New constraints on thermonuclear bursts from the highest precision X-ray spectra

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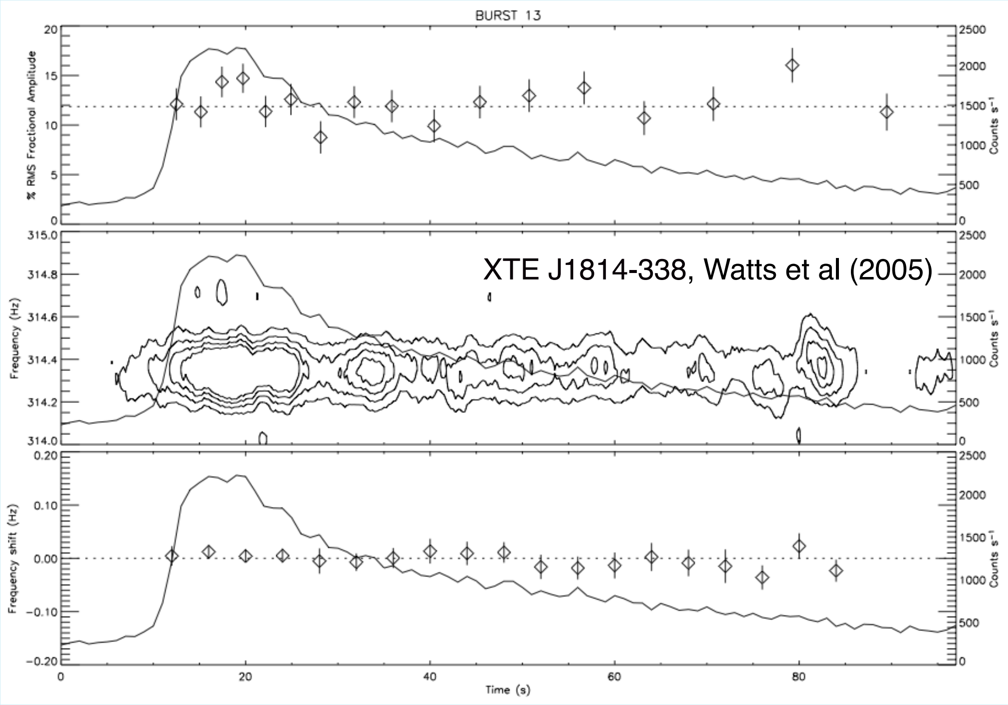
The story in brief

- Spectral modeling is a critical step in estimating neutron star masses and radii from X-ray bursts, e.g. from D, F_{TD}, T_{eff} or g, z
- We performed the first comparison of published spectral models, and Bose-Einstein models, with the best available RXTE measurements of burst spectra
- We found that B-E spectral models are consistent with the highest-precision RXTE spectral measurements
- In contrast, the most commonly used conventional-atmosphere spectral models are inconsistent with these measurements, calling into question inferences made using these models
- New atmospheric spectral models by Suleimanov et al. 2011 provide a better description of the data and show promise in constraining the composition
- Joint fits using such models may constrain the masses and radii of neutron stars via the dependence on gravitational redshift and surface gravity

Theoretical challenge of X-ray bursts

- 1D models of unstable thermonuclear burning have been able to explain the energetics and time scales of some bursts (e.g., Heger et al. 2002)
- Burst oscillations in every ~third burst reveal asymmetry in the nuclear-powered emission
- Oscillations phase locked and nearly identical to accretion-powered pulsations over whole burst:
- Recurrence time often too short to form a thick enough layer to burn over whole surface
- Emission from entire surface in tail still always assumed when deriving M & R constraints
- Degree of coverage of surface by burning is thus essential for understanding bursts and oscillations



Only method to constrain M & R without assuming the emitting fraction of the surface is by using the redshift and gravity from spectral fits (Majczyna & Madej 2005, Miller et al. 2011)

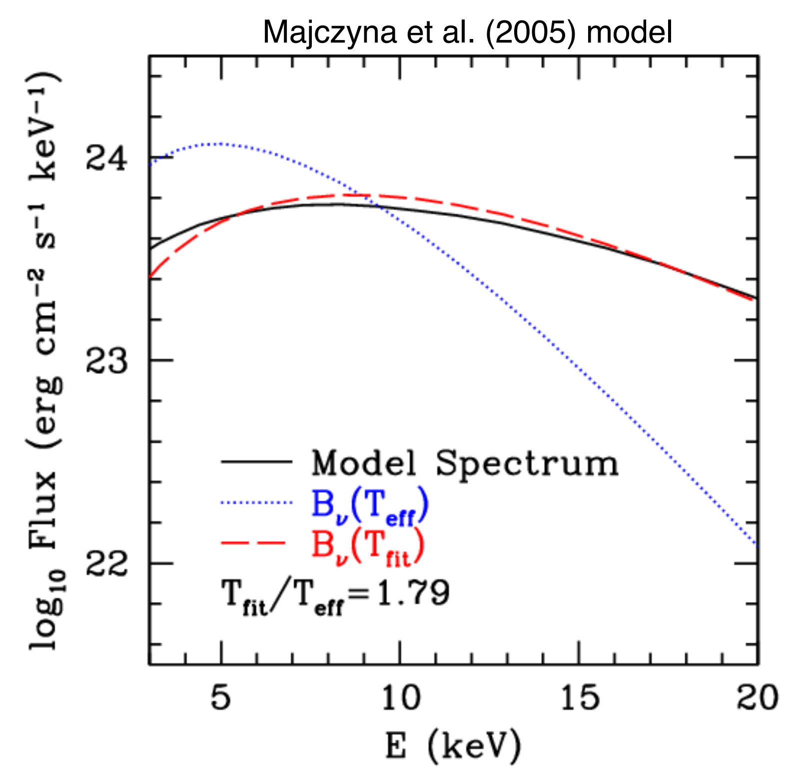
$$g = \frac{GM}{R^2}\left(1 - \frac{2GM}{Rc^2}\right)^{-1/2} \qquad 1 + z = \left(1 - \frac{2GM}{Rc^2}\right)^{-1/2}$$

Burst spectra

- The Planck function often fits burst spectra very well (Swank et al. 1977, Galloway et al. 2008)
- Saturated Comptonization in hot atmospheres can give a Bose-Einstein spectrum (Illarionov & Sunyaev 1975):

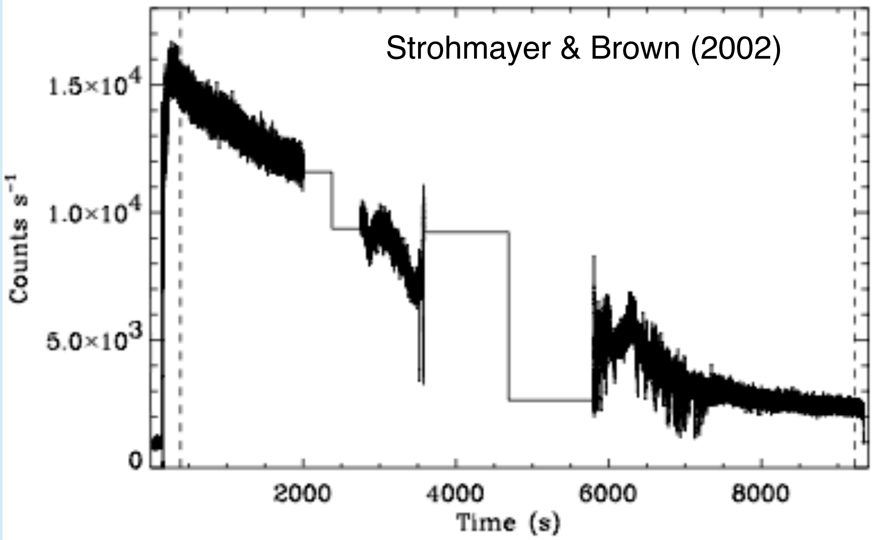
$$I(\nu, T) \sim \frac{1}{e^{(h\nu-\mu)/kT} - 1}$$

- Many spectral models (e.g., London 1984) have been computed assuming static, gas-pressure supported atmospheres, with a thickness ~1–10 m and a scale height of ~5 cm
- The peak of the spectrum occurs at a higher energy than for a Planck spectrum with the same surface flux ($T_{spectral}$>T_{eff}) because the back reflection of a fraction of the photons makes the emission inefficient
- The resulting spectral models have effective temperatures smaller than the temperature inferred from fitting a Planck function, by color factors ranging from f_c~1.3 (for 0.1<F/F_{Edd}<0.5) to ~2 (for F~F_{edd})
- The shapes of the model spectra deviate from the shape of a Planck spectrum at low and high energies



Testing burst spectral models

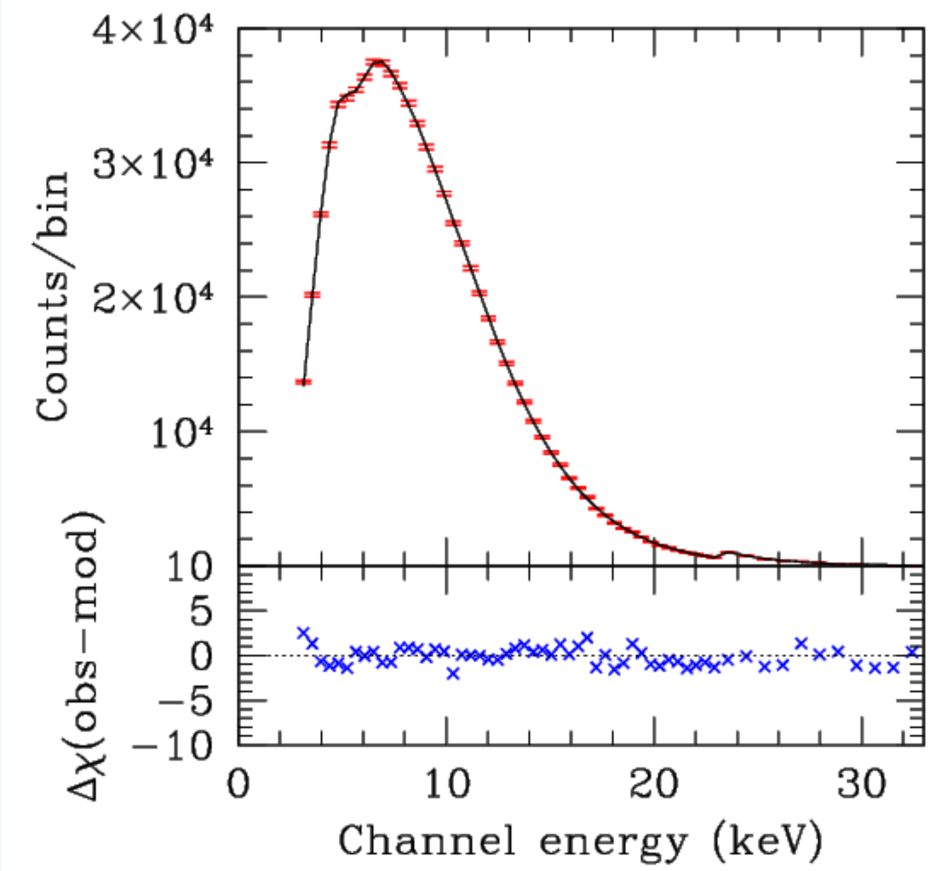
- Very few comparisons of models with burst data have been made previously (Foster et al. 1986), and not even most recent ones (Kusmierek et al. 2011) use data with enough counts to distinguish between qualitatively different spectral models (Planck, Wien, different atmospheric models, etc.).
- Only long stretches of data taken using the best current instrument (RXTE PCA) during intervals when the temperature is nearly constant can distinguish even very different spectral models.
- We found the optimal data length near the peak of the 4U 1820–30 superburst to be 64 seconds, which yielded ~ 900,000 counts. Data from a canonical ~100-s burst from GX 17+2 gave similar results.
- 4U 1820-30 is a neutron star in a compact binary thought to be accreting He from its companion star
- Although the nuclear processes in superbursts and canonical bursts are different, the burst atmospheres and spectra are the same.
- Fits to ~1 s segments show no evidence that the temperature changes on timescales less than tens of seconds



Bose-Einstein fit

$F(E,T) \sim E^3/[\exp((E-\mu)/kT)-1]$

Boutloukos, Miller, & Lamb 2010



- Subtracted background
- Included edge and Fe emission line at zero redshift
- Fitted data from 3–32 keV
- Detector flux ~ 90% of peak
- χ^2/dof = 55.8/50
- kT = 2.85 keV, μ = -0.76 keV

Fit is excellent!

B-E also fits the spectra measured at 100%, 80%, 25% of the peak detector flux

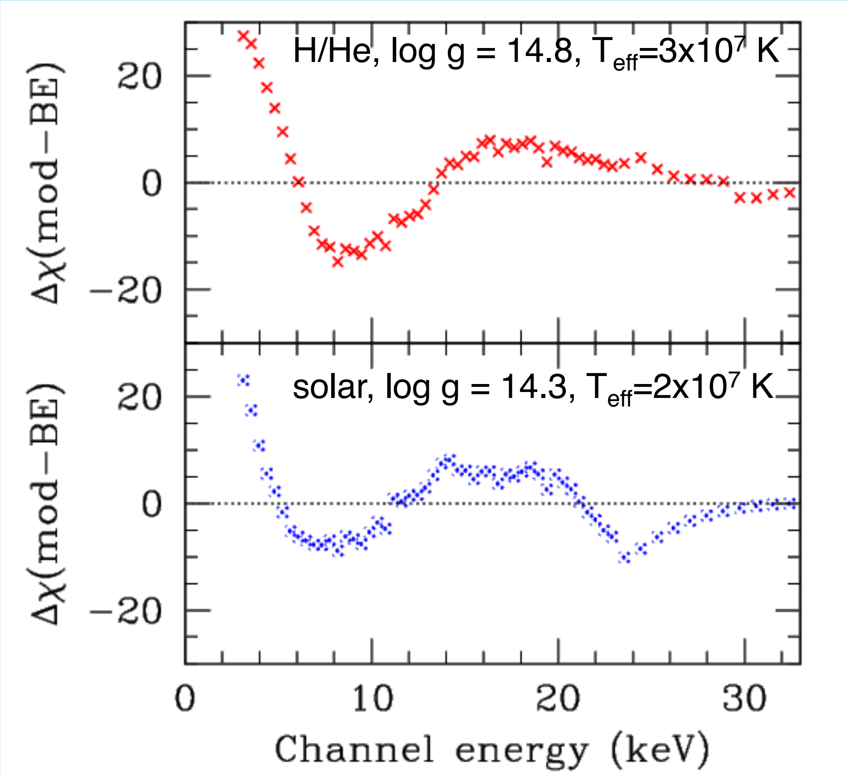
Conventional atmosphere models

Many are strongly disfavored

The Madej et al. (2004), Majczyna et al. (2005) grids are not fine enough for easy comparisons with data, but one can compare these models to known B-E shape of spectra.

The shapes of these model spectra typically deviate strongly (χ^2/dof>50), systematically, and similarly from the observed spectral shape, regardless of the gravity, composition, and temperature.

Comparison of the Majczyna et al. models to the shape of the spectrum in a 64-s segment at ~50% of the peak detector flux gave χ^2/dof=455.4/51. Best B-E fit gave 94.2/50.



Residuals for Madej et al ('04,'05) models

Fits of new models

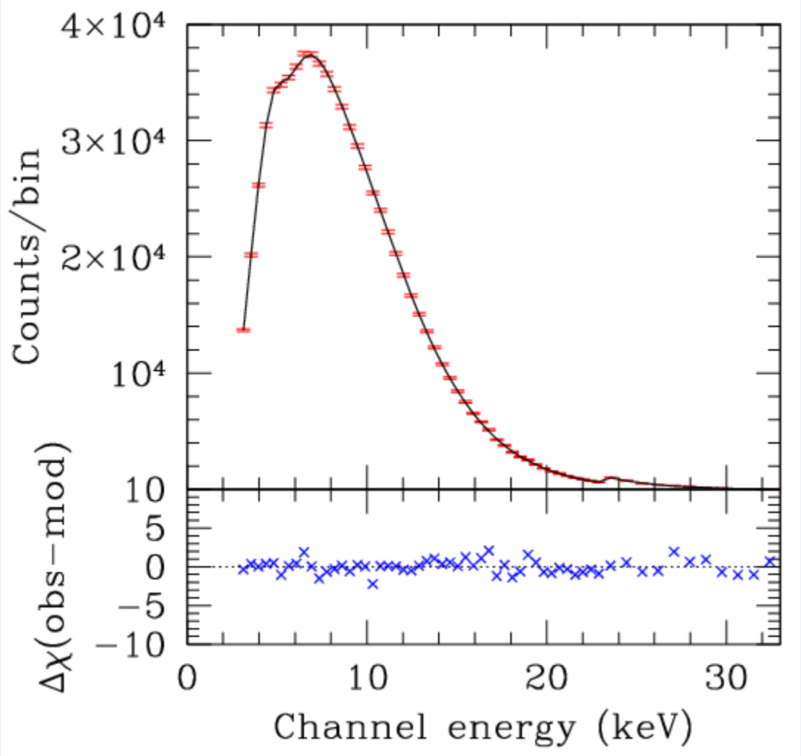
- Models from Suleimanov et al. 2011 may fit the data even better than B-E

  Best fit: χ^2/dof=42.3/48
  Best B-E fit: χ^2/dof=55.6/50

  Pure-He composition consistent with the tight binary orbit

- At half of peak detector flux, Suleimanov et al. 2011 model still does well:
  He: χ^2/dof=49.4/51
  solar: 61.2/51
  B-E: 94.2/50
  Best Majczyna et al. (solar): 455.4/51

64-second segment at peak temperature



Pure He, log g = 14.3, F=0.95F_{Edd}
Model from Suleimanov et al. 2011

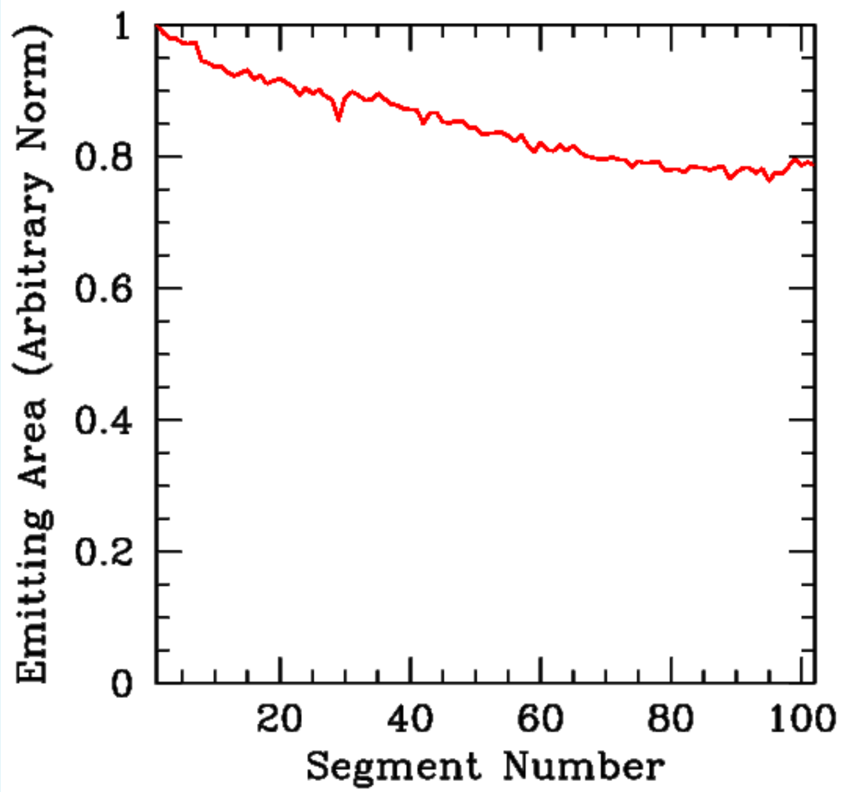
Note: shorter (e.g., ~1-s) segments of this same data can be fit by many very different spectral models; long data segments are needed to discriminate between different models

Joint fits

in collaboration with Suleimanov & Poutanen

- There are ~1600 s of clean data near the peak of 1820 superburst
- If atmosphere is on surface for the entire time, we should be able to find a joint fit with constant g, z
- Markov Chain Monte Carlo fits indicate that (1) formally good fits exist and (2) these are much better than B-E fits
- The fitted emitting area changes systematically; thus constraints derived using the van Paradijs method and color factors are still questionable
- Joint fits give z to three significant digits; g is less constrained
- Must treat systematics carefully (models, spatially uniform temperature, etc.)
- Now comparing the data to a new set of models with relativistically correct treatment of scattering
- Source distance and absolute flux calibration are irrelevant when using this method

Sample fit: z=0.535, log g = 14.6



χ^2/dof=5394.0/5200; best B-E: 5660.2/5100

A new emerging picture

- Burst emission can come from a varying fraction of the NS surface (this work)
- Recurrence times and accretion rates in 4U 1728–34 are too small to produce the expected ignition column depth over the whole star (Misanovic et al. 2010)
- The observed similarity and phase-locking of nuclear- and accretion-powered oscillations in some APMSPs suggests that the emitting regions during bursts are similar to the accretion-powered hot spots (Lamb et al. 2009)
- Burst oscillations from the 11 Hz accretion-powered pulsar in Terzan 5 exclude confinement by the Coriolis force (Cavecchi et al. 2011)
- The tangled magnetic field produced by turbulent convention during bursts could confine the burst atmosphere (SB, Miller, & Lamb 2010)

Conclusions

- We have made the first comparisons of model predictions with high-precision RXTE spectra
- These measured spectra are inconsistent with the most commonly used model spectra but are consistent with B-E spectra
- New spectral models by Suleimanov et al 2011 show great promise, but also indicate that the emitting area changes during a burst
- Constrains on M&R may still suffer from systematics
- Together with Suleimanov and Poutanen we are engaged in joint fitting of ~1600 s of data to models with relativistically correct treatment of scattering, to constrain the chemical composition, as well as g and z