Using Thermonuclear Burst Spectra to Constrain NS Masses and Radii

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in collaboration with

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The analysis described here was only possible with the unique capabilities of the Rossi X-ray Timing Explorer

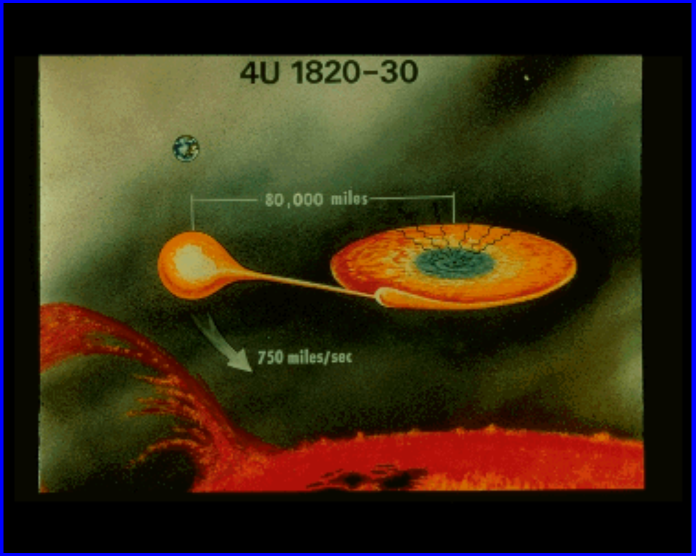
The Story in Brief

- Spectra from bursts might constrain neutron star M and R.
- No lines confirmed; must use continuum spectra, and must verify that those spectra are consistent with the best RXTE data.
- But we found that the most commonly used atmospheric spectral models are *inconsistent* with these measurements.
- New atmospheric spectral models must be developed and verified; initial work with the models of Suleimanov et al. shows great promise.
- Hope is that g, z can both be constrained, thus constraining M, R without the extra assumptions needed in standard approach.
- Caveat: good fit does not guarantee that physics and assumptions are correct!

(See Boutloukos, Miller, Lamb, ApJL, 2010)

Thermonuclear X-ray Bursts

- NS in binary accretes mass from companion
- Layer can become unstable to nuclear burning, lead to flash
- Helium ignition: duration of ~seconds
- Carbon (probably) superburst: ~hours
- But in either case the *spectrum* depends only on the surface layers



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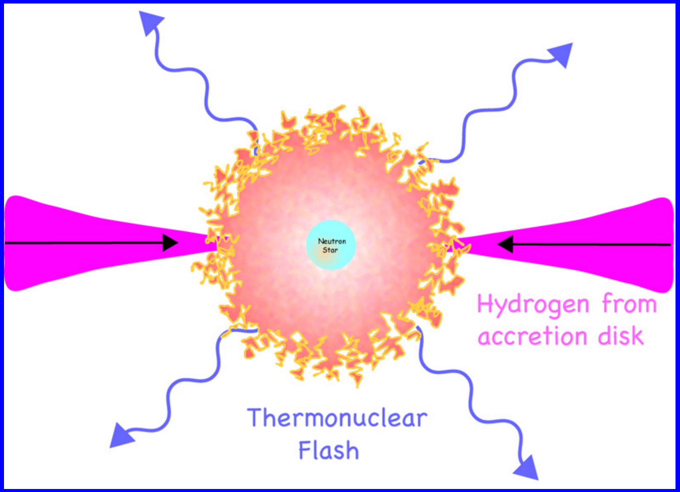

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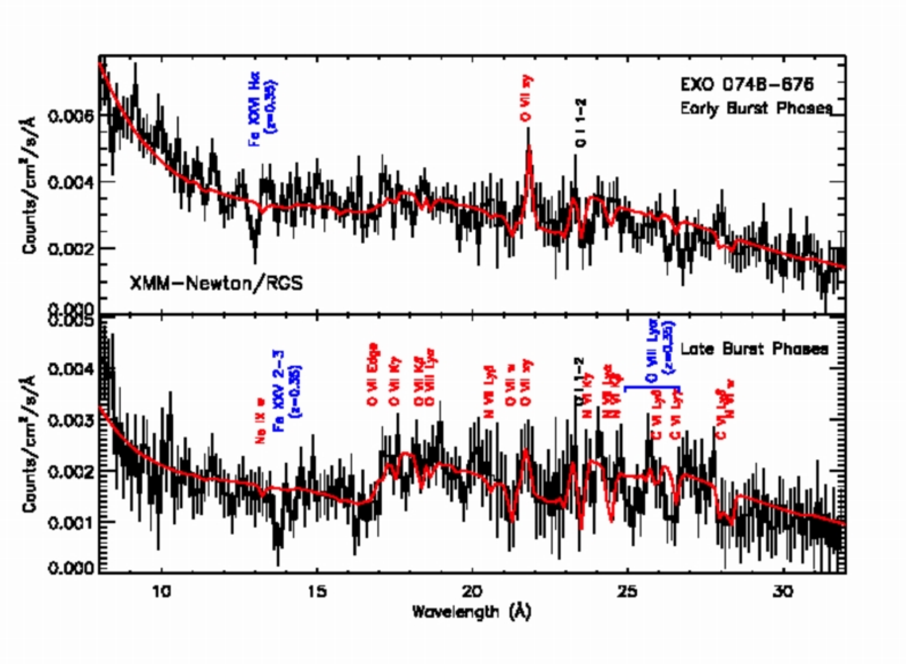
The Lack of Lines

- Identified surface atomic lines would immediately give z
- But H, He completely ionized, and heavier elements sink in seconds
- Continuous heavy element supply in burst sources? Maybe, but no confirmed lines
- Have to work with continuum



EXO 0748 spectrum, from Cottam, Paerels, and Mendez 2002. The z=0.35 lines were not confirmed in a later observation, but the source was in a different state. ν=550 Hz rotation makes sharp lines unlikely.

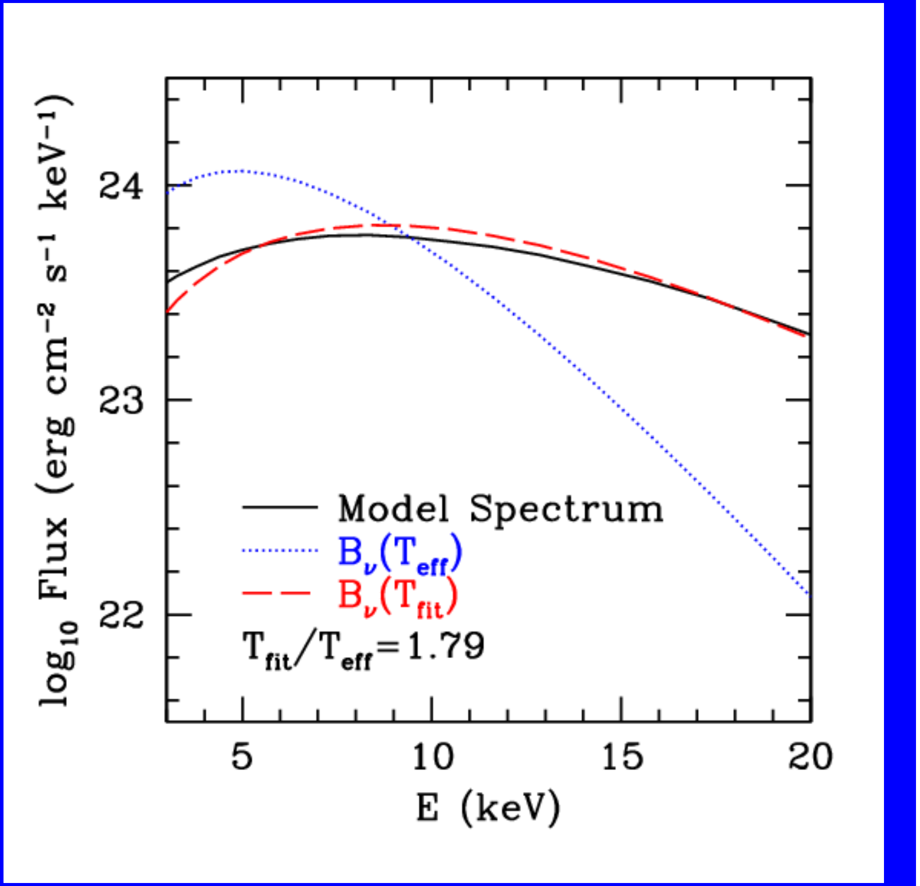
The Van Paradijs Method

- Unlike lines, which can often be interpreted directly, continuum spectra usually require ancillary assumptions
- Van Paradijs (1979) suggested a few:
  Assume whole surface burns uniformly
  Assume we can tell when $L=L_{Edd}$
  Assume we have measure of distance
  Assume we have correct model spectra
- Then we have enough info to get M, R
  Recent work by Ozel, Guver, et al.
  But systematic errors can be significant!

Conventional Atmosphere Spectral Models Prior to Our Work

- The peak of the spectrum occurs at a higher energy than for a Planck spectrum with the same surface flux.
- The spectral temperature is therefore higher than the effective temperature.
- The shape of the spectrum deviates from the shape of a Planck spectrum, especially at low energies.

Majczyna et al. 2005 Model



Testing Burst Spectral Models

- Very few previous comparisons have been done with burst data (Foster et al. 1986), none using data with enough counts to distinguish between qualitatively different spectral models (Planck, Wien, different atmospheric models, etc.).
- Only long stretches of data taken with the best instrument (the RXTE PCA) during intervals when the temperature is nearly constant can distinguish 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 ~ 800,000 counts. Data from a canonical GX 17+2 burst gave similar results.
- We fit this optimal 1820 data with a Bose-Einstein spectrum, and with a conventional model atmosphere spectrum

Results from 4U 1820–30 Analysis

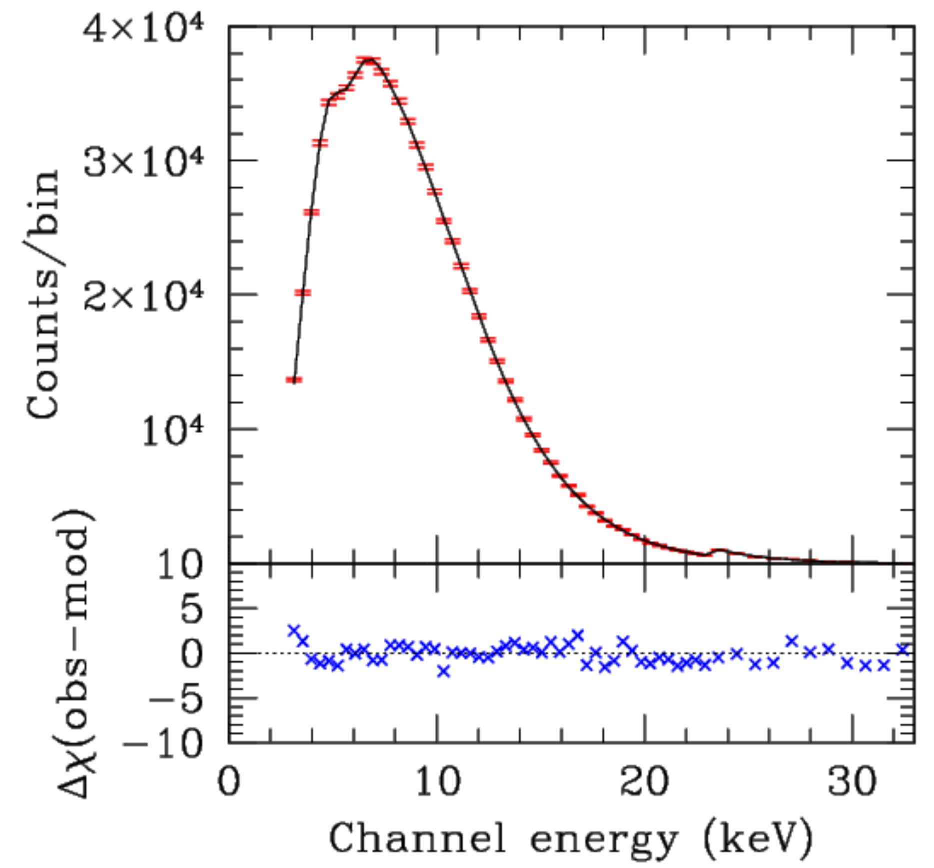
B-E: $F(E,T) \sim E^3/[\exp((E-\mu)/kT)-1]$

After Boutloukos, Miller, Lamb 2010

- Fe emission line included at zero redshift (obvious in data)
- Fit 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 measured spectra at 100%, 80%, 25% of peak detector flux.



The Spectrum Modeling Challenge

- Why are high-flux spectra so close to B-E ?
- Why are B-E chemical potentials so much smaller than kT?
- Lamb + Lo : at high fluxes, extended atmospheres with appropriate densities (low enough that scattering dominates, not so low that photons cannot be supplied at the required rate) can produce Bose-Einstein spectra with small chemical potentials. Are requirements met in realistic models?

Implications of These Results

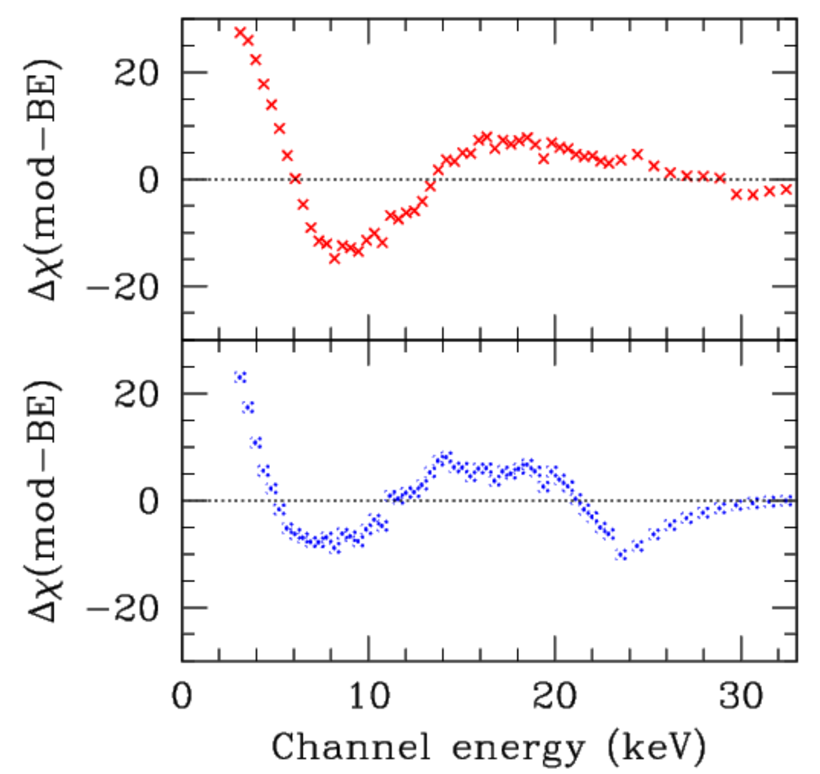
- Surprising result: Bose-Einstein spectra provide excellent descriptions of the highest-precision X-ray burst measurements
- Emission efficiency is unknown. Could be high, implying $F>F_{Edd}$, or low; very different consequences.
- To draw definite conclusions, need conventional atmospheric spectra to fit much better than B-E; can’t happen for single segment, because $\chi^2/\mathrm{dof} \sim 1$ for B-E spectral models.
- But how well do alternative models fit the highest-precision spectrum measurements?

Analysis of Other Spectral Models

The most commonly used models are by Madej et al. (2004), Majczyna et al. (2005). Grids are not fine enough for easy direct comparisons with data, but can compare to known B-E shape of spectra.

Find that shapes of these model spectra typically deviate strongly, systematically, and similarly from the observed spectral shape, regardless of gravity, composition, and temperature.

Residuals for two other models



Top: H/He, log g = 14.8, T_{eff}=3x10^7 K from Madej et al. 2004 [F=0.8 F_{Edd}]

Bottom: solar, log g = 14.3, T_{eff}=2x10^7 K from Majczyna et al. 2005 [F=0.5F_{Edd}]

Implications of These Results

- The most-used model atmosphere spectra are inconsistent with high-precision measurements: Are these not for the relevant conditions? Might the physics or solution methods be problematic? Being explored by Suleimanov+Poutanen, Madej+Majczyna groups to resolve discrepancies
- Spectral models that are inconsistent with the best data may introduce systematic errors in estimates of neutron star masses and radii
- Do there exist models consistent with the data?

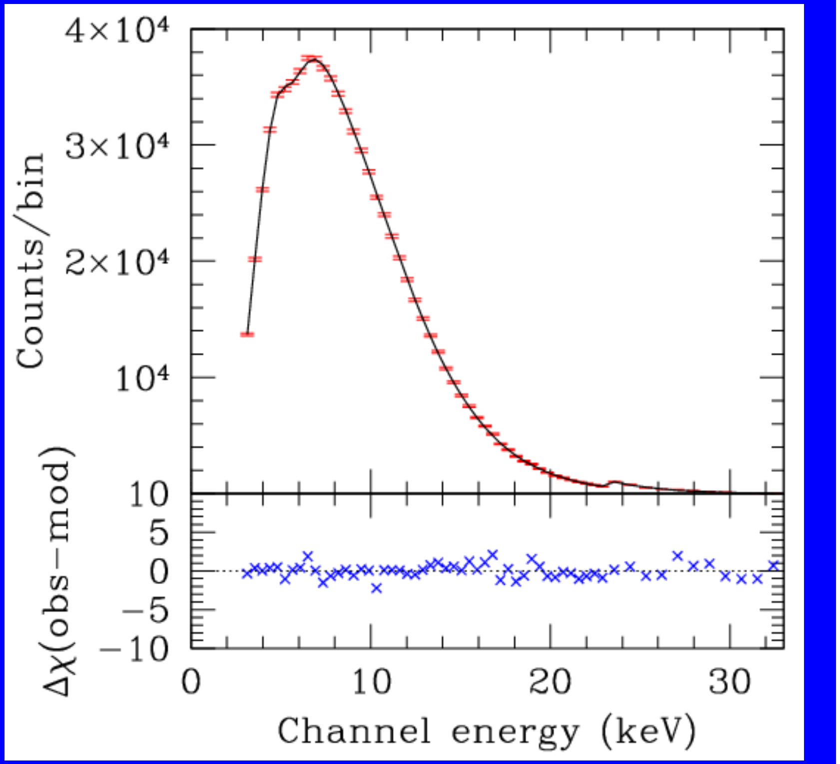
Fits of New Models

Yes! New models from Suleimanov et al. 2010 do seem to fit the data quite well.

This model has $F=0.95F_{Edd}$
Best fit: χ^2/dof=42.3/48
Best B-E fit: χ^2/dof=55.6/50

Note: published models use a simplified scattering treatment

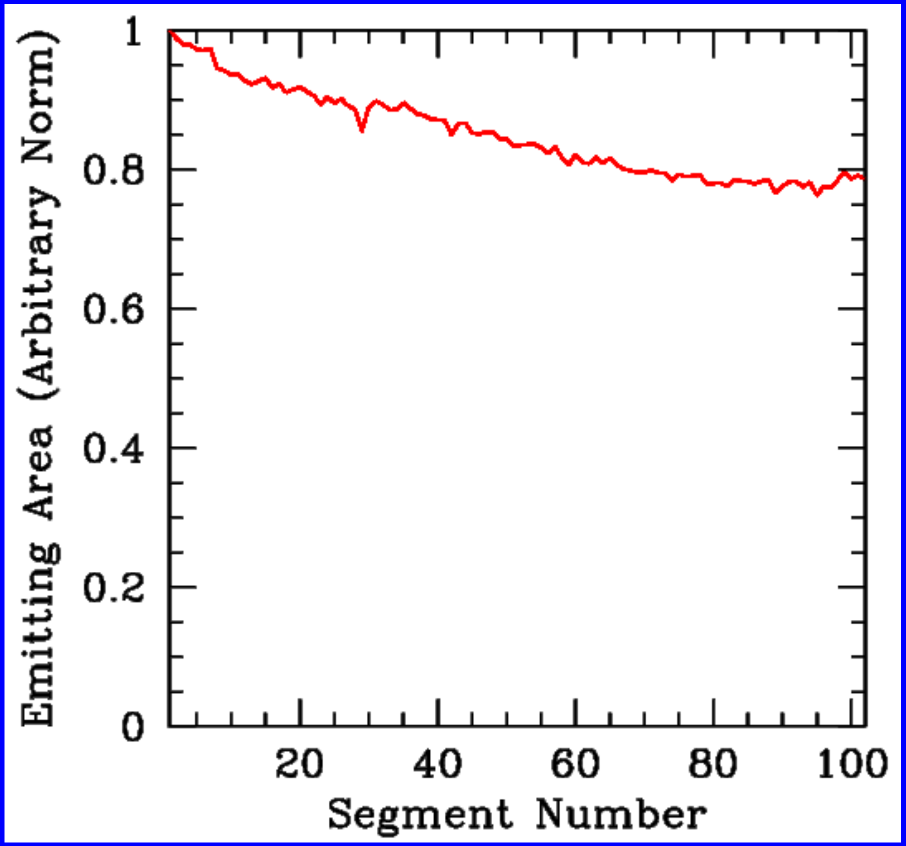
64-second segment at peak temperature



Pure He, log g = 14.3, $F=0.95F_{Edd}$
Model from Suleimanov et al. 2010

Use of New Models

- So is it a simple matter of using the color factors from the new models, with the van Paradijs method?
- Unfortunately, no
- Fitted emitting area changes systematically (even assuming g, z constant, so photospheric radius is constant)



Inferred relative emitting areas, for 102 16-s segments near the peak of the 1820 superburst

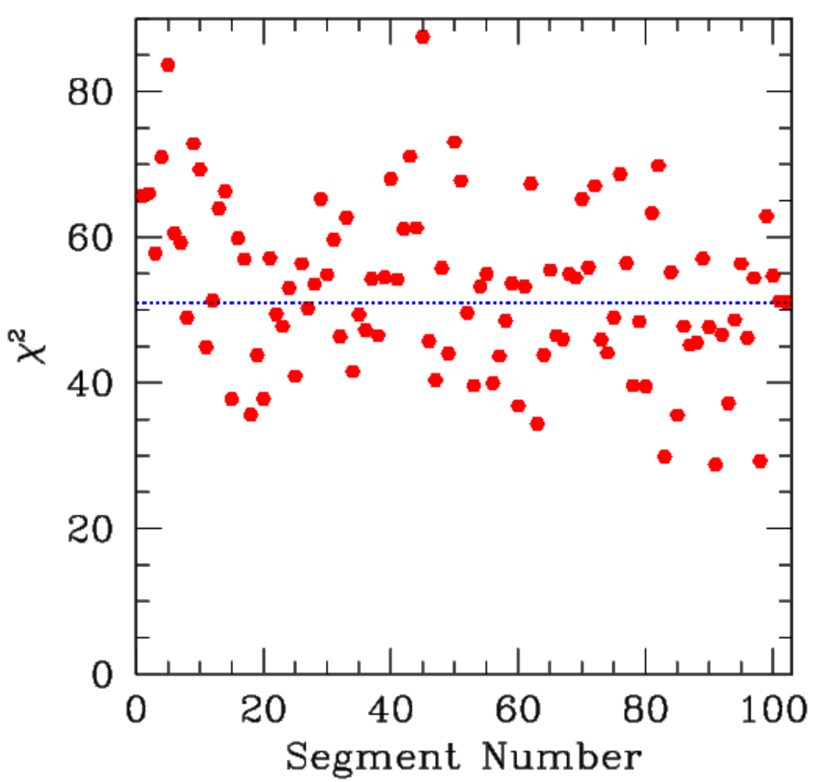
Additional Caveat

- As pointed out by Güver et al. (2010) and in more detail by Steiner et al. (2010), need to push observables to highly unlikely values to get consistent M, R using standard assumptions.
  E.g., only fraction 1.5×10^{-8} of input parameters allow any M, R solution for 1820.
- This might suggest that those underlying assumptions (const area, etc.) are incorrect
- So how can we profit from the promising fits of data using the newer models?

A New Approach

- There are ~1600 s of clean data near peak of 1820 superburst
- If atmosphere is on surface for the entire time, should be able to find a joint fit with constant g, z
- Preliminary fits indicate that (1) formally good fits exist, and (2) these are much better than B-E fits
- g and z give M and R!
  Majczyna and Madej 2005
- Must treat systematics carefully (models, spatially const temp, etc)
- Work in progress with Suleimanov and Poutanen; new relativistic scattering models

Sample fit: z=0.535, log g = 14.6



χ^2/dof=5394.0/5200

Best B-E: 5660.2/5100

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 show great promise, but also indicate changing emitting area during burst
- We are engaged in joint fitting of ~1600 s of data, to constrain g and z and thus M and R
- Caveat: good fit does not guarantee that physics and assumptions are correct!