1808.4-3658; Chakrabarty et al. ‘03

XTE J1814-338; Strohmayer et al. ‘03
Also see recent work by Watts et al. ‘05

- Burst oscillation frequency = spin!
- No frequency drift, likely due to large B-field (Cumming et al. 2001)

~ 100 sec decay like H/He burst!
What Creates Burst Oscillations in the Non-pulsar Neutron Stars?

Important differences:

• Non-pulsars only show oscillations in short (~ 2-10 s) bursts, while pulsars have shown oscillations in longer bursts (~ 100 s)

• Non-pulsars show frequency drifts often late into cooling tail, while pulsars show no frequency evolution after burst peak

• Non-pulsars have highly sinusoidal oscillations (Muno et al. ‘02), while pulsars show harmonic content (Strohmayer et al. ‘03)

• The pulsed amplitude as a function of energy may be different between the two types of objects (unfortunately, pulsars only measured in persistent emission) (Muno et al. ‘03; Cui et al. ‘98)

These differences support the hypothesis that a different mechanism may be acting in the case of the non-pulsars.
Perhaps Nonradial Oscillations?

Initially calculated by McDermott & Taam (1987) BEFORE burst oscillations were discovered (also see Bildsten & Cutler ‘95). Hypothesized by Heyl (2004).

- Most obvious way to create a late time surface asymmetry in a non-magnetized fluid.
- Supported by the HIGHLY sinusoidal nature of oscillations
- The angular and radial eigenfunctions are severely restricted by the main characteristics of burst oscillations.

What angular and radial structure must such a mode have?…

Graphic courtesy of G. Ushomirsky
Heyl (‘04) identified crucial properties:

- Highly sinusoidal nature (Muno et al. ‘02) implies \( m = 1 \) or \( m = -1 \)
- The OBSERVED frequency is
  \[
  \omega_{\text{obs}} = |m\Omega - \omega|
  \]
  If the mode travels PROGRADÉ (\( m = -1 \)) a DECREASING frequency is observed
  \[
  \omega_{\text{obs}} = \Omega + \omega
  \]
  If the mode travels RETROGRADÉ (\( m = 1 \)) an INCREASING frequency is observed
  \[
  \omega_{\text{obs}} = \Omega - \omega
  \]
Rotational Modifications

Since layer is thin and buoyancy is very strong, Coriolis effects ONLY alter ANGULAR mode patterns and latitudinal wavelength (through $\lambda$) and NOT radial eigenfunctions! (Bildsten et al. ‘96)

\[ l = 2, m = 1 \]

Inertial R-modes \qquad l = m, Buoyant R-modes \qquad Buoyant R-mode

\[
\omega = \frac{2m\Omega}{l(l + 1)}
\]

Only at slow spin.
Not applicable.

\[
\lambda \sim \left( \frac{2\Omega}{\omega} \right)^2 \sim 10 - 10^3
\]

Too large of drifts and hard to see.

\[
\lambda = 0.11
\]

Just right. Gives drifts as observed and nice wide eigenfunction
Modes On Neutron Star Surface

<table>
<thead>
<tr>
<th>Depth</th>
<th>Density</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1 m</td>
<td>$10^4$ g cm$^{-3}$</td>
</tr>
<tr>
<td>$H_b \approx 2$ m</td>
<td>$10^6$ g cm$^{-3}$</td>
</tr>
<tr>
<td>$H_c \approx 20$ m</td>
<td>$10^9$ g cm$^{-3}$</td>
</tr>
</tbody>
</table>

Shallow surface wave

$$\omega_s^2 = gH_b k^2 \frac{\Delta \rho}{\rho}$$

$$k^2 = \frac{\lambda}{R^2}$$

Crustal interface wave

$$\omega_c^2 = gH_c k^2 \frac{\mu}{P}$$

$$\frac{\mu}{P} \approx 10^{-2}$$

Piro & Bildsten 2005a

Strohmayer et al. ‘91
The First 3 Radial Modes
(using $\lambda = 0.11$)

- Mode energy is set to $5 \times 10^{36}$ ergs
- $10^{-3}$ of the energy in a burst (Bildsten ‘98)
- Estimate radiative damping time using “work integral” (Unno et al. ‘89)
- Surface wave (single node) has best chance of being seen (long damping time + large surface amplitude)
Avoided Mode Crossings

The two modes meet at an avoided crossing.

Piro & Bildsten 2005b
Avoided Mode Crossings

Definitely a surface wave!

Mode with Single Node

Mode with 2 Nodes

Piro & Bildsten 2005b
Avoided Mode Crossings

In between surface/crustal

Mode with Single Node

Mode with 2 Nodes

Piro & Bildsten 2005b
Avoided Mode Crossings

Definitely a crustal wave!

Mode with Single Node

Mode with 2 Nodes

Piro & Bildsten 2005b
Calculated Frequencies

400 Hz neutron star spin

\[ \omega_{\text{obs}} = |m\Omega - \omega| \]

- Lowest order mode that matches burst oscillations is the \( l = 2, m = 1, \) r-mode

\[ \lambda \approx 1/9 \approx 0.11 \]

- Neutron star still spinning close to burst oscillation frequency (\( \sim 4 \) Hz above)

All sounds nice… but can we make any predictions?

Piro & Bildsten 2005b

\[ \sim 5 \text{ Hz drift} \]

\[ \text{switch to crustal mode} \]

\[ \sim 3 \text{ Hz drift} \]

\[ \text{He burst with hot crust} \]

\[ \text{no switch?!} \]

\[ \text{H/He burst composition} \]
Comparison with Drift Observations

- The observed drift is just the difference of
  \[ \frac{\omega_s}{2\pi} \approx 9.5 \text{ Hz} \]
  \[ \frac{\omega_c}{2\pi} \approx 4.3 \text{ Hz} \left( \frac{64}{A_c} \frac{T_{c,8}}{3} \right)^{1/2} \]

- We calculated drifts using these analytic frequencies with crust models courtesy of E. Brown.

- We compared these with the observed drifts and persistent luminosity ranges.

- Comparison favors a lighter crust, consistent with the observed He-rich bursts.

\[ L_{Edd} \approx 3 \times 10^{38} \text{ erg s}^{-1} \]
Could other modes be present during X-ray bursts?

- Nothing precludes the other low-angular order modes from also being present.
- Such modes would show 15-100 Hz frequency drifts, so they may be hidden in current observations.

Piro & Bildsten 2005b
Amplitude-Energy Relation of Modes
Also see Heyl 2005 and Lee & Strohmayer 2005

Mode amplitude is unknown => we can ONLY fit for SHAPE of relation

• Linearly perturbed blackbody
  \[
  \frac{\Delta I}{I} = \frac{E'}{kT} \frac{e^{E'/kT}}{e^{E'/kT} - 1} \frac{\Delta T}{T}
  \]

• Low energy limit
  \[E < kT \sqrt{1 - r_g/R}\]
  \[\Delta I/I \propto \text{constant}\]

• High energy limit
  \[E > kT \sqrt{1 - r_g/R}\]
  \[\Delta I/I \propto E/kT\]

Compares favorably with full integrations including GR! (when normalized the same)
Comparison with Observations

- Data from Muno et al. ‘03
- Demonstrates the difficulty of attempting to learn about NSs
- Low energy measurement would allow fitting for
  \[ kT \sqrt{1 - \frac{r_g}{R}} \]
- This begs the question: What is the energy dependence of burst oscillations from pulsars! (these differ in their persistent emission)
Conclusions

• A surface wave transitioning into a crustal interface wave can replicate the frequency evolution of burst oscillations. Only ONE combination of radial and angular eigenfunctions gives the correct properties!

• The energy-amplitude relation of burst oscillations is consistent with a surface mode, but this is not a strong constraint on models nor NS properties

Future work that needs to be done

• IMPORTANT QUESTION: What is amplitude-energy relation for pulsars DURING burst oscillations?

• Can burst oscillations be used to probe NS crusts?

• More theory! Why only 2-10 sec bursts? What is the excitation mechanism? (Cumming ‘05)