Pulse Profile Modelling of Thermonuclear Burst Oscillations

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Intro

Accretion leads to thermonuclear bursts

Thermonuclear burst: sudden and intense release of X-rays that happens in a neutron star’s outer layers and caused by a runaway nuclear fusion process.
Intro

Accretion leads to thermonuclear bursts

Thermonuclear burst: sudden and intense release of X-rays that happens in a neutron star’s outer layers and caused by a runaway nuclear fusion process.
What is thermonuclear burst?

**Intro**

**Properties**
(normal burst)

- Fuel: H/He
- Duration: 10-100 s
- Energy released: $10^{39}$ ergs
- Recurrence time: hours – days

**Burst light curve**

![Burst light curve graph](image)
What are burst oscillations?

Burst oscillations (BOs): coherent pulsations found in some of the burst light curves of some neutron stars.

1. Rise
2. Decay
3. Throughout
4. No oscillation

Cause: Uneven heat distribution on the NS surface or in their atmosphere.
**Motiv.** What makes BOs sources interesting for PPM?

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<tbody>
<tr>
<td>1</td>
<td>The pulsations</td>
<td>Used to constrain the stellar properties: Mass, radius, etc.</td>
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<td></td>
<td></td>
<td></td>
<td>See Bas’ talk</td>
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<td>2</td>
<td>Spin very fast</td>
<td>Helps constrain the mass &amp; radius separately</td>
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<td>$f \sim 250 - 620$ Hz</td>
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<td>3</td>
<td>Different population</td>
<td>Allows for independent cross-checks</td>
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<td>4</td>
<td>Very bright events</td>
<td>Accumulation of more photons</td>
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<td></td>
<td>Energy released $\sim 10^{39}$ ergs</td>
<td>Hence tighter constraints on parameters</td>
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Modelling BOs is challenging

What is the origin of uneven heat distribution?

- **Burst ignites**
  - e.g. Stromahyer et al. 1997, Spitovsky et al. 2002, Cavecchi et al. 2013

- **Flame spreading**
  - e.g. Stromahyer et al. 1997, Spitovsky et al. 2002, Cavecchi et al. 2013

- **Flame stall: magnetic/Coriolis confinement?**
  - e.g. Spitovsky et al. 2002, Cavecchi et al. 2013

  - **R-modes**

- **Flames engulf the surface?**

  - **Convective patterns**
    - e.g. Garcia et al. 2019

Image credit: Spitkovsky
Modelling BOs is challenging

Motiv.

RMPs have very stable light-curves & pulsations, still modelling is computationally expensive. See Bas’ & Devarshi talk.

Burst light-curves are highly variable; modelling even more computationally expensive.
Modelling BOs is challenging?

Recap

- Origin of pulsation uncertain
- Variable light-curves
- Pulse fraction variable
- Frequency drift
Properties of XTE J1814-338

What makes J1814 Interesting?

1. Very stable pulsations
2. High pulse fraction: ~ 10%
3. Harmonic content
Recap

- Origin of pulsation uncertain
- Variable light-curves
- Pulse fraction variable
- Frequency drift (crossed out)
Phenomenological models

Models that mimic J1814 bursts light-curves & oscillation properties

$T_{\text{spot}}$ varies

$\zeta_{\text{spot}}$ varies

$T_{\text{star}}$ varies

Time
Study case: XTE J1814-338

Model.

Synthetic bursts

24 bursts of $10^5$ counts each
RXTE data like

24 bursts of $10^6$ counts each
e-XTP & STROBE-X data like

24 bursts of $10^7$ counts each
Combining bursts of e-XTP & STROBE-X
Results

XTE J1814-338

1st Approach: neglecting variability

Synthetic data produced with models that has variability

Inference runs performed with a model that has no time dependance
Results

**XTE J1814-338**

$CI_{68\%} = 9.79^{+2.14}_{-1.93}$

$CI_{68\%} = 7.12^{+1.00}_{-0.65}$

$CI_{68\%} = 15.21^{+0.15}_{-0.25}$

- **$10^5$ counts**
  - **$10^6$ counts**
  - **$10^7$ counts**

$CI_{68\%} = 1.34^{+0.24}_{-0.22}$

$CI_{68\%} = 1.47^{+0.12}_{-0.10}$

$CI_{68\%} = 1.38^{+0.03}_{-0.04}$

**$10^5$ counts:** Broad posteriors

**$10^7$ counts:** median of the distribution is very far from the injected value.
Results

XTE J1814-338

1st Approach: neglecting variability

When variability is neglected:
Mass and radius are incorrectly recovered.

PP-Plots
Study case: XTE J1814-338

2\textsuperscript{nd} Approach: keeping track of varying parameters using only $10^6$ counts data set

**Inference runs** performed with a model that has now time dependence
Results

XTE J1814-338

2\textsuperscript{st} Approach: accounting for variability

When variability is accounted for: Mass and radius are correctly recovered.

PP-Plots
Study case: XTE J1814-338

2\textsuperscript{st} Approach: accounting for variability

Results
Modelling burst oscillations to constrain NS masses and radii is possible.
Modelling is challenging.
Variability needs to be addressed to get useful constraints.
We need theoretical models to reduce some of the uncertainties.