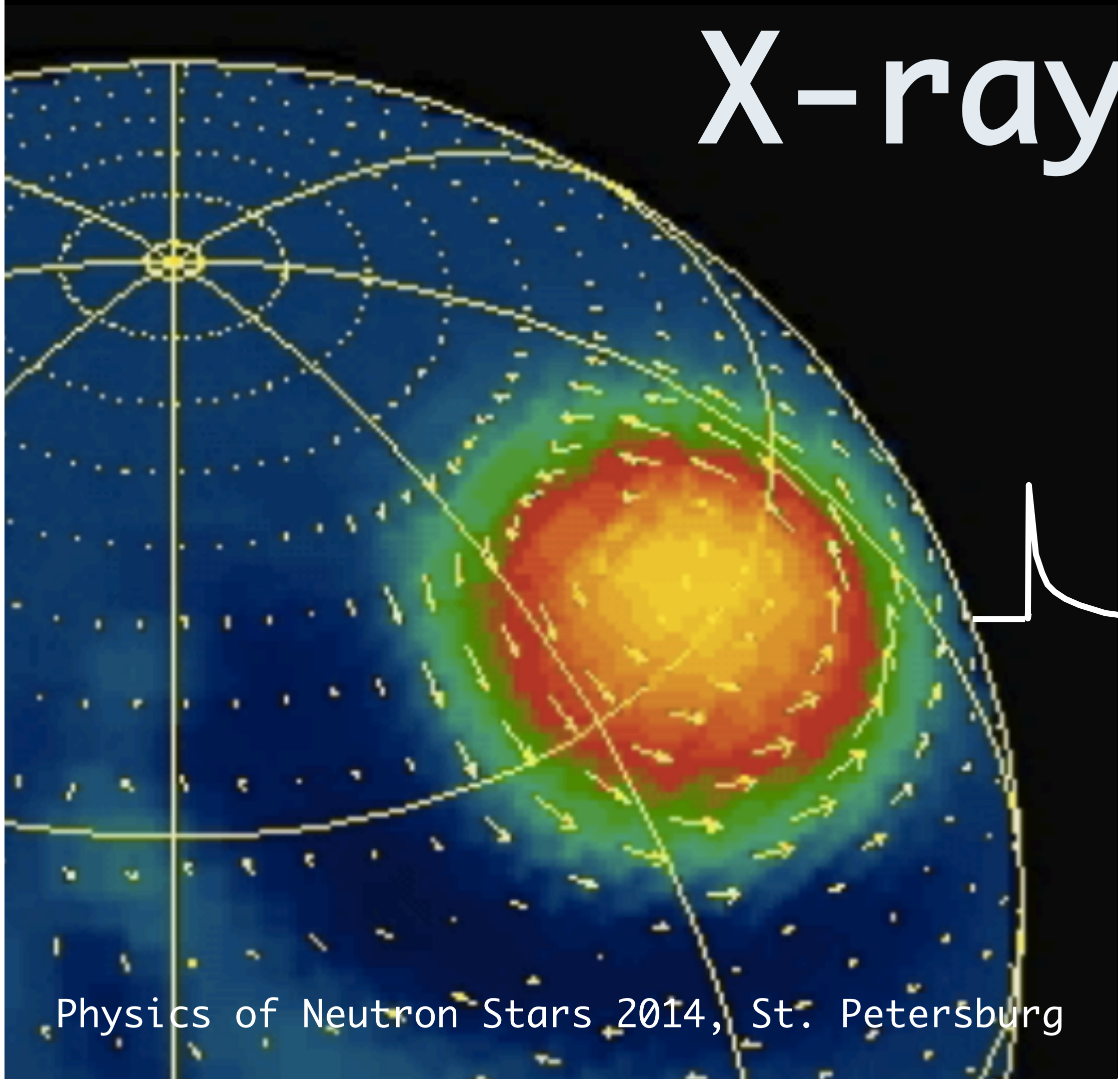
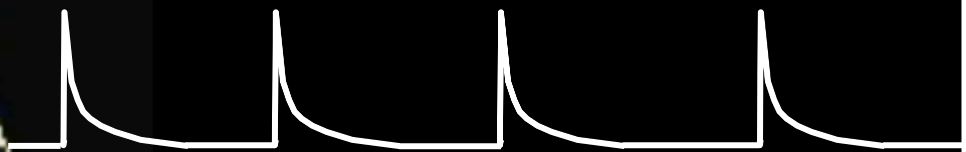
MONASH University

MoCA Monash Centre for Astrophysics

Observations of X-ray bursters





Physics of Neutron Stars 2014, St. Petersburg

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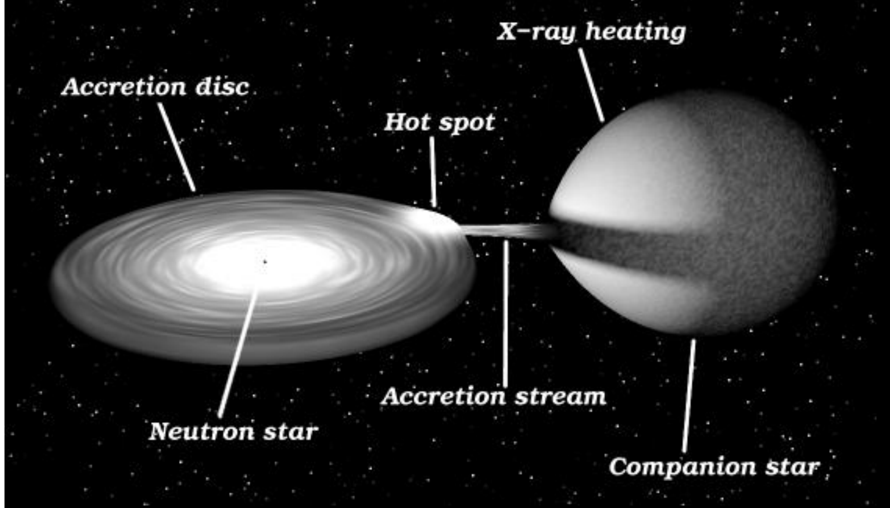
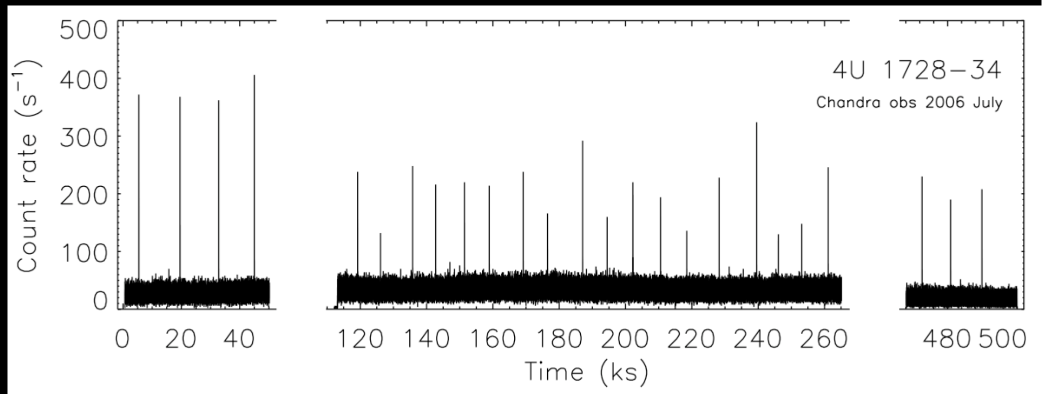
Monash University
Jean in 't Zand
SRON

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

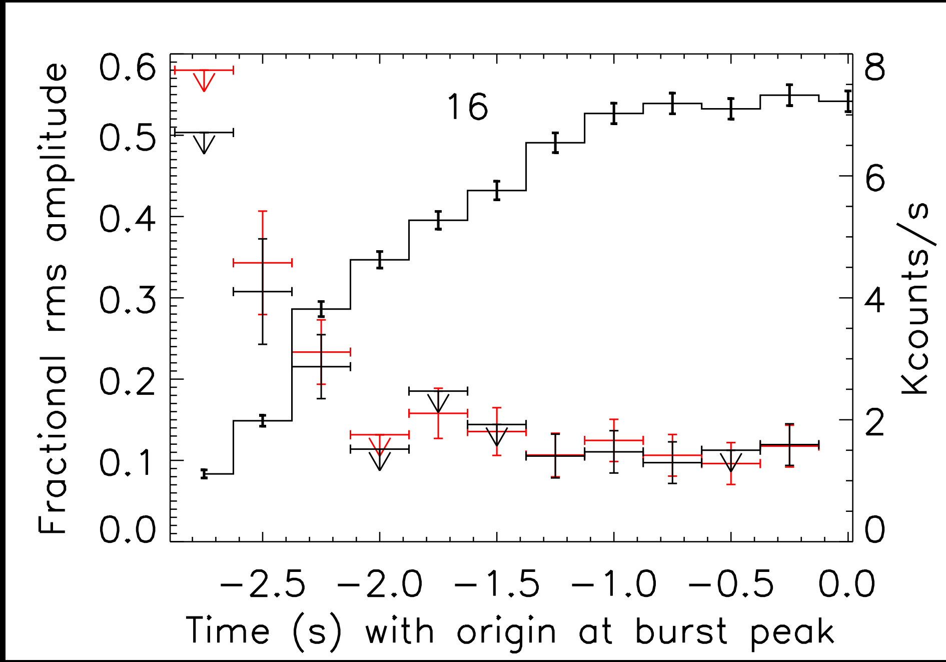
… see also in 't Zand, arXiv:1102.3345, Strohmayer & Bildsten 2003

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

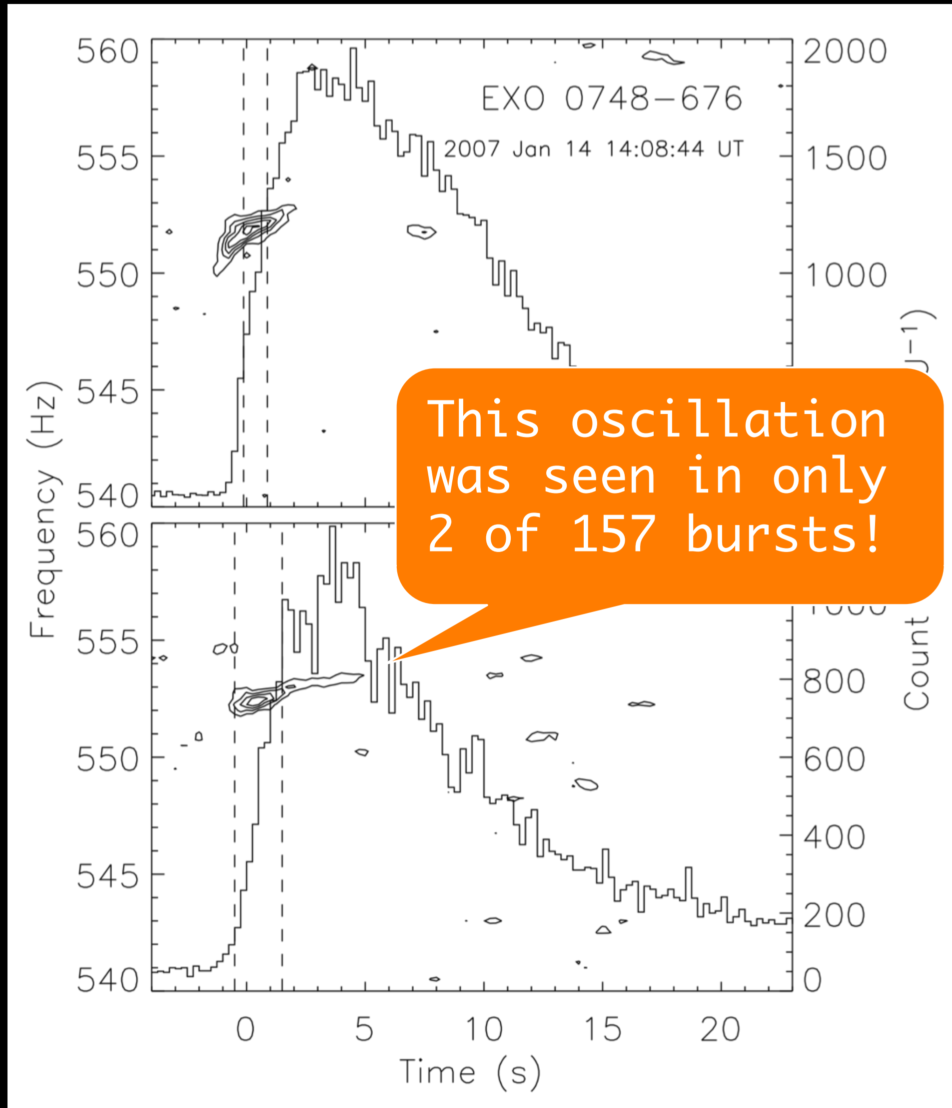


Chakraborty et al. 2014, arXiv:1407.0845

- Oscillations in the tail (present in the majority of bursts with oscillations) harder to understand
- Attempts to explain via r-modes etc…

A bleak future

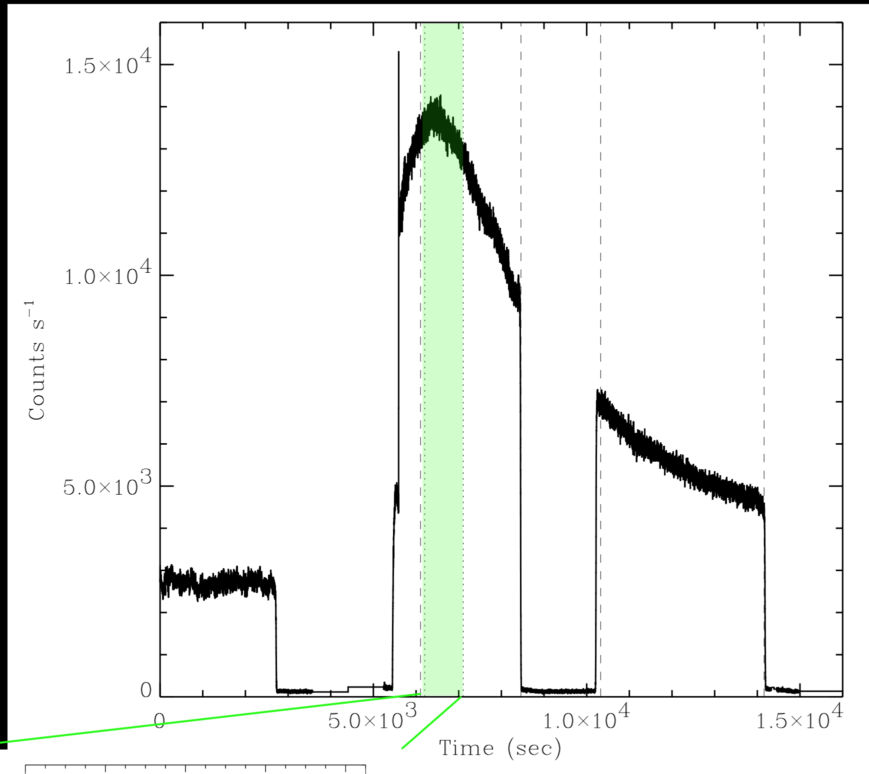
- *RXTE* end-of-mission (Jan 2012) crippled high-time resolution X-ray capability
- Archival searches?
- *XMM-Newton* can play a role, with 570 Hz timing limit & lower sensitivity (e.g. IGR J18245-2452)
- Future missions include *ASTROSAT* and *LOFT* (ESA ~~M3~~ M4 candidate, >2020)

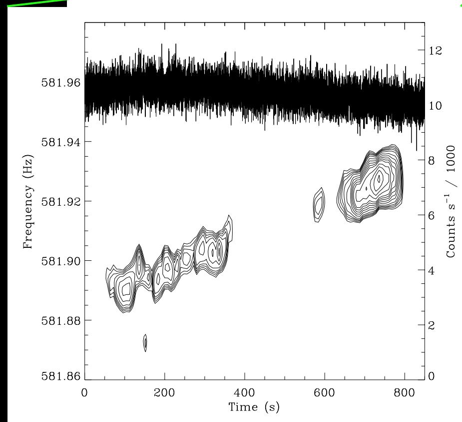


Galloway et al. 2010, ApJL 711, 148

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





4U 1636-536
Strohmayer & Marwkardt (2002), ApJ 577, 337

Zooming in on precursors

- *RXTE* data been analysed in more sophisticated ways to reveal photospheric radius-expansion in a superburst precursor
  Keek et al. 2012, ApJ 756, 130
- Calibrated propane layer data to circumvent loss of high-time resolution spectral data
- PRE phase unusually energetic -> detonation & shock heating?

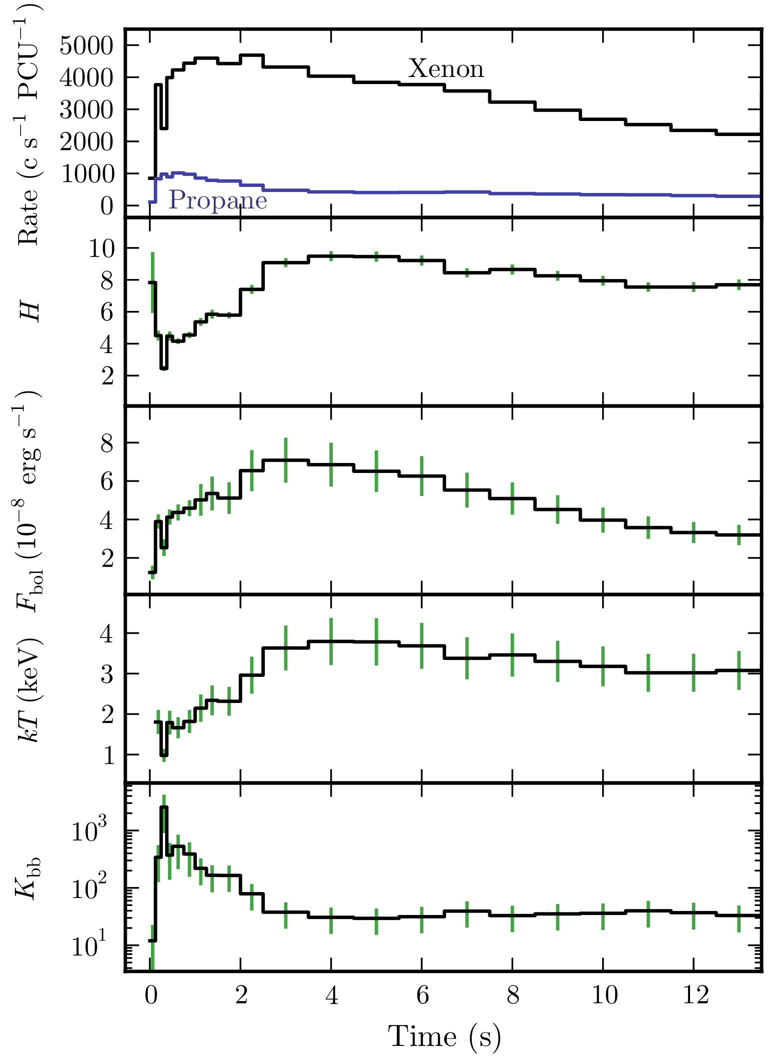
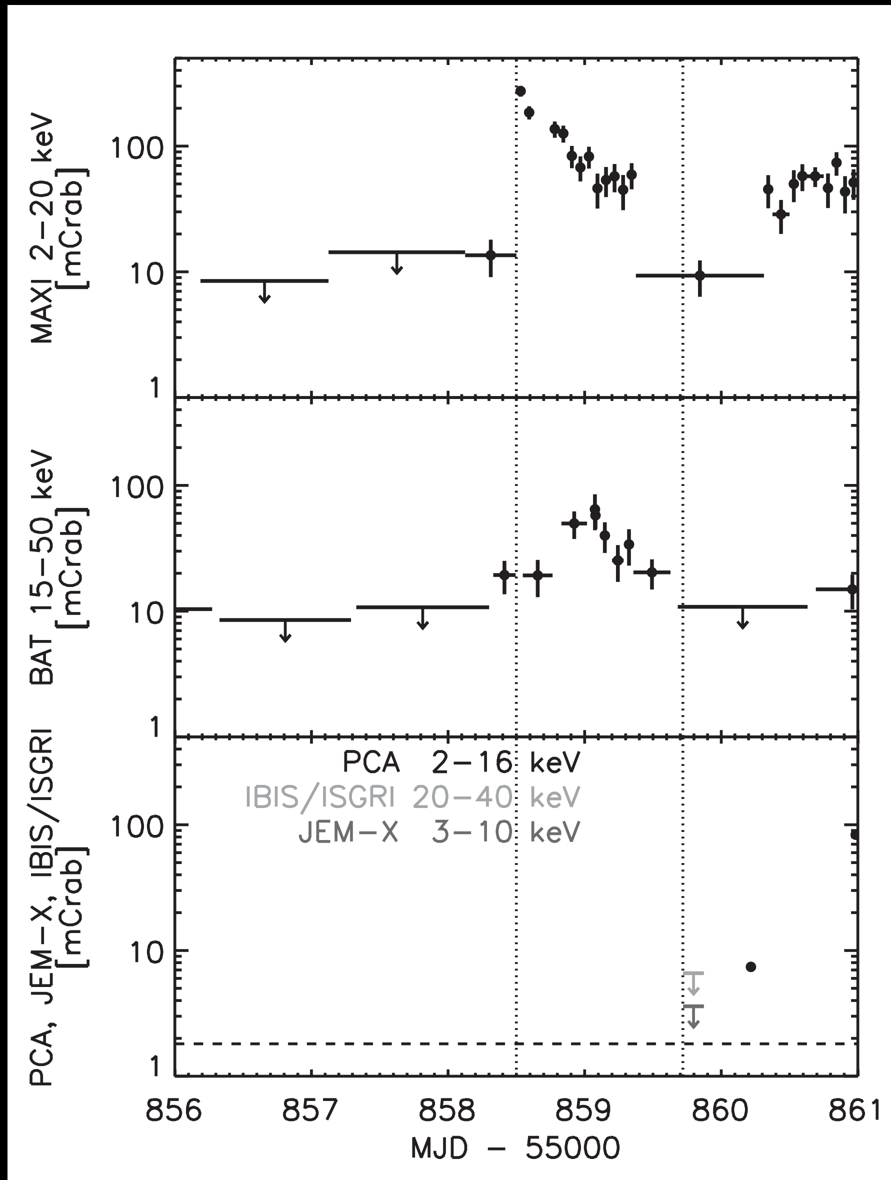


Figure 4. Similar to Figure 1 for the precursor of the 4U 1820–30 superburst.

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

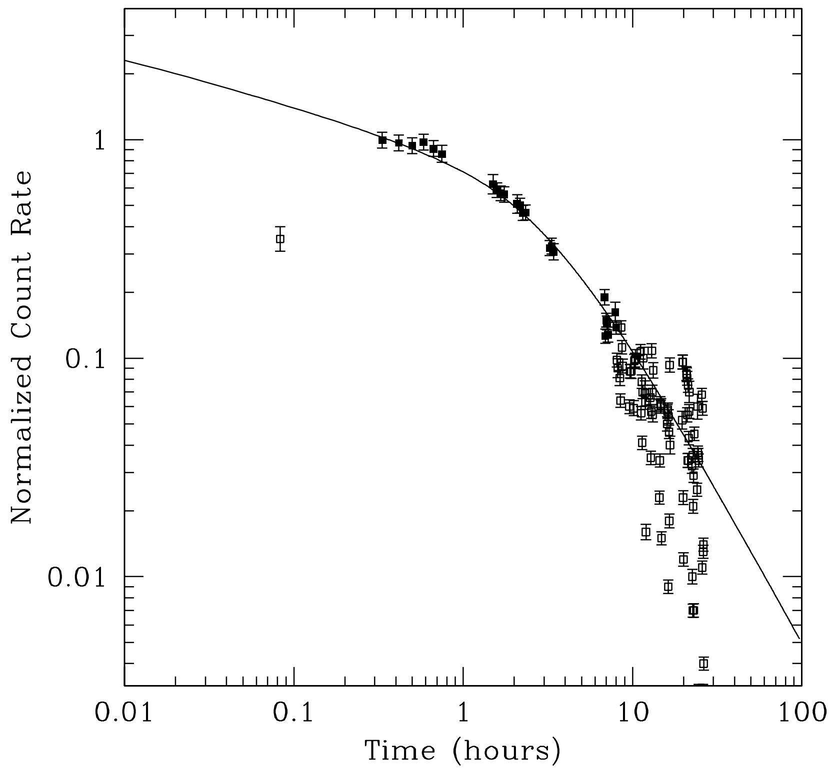


FIG. 5.—Fitted light curve for KS 1731−260, assuming the distance given in Table 1. Solid data points are included in the fit, open data points (with fluxes less than 0.1 of the peak flux) are not included.

Cumming et al. 2006

- 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
  Misanovic et al. 2010, ApJ 718, 947

3. NS parameters from burst spectra

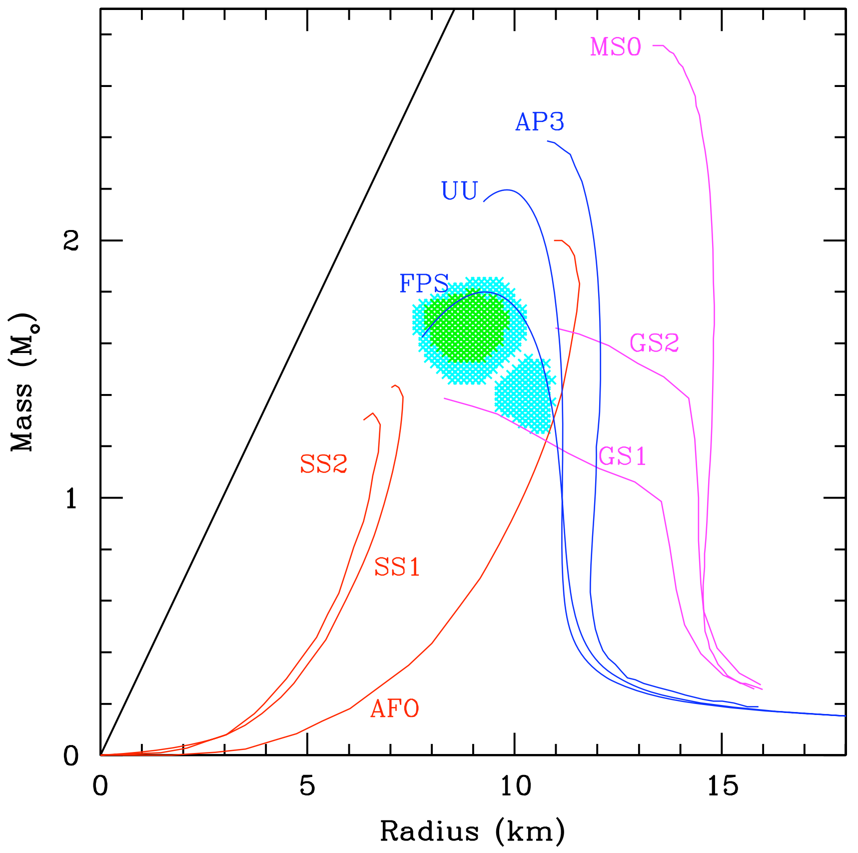
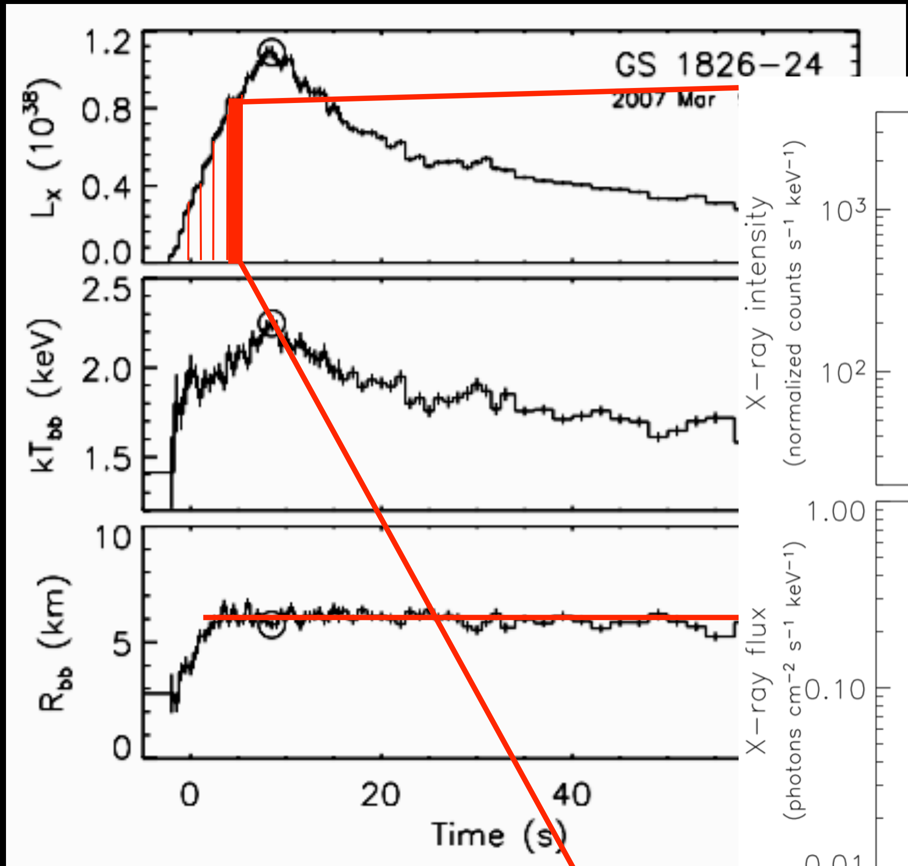


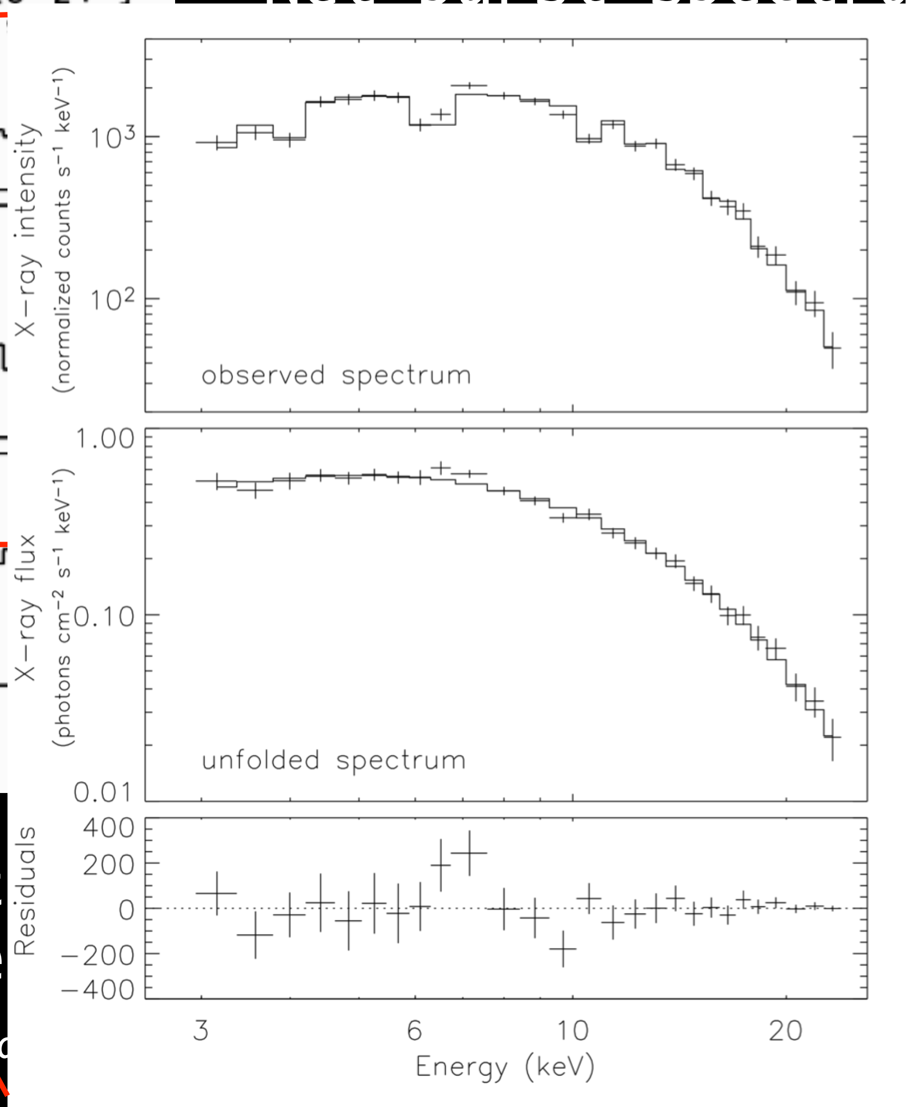
Figure 5. Plot of 1σ and 2σ contours for the mass and radius of the neutron star in EXO 1745−248, for a hydrogen mass fraction of $X = 0$, based on the spectroscopic data during thermonuclear bursts combined with a distance measurement to the globular cluster. Neutron star radii larger than $\sim$ 13 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).

Özel &c 2009, ApJ 693, 1775

- 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
  Steiner et al. 2010, ApJ 722, 33

Standard spectral analysis





- Net burst spectrum

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- The spectrum is t slightly; a corre ally applied (e.g. Madej et a

Issues for inferring *R*

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

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

  where *d* is the distance, and ξ 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
- Characteristic variation of R_{bb} also depends on persistent spectral state Poutanen et al. 2014, arXiv:1405.2663; Kajava et al. 2014, arXiv:1406.0322
- Observational evidence for a different type of f_c variation Galloway & Lampe 2012, ApJ 747, #75; see also Zamfir &c 2012, ApJ 749, #69

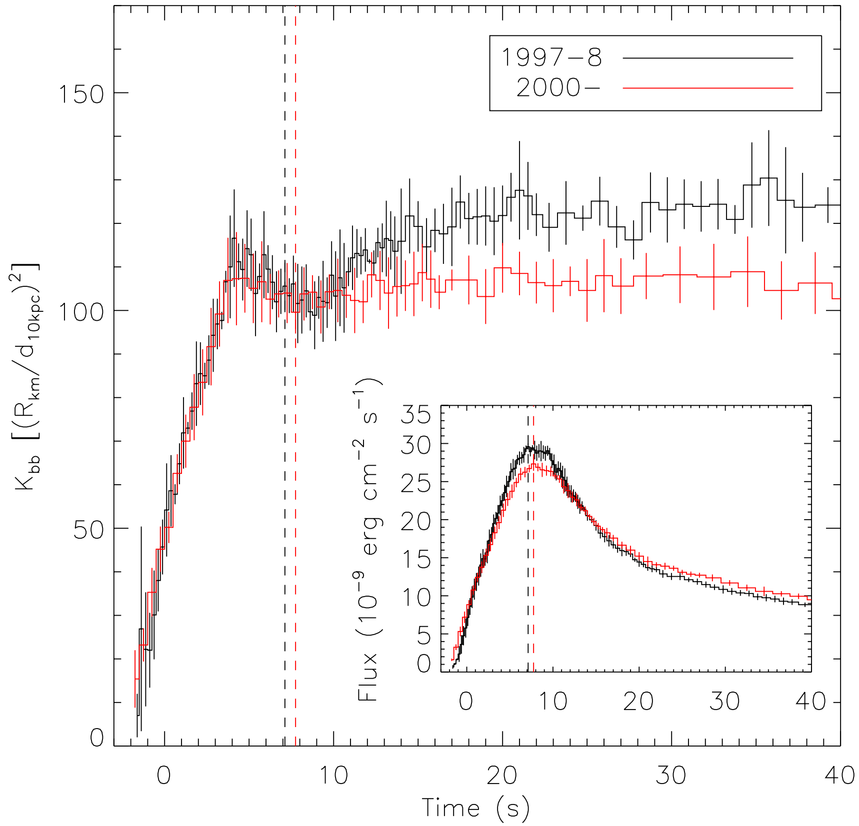


Figure 4. Comparison of averaged blackbody normalization profiles for bursts from GS 1826−24 measured in 1997–1998 (nos. 1–5 of G08) and 2000–2007 (nos. 9, 10, 11, 12, 13, 16, 17, 19, 20). The vertical dashed lines indicate the time of maximum flux for each set of bursts. Note the agreement in the normalization 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

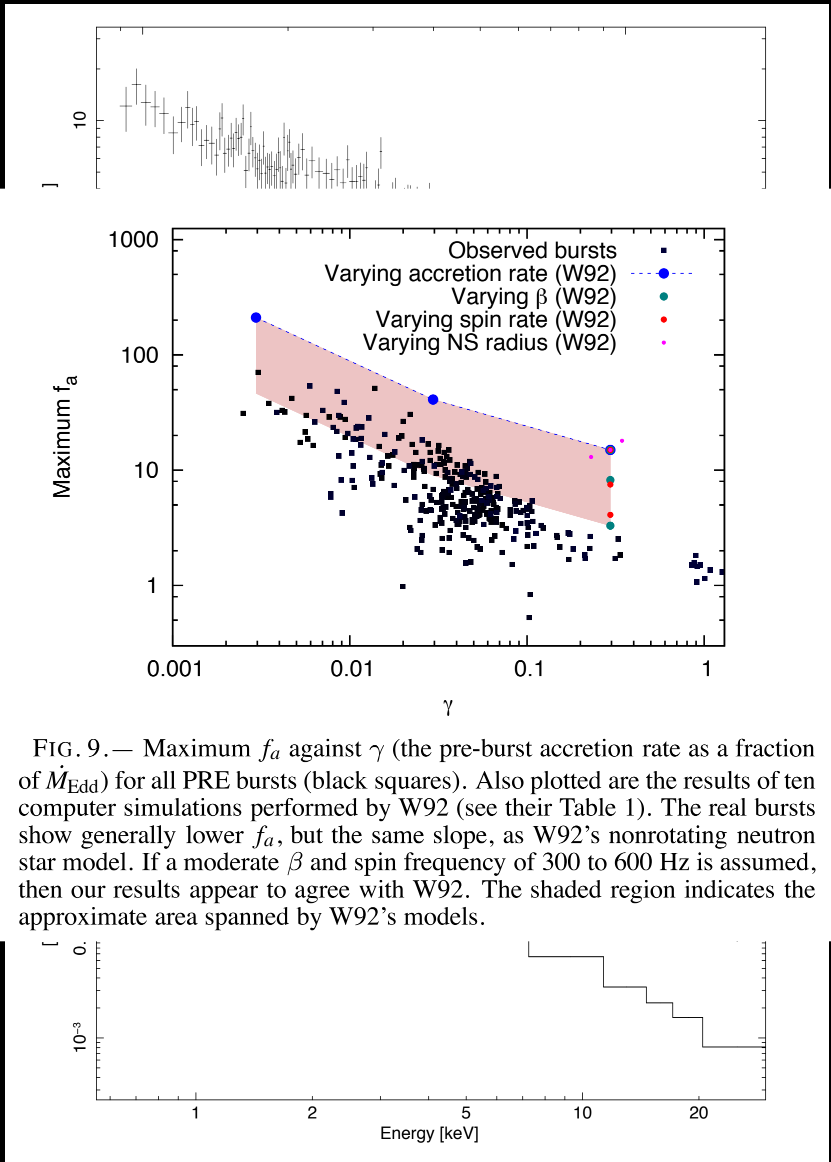


FIG. 9.— Maximum f_a against γ (the pre-burst accretion rate as a fraction of $\dot{M}_{\rm Edd}$) for all PRE bursts (black squares). Also plotted are the results of ten computer simulations performed by W92 (see their Table 1). The real bursts show generally lower f_a, but the same slope, as W92's nonrotating neutron star model. If a moderate β and spin frequency of 300 to 600 Hz is assumed, then our results appear to agree with W92. The shaded region indicates the approximate area spanned by W92's models.

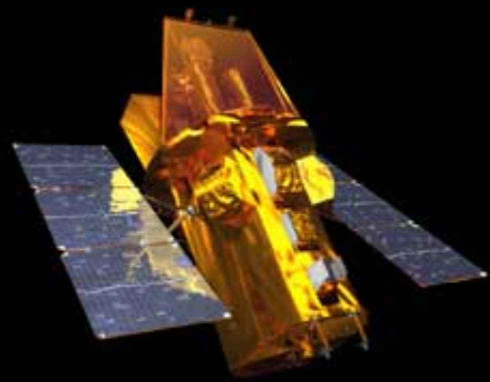
- Burst spectra are generally not well fit by blackbodies alone
- Joint *RXTE-Chandra* observations of a bright burst from SAX J1808.4-3658 suggest that the accretion rate *increases* during the burst

  In 't Zand et al. 2013, A&A 553, #A83
- Confirmed by comprehensive analysis of archival *RXTE* data

  Worpel et al. 2013, ApJ 772, 94

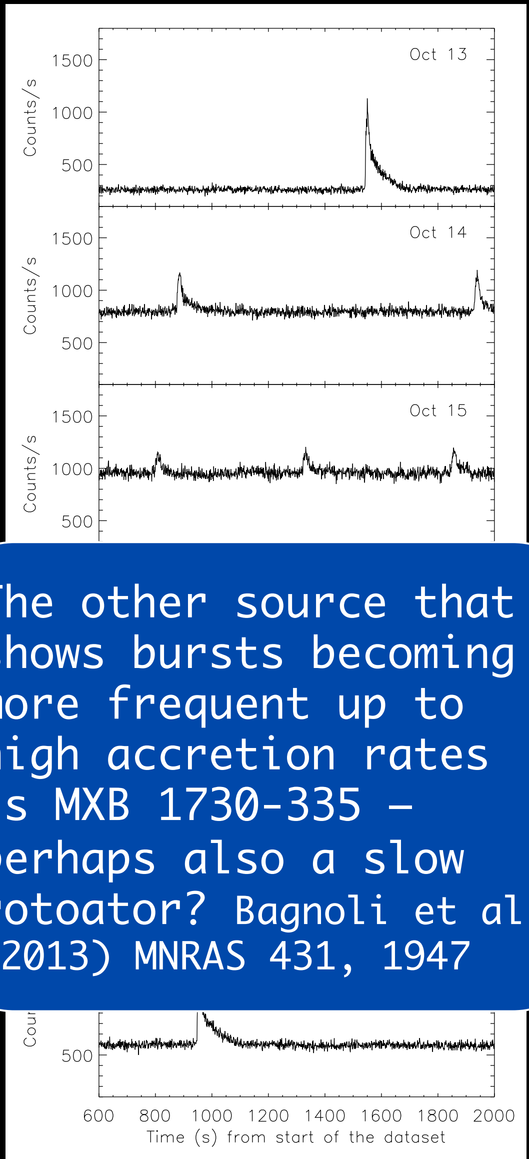
4. New sources

- 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



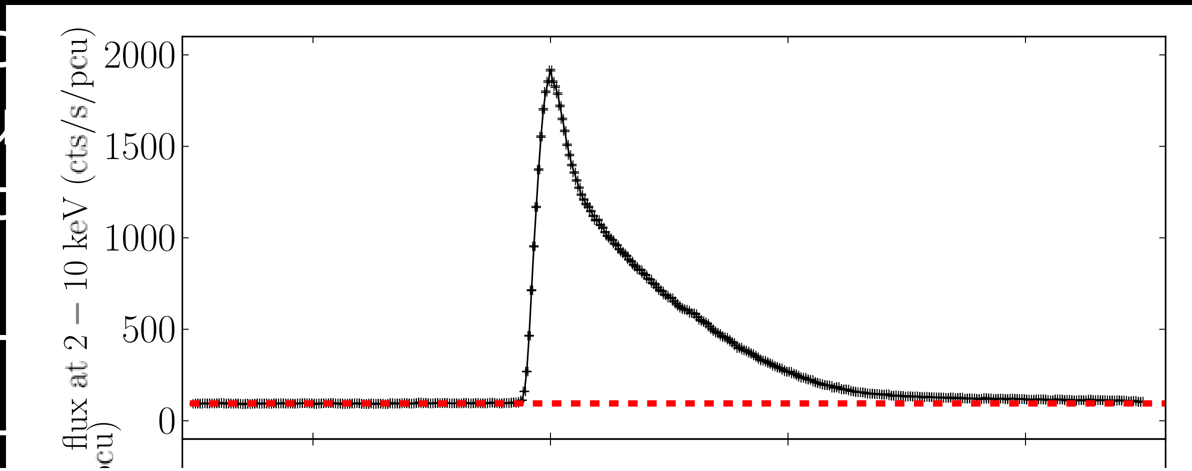
The other source that shows bursts becoming more frequent up to high accretion rates is MXB 1730-335 – perhaps also a slow rotoator? Bagnoli et al. (2013) MNRAS 431, 1947

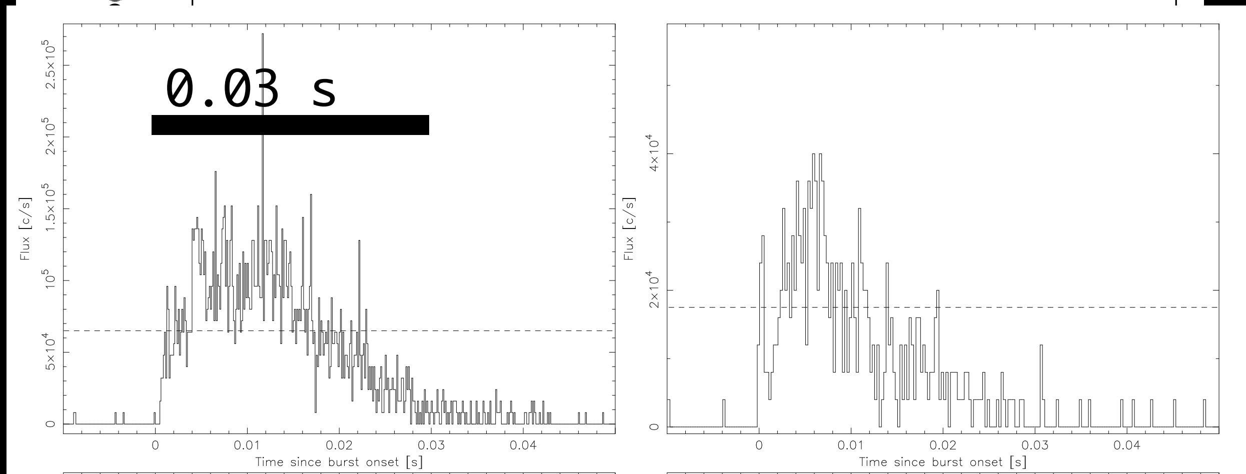
- A new transient outburst of a previously unknown globular cluster LMXB Atel #2919
- 11 Hz pulsations (<< typical freq); 21-hr orbit Atel #2919
- Bursts occurred more frequently as the luminosity approached Eddington -> quasi-stable burning
- First time this transition has been observed, although details 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.

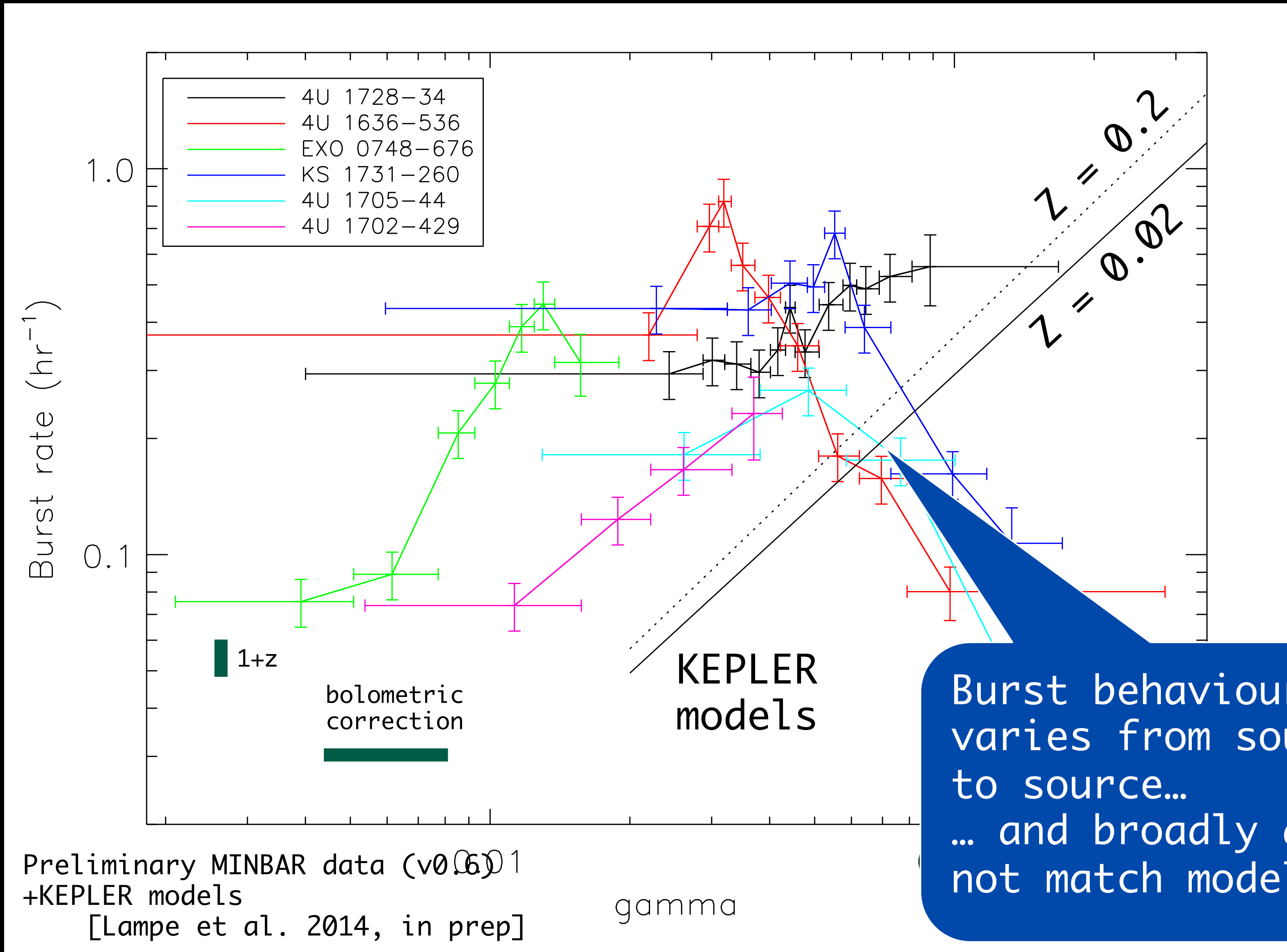
Other notable results

- Detection of high-energy deficit following bursts; e.g. Ji et al. 2014 ApJ 782, 40
- Analysis of c
  providing clu
  capacity of t
  A&A 562, A16
- Short, super-
  mildly relati
  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(?)

спасибо!