Observations of X-ray bursters

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Jean in ‘t Zand
SRON
Thermonuclear X-ray bursts

- Occur in neutron stars accreting from low-mass binary companions; ~100 bursters known, ~$10^4$ bursts observed since early 1970s

- Understood since the `80s as resulting from unstable ignition of accreted H/He on the NS surface (e.g. Fujimoto et al. 1981, ApJ 247, 267)
Observational milestones

• Photospheric radius-expansion bursts reach the (local) Eddington limit; utility as standard candle Basinska et al. 1984; Kuulkers et al. 2003

• Burst oscillations measure the neutron star spin; exhibit 1–2 Hz drifts Strohmayer et al. 1996; Chakrabarty et al. 2003; Watts 2012

• “Superbursts” with durations of hours likely arising from carbon burning Cornelisse et al. 2000

• “Intermediate duration” bursts arising in low-accretion rate systems, burning of large pure-He fuel reservoirs Falanga et al. 2009

• Burst spectra exploited to measure neutron star $M, R$ Özel et al. 2006, 2009, 2012 etc; Steiner et al. 2010

... see also in ‘t Zand, arXiv:1102.3345, Strohmayer & Bildsten 2003
Outstanding questions

• What causes burst oscillations?
• What causes the decrease in burst rate, observed for most sources at accretion rates above ~5% Eddington?
• Can we use bursts to unambiguously measure neutron star mass and radius?
• What ignites in superbursts?
• Why do all types of bursts – short, intermediate-duration, and super – seem to ignite at columns well below theoretical predictions?
• Can we use bursts to constrain (or measure) nuclear reactions?
1. Burst oscillations

- Detected in 17 sources, including 5 millisecond pulsars and 2 intermittent pulsars [Watts 2012]
- Not present in every burst (why?)
- Oscillations in the rise expected from a spreading hot spot
- Oscillations in the tail (present in the majority of bursts with oscillations) harder to understand
- Attempts to explain via r-modes etc...


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A bleak future

• **RXTE** end-of-mission (Jan 2012) crippled high-time resolution X-ray capability

• Archival searches?

• **XMM-Newton** can play a role, with 570 Hz timing limit & lower sensitivity (e.g. IGR J18245-2452)

• Future missions include **ASTROSAT** and **LOFT** (ESA M3 M4 candidate, >2020)

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2. Superbursts

- Very long burst-like profiles with timescales of hours, 24 events observed from 15 sources Oct ’13
- Energetics implies ignition at a column where no H/He could survive – fuel is C instead?
- Serious issues producing and retaining enough fuel e.g. Cumming et al. 2006

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Zooming in on precursors

- **RXTE** data been analysed in more sophisticated ways to reveal photospheric radius-expansion in a superburst precursor
- Calibrated propane layer data to circumvent loss of high-time resolution spectral data
- PRE phase unusually energetic -> detonation & shock heating?

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New superbursts challenge theory

- Superbursts from transients should not occur, as there is insufficient time to build up enough carbon fuel
- First of these from 4U 1608-52
  Keek et al. (2008) A&A 479, 177
- More recently a superburst from EXO 1745-248
  Altamirano &c (2012) MNRAS 426, 927
Crust and core

- Long bursts (both intermediate duration and “super” bursts) are sensitive to thermal conditions in the crust
- These rare (~80 known since ~1970s) events are priorities for observations
- Also He-rich bursts

Fig. 5.—Fitted light curve for KS 1731–260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.

Cumming et al. 2006
3. NS parameters from burst spectra

- Use 3 measurables to solve for the mass and radius, under a number of assumptions
  Özel 2006, Nature, 441, 1115

- Presented results so far on EXO 0748–676 and 5 additional sources: 4U 1608-52, EXO 1745–248, 3A 1820–30, KS 1731–26 and GRS 1748.9–2021

- Criticism has been raised regarding the assumptions and the statistical treatment


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Figure 5. Plot of 1σ and 2σ contours for the mass and radius of the neutron star in EXO 1745–248, for a hydrogen mass fraction of $X = 0$, based on the spectroscopic data during thermonuclear bursts combined with a distance measurement to the globular cluster. Neutron star radii larger than $\sim 13$ km are inconsistent with the data. The descriptions of the various equations of state and the corresponding labels can be found in Lattimer & Prakash (2001).
The spectrum is thought to be distorted slightly; a correction factor $f_c$ is generally applied (e.g. Madej et al. 2004, ApJ 602, 904).

Net burst spectrum (subtracting the pre-burst, persistent emission as background) is usually fitted with a blackbody.

Such spectra are characterised by the temperature and the apparent radius of the emitting object.

Standard spectral analysis

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Issues for inferring $R$

- Apparent radius (blackbody normalisation) depends on the distance, redshift ($M$ & $R$), spectral correction factor $f_c$:

$$R = R_{bb} df_c^2 \xi^{1/2} (1 + z)^{-1}$$

where $d$ is the distance, and $\xi$ parametrises the anisotropy of the burst emission

- Distance must be determined independently (i.e. not from PRE bursts, since the peak PRE burst flux is one of the other required measurables)

- Anisotropy always appears in combination with distance; analytic estimates only, based on inclination (usually unknown)
How does $f_c$ vary – if at all?

- Constant $R_{bb}$ in some bursts suggest constant $f_c$ with flux, counter to models

Figure 4. Comparison of averaged blackbody normalization profiles for bursts from GS 1826–24 measured in 1997–1998 (nos. 1–5 of G08) and 2000–2007 (nos. 9, 10, 11, 12, 13, 16, 17, 19, 20). The vertical dashed lines indicate the time of maximum flux for each set of bursts. Note the agreement in the normalization throughout the burst rise and maximum, and the increasing discrepancy from 10 s after the burst start. The inset shows the corresponding variation of the averaged burst flux.
One of many systematic issues

- Burst spectra are generally not well fit by blackbodies alone
- Joint RXTE-Chandra observations of a bright burst from SAX J1808.4-3658 suggest that the accretion rate increases during the burst
  
  In 't Zand et al. 2013, A&A 553, #A83
- Confirmed by comprehensive analysis of archival RXTE data
  

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4. New sources

- Wide-field X-ray monitoring of the sky with *Swift*, *MAXI* (onboard ISS) and *INTEGRAL*

- Regularly discovering new transients; detection of bursts a key step to confirming nature of compact object (NS or BH)
Terzan 5 X2

- A new transient outburst of a previously unknown globular cluster LMXB Atel #2919
- 11 Hz pulsations (<< typical freq); 21-hr orbit Atel #2919
- Bursts occurred more frequently as the luminosity approached Eddington -> quasi-stable burning
- First time this transition has been observed, although details differ from models e.g. Chakraborty et al. 2012, MNRAS 422, 2351; Motta et al., 2011, MNRAS 414, 1508; Linares et al., 2012, ApJ 748, 82L; Cavecchi et al., 2011, ApJ 740, 8; etc. etc.

The other source that shows bursts becoming more frequent up to high accretion rates is MXB 1730-335 – perhaps also a slow rotoator? Bagnoli et al. (2013) MNRAS 431, 1947
Other notable results

- Detection of high-energy deficit following bursts; e.g. Ji et al. 2014 ApJ 782, 40
- Analysis of data providing clues to the specific heat capacity of the corona temperature. In practice, based on the fitting results in A&A 562, A16
- Short, super-Eddington precursors indicating mildly relativistic outflows providing clues to the specific heat capacity of the corona temperature

arXiv:1407.0300
5. Burst observations vs. models

Burst behaviour varies from source to source... and broadly does not match models.
The future

• Burst oscillations
  - Further theoretical work on spreading, detectability of oscillations, correlation with source spectral state

• Mass/radius measurements
  - Substantial shortfall in our understanding of spectral formation during bursts, which needs to be addressed
  - Influence of accretion disk; spectral state etc.

• Thermonuclear burning
  - Detailed observation/model comparisons can provide constraints on fuel composition, individual reaction rates, NS properties(?)