Burst Oscillations: Problems and Prospects

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Burst Oscillations: Neutron Star Spins

- Discovered in Feb. 1996, shortly after RXTE’s launch (Strohmayer et al, 1996)
- First indication of ms spins in accreting LMXBs.
- 4U 1728-34, well known, frequent burster.
- Power spectra of burst time series shows significant peak at 363 Hz.
Outline, Assumptions

• Burst oscillations are due to spin modulation of “brightness asymmetries” on the neutron star surface.
• What do observations say about how such asymmetries form, evolve, and radiate?
• Incomplete observational overview.
• What are some of the remaining puzzles?
• How might we resolve them?
• Recent, and ongoing work on phase-resolved spectra of burst oscillations, searches for oscillation modes, 4U 1636-536 superburst.
Oscillations at Burst Onset and Rise

An X-ray burst from 4U 1636-53 with 1.7 ms oscillations.
Burst Oscillation Amplitudes at Onset

- Oscillations at rising edge approach 100% modulation of the burst flux (persistent flux level subtracted).

Timing and Spectral Evidence for Rotational Modulation

- Oscillations at onset caused by hot spot on rotating neutron star
- Modulation amplitude drops as spot grows.
- Spectra track increasing size of X-ray emitting area on star.

Strohmayer, Zhang & Swank (1997)
Coriolis Force influences spreading speed

- Spitkovsky, Levin & Ushomirsky (2002) showed Coriolis force relevant to ignition and spreading.
- Flame speed faster at equator, slows with increasing latitude.

Modelling of near-equatorial ignition, and Coriolis dependent spreading, can better explain amplitude evolution of some bursts.
Burst Rise: Amplitude Evolution

- Amplitude evolution during burst rise, encodes information on nature of flame spreading.
- Some bursts show high initial amplitude, rapid decrease, and then persist at lower amplitude.
Watts & Maurer (2007) explore shapes of burst rising phases.

Find that bursts group according to peak flux and “convexity,” and suggest that ignition latitude varies with accretion rate.

Negative convexity bursts ignited at high latitude (near the pole).

High flux, positive convexity bursts are He ignited near the equator.
Burst Rise Oscillations: 4U 1636-536

- Systematic study of “all” 4U 1636-536 bursts with rise oscillations.
- Amplitude decreases with time during rise.
- Amplitude evolution consistent with “concave up” shape.
- Nuclear flames spread! And evidence supports a latitude dependent spreading (perhaps like Coriolis).
- General consistency with Maurer & Watts.

Chakraborty & Bhattacharyya (2014)
Oscillations in the Cooling Phase

- Pulsations in the cooling tails can be as large as 15 - 20% \( \frac{f_{\text{max}} - f_{\text{min}}}{f_{\text{max}} + f_{\text{min}}} \)
- If the whole surface is burned, what causes the flux asymmetry?
- Oscillation modes (Heyl 2002 suggests \( r \)-modes; Piro & Bildsten 2005, Lee & Strohmayer 2005, Heyl 2005; Cumming 2005)?
- Frequency and phase can evolve be modeled.
What Breaks the Symmetry?

• Global Oscillation modes could provide late time asymmetry.

• r-modes suggested by Heyl (2005), Lee & Strohmayer (2005). Are the modes unstable?

• Spitkovsky et al. suggest vortices “trapped” in zonal wind set up by differential cooling. Equatorial waveguide, modes.

• Cumming (2005) finds dynamically unstable shear modes, associated with differential rotation, perhaps “self-excited” by bursts.

• Cooling wake, what does cooling over the whole surface produce?
Puzzle: Frequency Evolution of Burst Oscillations

- Expanding layer slows down relative to bulk of the star.

- Change in spin frequency crudely consistent with expected height increase, but perhaps not for most extreme variations.

- X-ray burst expands surface layers by ~30 meters.
Spin Down of Burst Oscillations in 4U1636-53

- Small fraction of bursts show episodes of spin down (Miller 1999; Strohmayer 1999; Muno 2001).
- Spin down in 4U 1636-53 is associated with extended thermal tail and transition evident in spectral evolution.
- Magnitude of spin down may reflect an expansion of the surface layers by only 10 - 30 meters!
Coherence of Burst Oscillations

4U 1702-429: Strohmayer & Markwardt (1999)

- Burst oscillations generally have high coherence ($Q > 4,000$)
- Exponential recovery in some bursts.

Model: $f(t) = f_0 \left( 1 - \delta e^{-t/\tau} \right)$
EXO 0748-676: The Burst Oscillation Frequency

- Pulsations seen on rising edge, two bursts (552 Hz; Galloway et al. 2010).
- Frequency drifts by ~1 Hz during rise.

- Low fraction of bursts with detectable oscillations?
- And only on rise?
Frequency Drifts due to Hydrostatic Expansion

From Cumming et al. (2002)

• Fractional frequency shifts appear to be a bit too large in some sources for hydrostatic expansion alone.

• If differential rotation persists, then top layers can spin down enough, but seems unlikely.

• Hydrodynamics important?
Presence of Shearing Layer, and Vertical Heat Transport

• Coherent frequency drifts indicate shearing layers during bursts. ~ 10s of “phase wraps” in some cases.
• If timescale to transport heat across the layer is long compared to “shearing” time, then modulations will be smeared out (Cumming and Bildsten, H vs He layers).
• Could account for variations in amplitudes (non-detections for some bursts).
• Probably needs to be better modeled for future.
Burst Oscillations and Source State

- Bursts with oscillations correlated with position in the X-ray CC diagram

4U 1728-34: Franco (2001)


- Connection with mass accretion rate dependence of nuclear burning
Properties of Burst Oscillations

[Graph showing frequency and count rate over time for bursts 13, 17, and 6]
• Local accretion rate is higher at the equator. Preference for ignition near equator.

• Ignition stabilizes above a critical local accretion rate.

• At higher accretion rates, ignition could move of equator to higher latitudes (Cooper & Narayan 2007).

• Can we see this?

\[ P = y g_{\text{eff}} = \text{const} \]

Independent of latitude.
Rapid Spin and Ignition Latitude

• Variation in effective gravity with latitude, give changes in ignition timescale with latitude.

• Higher accretion rates yield shorter ignition times away from equator.

• Need fast rotation.

Cooper & Narayan (2007)
Accretion State Dependence of Oscillations

- Mass accretion rate
- Composition? → Mode visibility
- Latitude of ignition?
- Ignition depth, spreading speed, PRE?

Given the above, perhaps a dependence on accretion state is then not unexpected, but disentangling the various effects appears to be difficult!
Properties of Oscillations: Phase-resolved Spectra (rises)

- Extracted phase-resolved spectra (RXTE/PCA) for bursts from 4U 1636-536. typical interval \( \sim 0.5 \) s.
- Compute the full band count rate, and the mean PCA energy channel versus pulse phase.

![Single burst, 4U 1636-536](image1)

![Sum from 8 bursts](image2)

- Mean channel is a measure of spectral hardness (temperature).
- Extract single burst data (left) as well as coherently adding spectra from several bursts (coherent sum from 8 burst rises (right).
Modeling Emission from a Rotating Neutron Star

- Rotating star
- X-ray emitting hot-spot
- Relativistic effects:
  - Light bending in a Schwarzschild geometry
  - Gravitational redshift
  - Doppler shifts
  - Relativistic aberration

(Beloborodov 2002; Poutanen & Gierlinski 2003; Morsink et al 2007; Lo et al. 2013)

Pulse profiles consistent with the results of the LOFT Science Working Group on Dense Matter. (Poutanen, Lamb, Morsink, Psaltis et al.)
Phase-resolved Spectra: Modeling

- Use fully relativistic model (Schwarzschild+Doppler) to compute same observables from the model.
- Fold physical model spectrum through PCA response matrix.

Portion of model with expanding spot on rise.

- For 4U 1636-536, use $f_{\text{spin}} = 582$ Hz, $M=1.6 \, M_{\odot}$, $R=10 \, \text{km}$.
- Use isotropic emission from single temperature hot-spot (right).
- Modeling still in progress, but model-predicted “leads” do not seem to be evident in the data.
Properties of Oscillations: Phase-resolved Spectra (tails)

• Compute several models and PCA observables, for comparison with data.
• Modulation in mean PCA channel is IN PHASE with pulsed light curve. Single temperature spot models predict a lead.

• Extracted phase-resolved spectra from bursts from 4U 1636-536, oscillations in the cooling tail, typical pulse interval, 5 s.
• Compute count rate (full band) and mean PCA channel vs pulse phase

Single burst

Sum for 11 bursts
Whereas burst oscillations from 4U 1636-536 show a strong “color” modulation, curiously there is no significant variation in mean PCA channel with phase in J1814.

J1814 has a slower spin rate, 314 Hz, and is a persistent pulsar (when in outburst).

What accounts for the differences with 4U 1636?
Phase-resolved spectroscopy: Implications

• Significant and substantial modulation of mean PCA channel, a “color” oscillation, but apparently “in phase” with the flux modulation in 4U 1636-536 (rises and tails, but seems most solid for tail oscillations).
• Doppler shifts associated with fast rotation of a constant kT spot should “lead” the flux modulation (see Artigue et al. 2014, for example).
• Models with kT gradients are less out of phase, but still lead.
• Are there other effects (physics) needed in the modeling? Angular dependence of the emissivity and spectrum, eg., full atmosphere modeling.

I(\(\mu\)), T(\(\mu\))

Work in progress!
Neutron Star Seismology

- Stellar oscillations are a powerful probe of internal structure (e.g. helioseismology).
- For example, p-modes sense the sound speed. Mode frequencies scale as $<\rho>^{1/2}$ (thus M and R).
- Solid crust supports torsional shear modes, $t_n$ for $n = 0$ modes, effective wavelength is $R$, for $n > 0$ it is $\Delta R$, if $V_s =$ constant, then $f_{n=0} / f_{n>0} \sim \Delta R/R$, constrain crust thickness (magnetar QPOs).
- g-modes supported by buoyancy (thermal and density gradients), can probe $R$, and envelope structure.

Brightness pattern for an $l=2, m=1$ g-mode (slow rotation limit).
How Might Non-radial Oscillations be Observed?

- Pulsation modes can modulate the temperature (flux) across the neutron star’s surface – coupled with spin can produce flux modulation at mode’s inertial frame frequency (Lee & Strohmayer, Heyl 2005).

- Surface displacements generated by pulsation modes can periodically distort the X-ray emitting hot-spot (Numata & Lee 2010). Works for transverse (quasitoroidal) displacements. Such modes include surface g-modes, and r-modes.

- Since hot-spot rotates with the star, the modulation frequency seen by a distant observer is the co-rotating frame frequency (Strohmayer & Mahmoodifar 2014, ApJ, 784, 72).
Coherent Searches for Pulsation Modes

• Use orbit model to remove time delays associated with neutron star’s orbital motion. Observer is effectively at the binary’s center of mass.

• “Coherence Recovery,” improves sensitivity to weak, coherent signals. Narrow band signal is not “smeared” into many Fourier bins.

• “Targeted” search for r-modes and surface g-modes. Spin frequency is known, so search mode frequency range (relative to spin) that is expected theoretically. Keeps $N_{trial}$ low and thus improves overall sensitivity.

\[
0.417 \leq \sigma / \Omega \leq 0.757 \text{ (rotating frame)}
\]

\[
1.243 \leq \sigma / \Omega \leq 1.583 \text{ (inertial frame)}
\]

• Bin light curve using corrected times (4096 Hz sampling).

• Create power spectra using 4 energy ranges (focusing on superburst thermal component).
• Orbital period known (3.79 hr), fit for other parameters; $v_{spin}$, $v_{ns}$ and epoch of $T_{90}$ (Strohmayer & Markwardt 2002).
• Barycenter, then remove orbital time delays.

• 582 Hz spin pulsations detected for ~800 s near burst peak.
• Frequency drift consistent with orbital motion of the neutron star.
\[ N_{\text{bins}} \approx \frac{\Delta v}{v} = \frac{v_{\text{ns}}}{c} = \left(\frac{0.5}{582}\right) \times \frac{835}{1/8000} = 5700! \]
Coherent Search in the Superburst

Estimated significance: $2.5 \times 10^{-4}$

$$\exp(-49.3/2) \times N_{\text{trials}} = \exp(-49.3/2) \times (4 \times 3.17 \times 10^6)$$
Possible Mode Identifications


• latitudinal dependence of Coriolis force “squeezes” modes closer to equator.

• Observed frequency (835 Hz) is larger than spin, so, if |m|=1, need prograde (m=-1) mode (this is a Kelvin mode), but frequency is not high enough to reach observed (likely rules out l=1). So, |m|=2. Then l=2, m=2 or l=2, m=-1 appear plausible.