HIGH RESOLUTION PHOTOSPHERIC SPECTROSCOPY of NEUTRON STARS

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1. Introduction; some fiducial numbers
2. Spectroscopy of isolated NS
3. Spectroscopy of X-ray bursts in EXO 0748-676

Physics & Astrophysics of Neutron Stars, Santa Fe, July 29, 2003

1. INTRODUCTION

Neutron Star Mass and Radius:

- orbital dynamics binaries : M
- fast variability XRB
- absolute flux and luminosity
  ($f_\nu = F_\nu (R/D)^2$) : R(M)
- photospheric spectroscopy R, M

photospheric spectroscopy:

high resolution, high sensitivity
with diffraction grating spectrometers
on Chandra and XMM-Newton
(required)

→ chemical composition
surface temperature (T_{eff})
gravity at surface
spin rate
magnetic fields
gravitational redshift

SOME FIDUCIAL NUMBERS :

① T_{eff} : isolated NS : $10^5 - 10^6$ K
X-ray bursters : $\sim 10^7$ K

② photospheric density :
hydrostatic equilibrium, fully ionized H,

at $\tau_{es} = 1$:

$$n_e = \frac{\mu m_p g}{\sigma_T k T} = 3 \times 10^{23} \mu M_{1.4} T_7^{-1} R_6^{-2} \text{ cm}^{-3}$$

within two orders of solid density!
→ non-ideal effects

③ composition : effects of rapid diffusion in strong gravitational field.

$$\tau_{e.s.} = 1 : \ l \sim \frac{1}{n_e \sigma_T} \sim 15 \, n_{23}^{-1} \text{ cm}$$

$$t_{diff} \sim l / v_{diff} \sim 15 \, n_{23}^{-1} v_1^{-1} \text{ sec}$$

⇒ rapid stratification!
⇒ pure surface composition (H, He, whatever)

In accreting sources: trace abundance:

$$\frac{A_{photo}}{A_{accr}} = \frac{\dot{M}}{\dot{M} + 4\pi R^2 n m_p V_{diff}}$$

$$\rightarrow \dot{M}_{crit} = 4\pi R^2 n m_p V_{diff} =$$

$$= 2\times10^{12}\, n_{23} V_1 R_6^2 \ \text{gr s}^{-1}$$

$$\Rightarrow L_{crit} = \frac{G M \dot{M}_{crit}}{R} =$$

$$= \underline{4\times10^{32}}\, M_{1.4}\, n_{23} V_1 R_6 \ \text{erg s}^{-1}$$

$$\begin{cases} L > L_{crit} : A_{photo} \sim A_{accr} \\ L < L_{crit} : A_{photo} \rightarrow 0 \,! \end{cases}$$

compare:

$$L_{photo} = 4\pi R^2 \sigma T_{eff}^4 =$$

$$= \underline{8\times10^{32}}\, R_6^2 T_6^4 \ \text{erg s}^{-1}$$

Need $T \gg 10^6$ K : <u>X-ray bursts</u>

PHOTOSPHERIC SPECTROSCOPY

1. gravitational redshift: trivial
2. DENSITY sensitivity of absorption spectrum: STARK effect

order of magnitude:

Lyα, ion Z, non-relativistic:

Stark shift $\Delta E = 3 a_0 e |\vec{E}| / Z$

electric field

substitute nearest-neighbor field:

$$\Delta E = 6 \left(\frac{4\pi}{3}\right)^{2/3} \frac{a_0 z e^2}{Z} n_{pert}^{2/3}$$

(z: perturber charge
n_{pert}: " density)

$$\Rightarrow \Delta E = \frac{163}{Z} M_{1.4}^{2/3} R_6^{-4/3} T_6^{-2/3} \text{ eV}$$

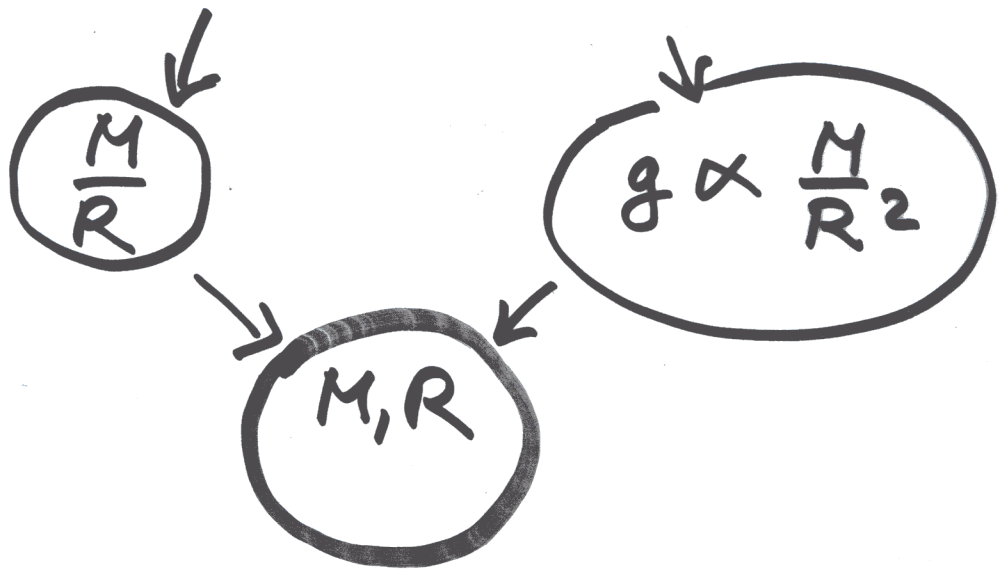
("pressure broadening;
pressure ionization)

O VIII Ly α : $\frac{\Delta E}{E} \sim 0.03$!

Fe XXVI Ly α : $\frac{\Delta E}{E} \sim 9 \times 10^{-4}$

(easily overwhelmed)

combine redshift, Stark broadening:



3. Rotational Broadening :

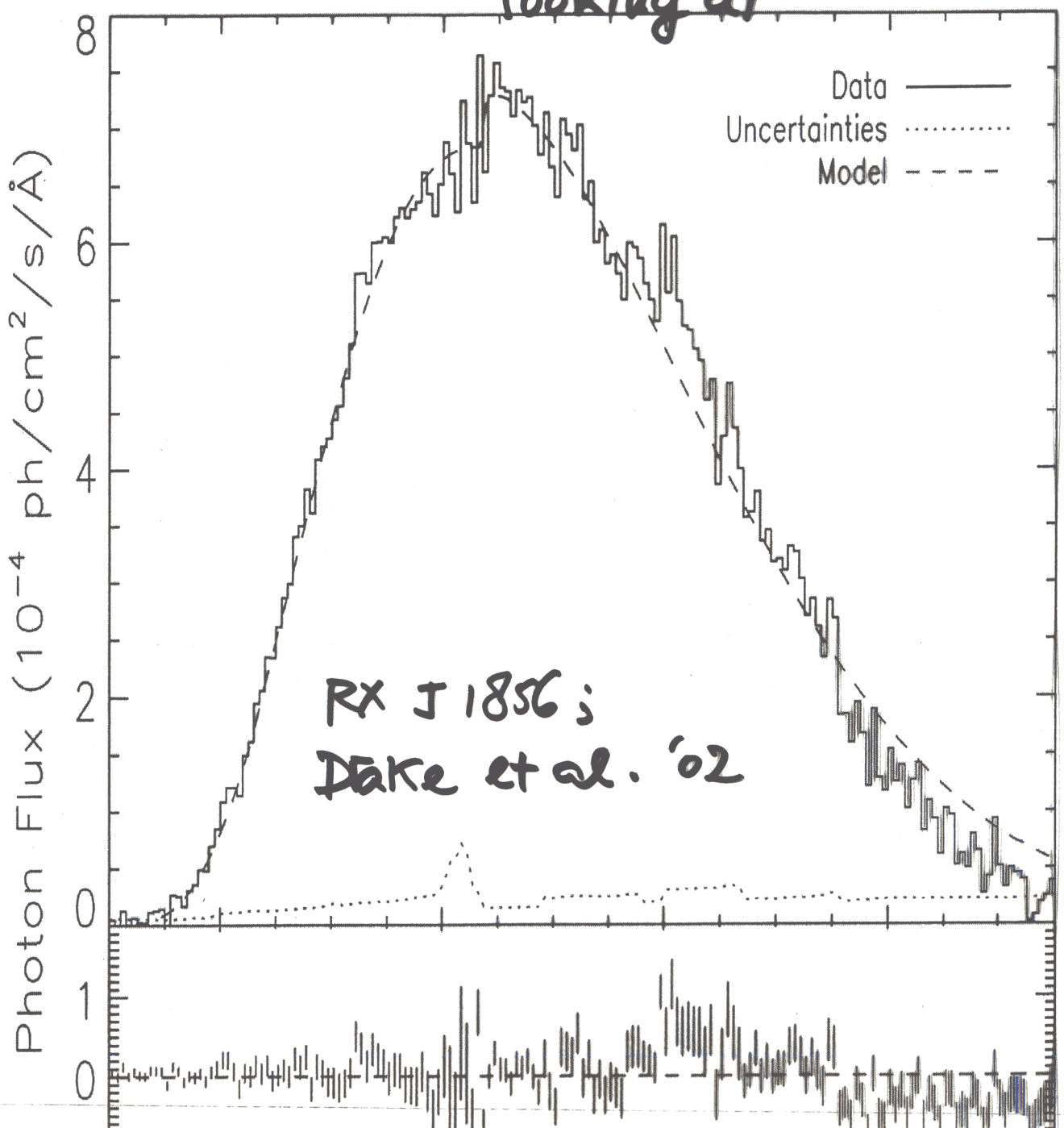
$$\frac{\Delta E}{E} \sim \frac{v}{c} \sim \frac{2\pi R}{Pc} = 0.20 R_6 P_{ms}^{-1} \; !!$$

potentially huge!

Relativistic Effects : boosting, lensing, frame dragging (if P ~ ms) → characteristic asymmetric profile ; sensitive to M/R, R (Özel & Psaltis '03)

2. SPECTROSCOPY OF ISOLATED NS

Biggest Uncertainty: don't know what we're looking at



Recent Progress: features in three isolated objects, + 2SGR

nature letters to nature

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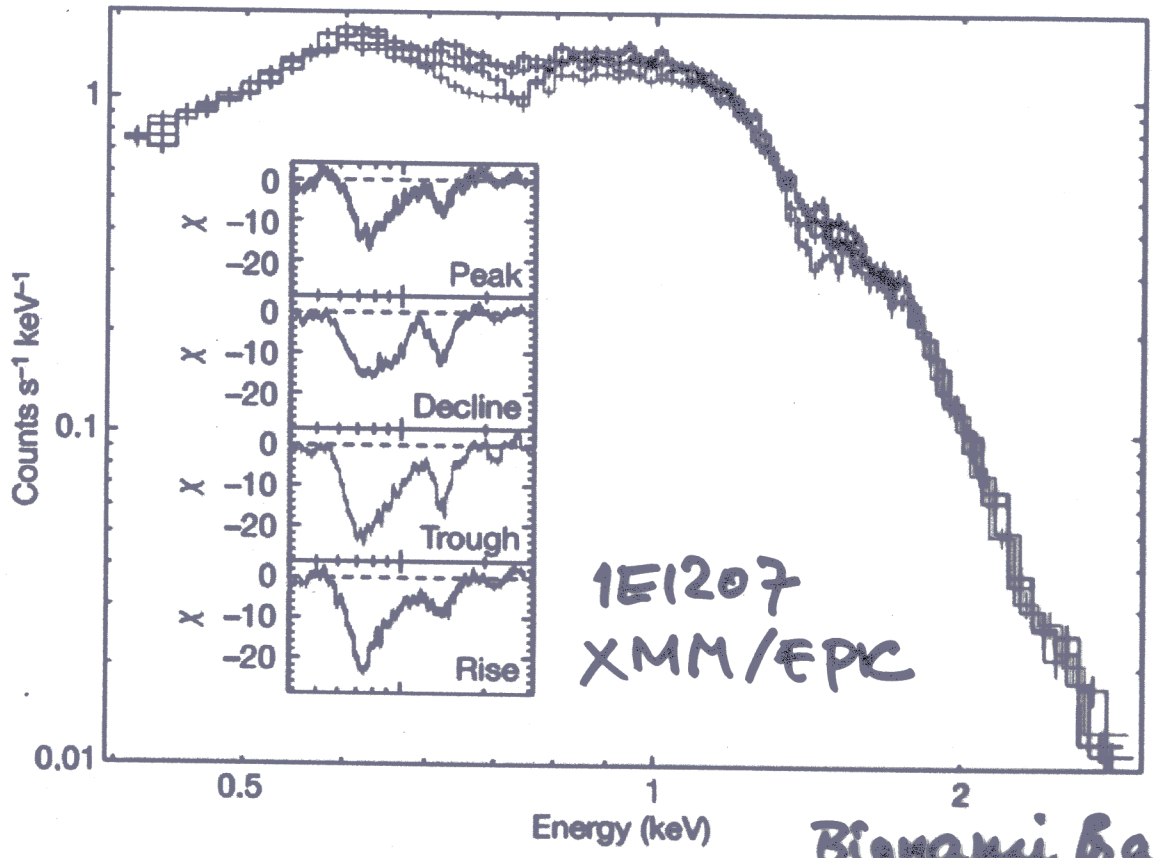

Bignami et al., '03

Figure 3 Comparison of the four PN spectra for phase intervals as defined in Fig. 2. Note that absolute (counts s^{-1} keV^{-1}) spectra are plotted. Colours indicate spectral variation: black, peak; red, decline; green, trough; blue, rise. The peak of the total light curve corresponds to the phase interval where the absorption lines are at their minimum (black data points) while the light-curve trough happens when the absorption lines are more important (green data points). Inset, the four panels show the residuals of the phase-dependent spectra from the two-blackbody fit used in Fig. 1a. Phase variations in both shape and intensity for all features are apparent. The comparison of phase-dependent residuals with Fig. 3 of ref. 11 shows the improvement achieved with the present long observation.

← item →

Note: Figures may be difficult to render in a web browser. In such cases, we recommend downloading the PDF version of this document.

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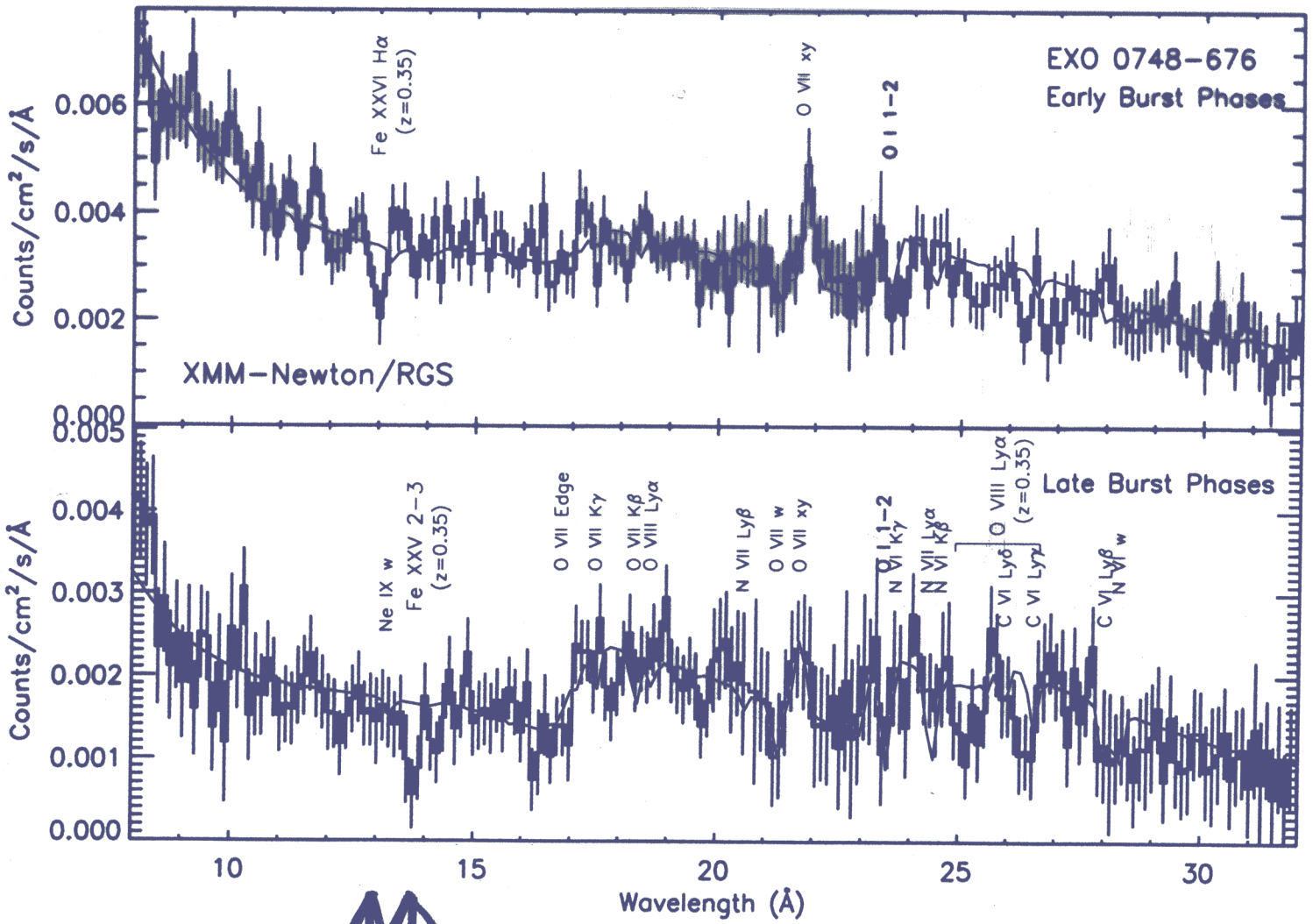
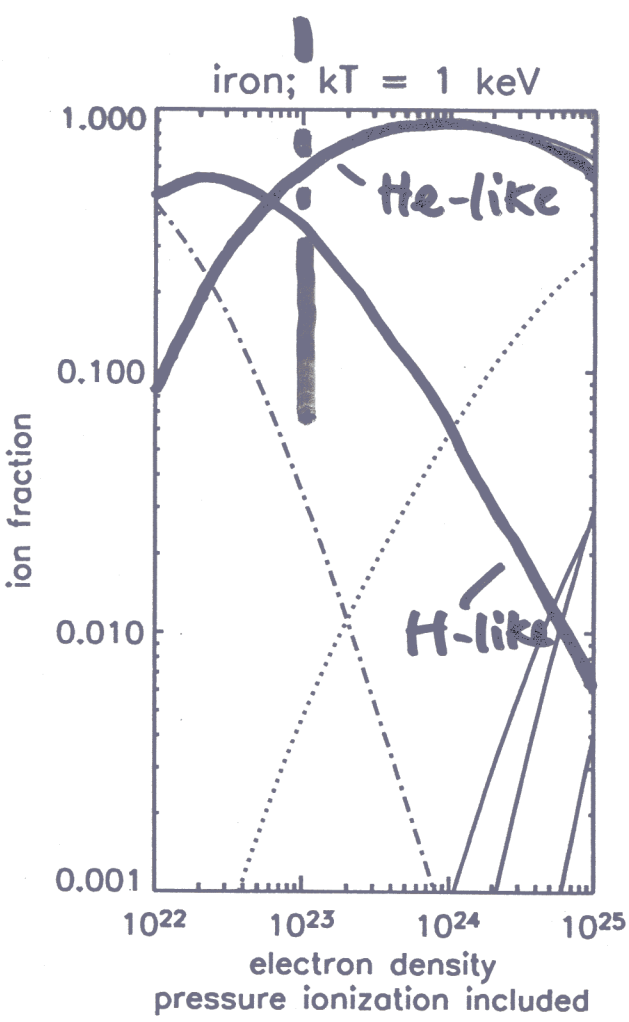
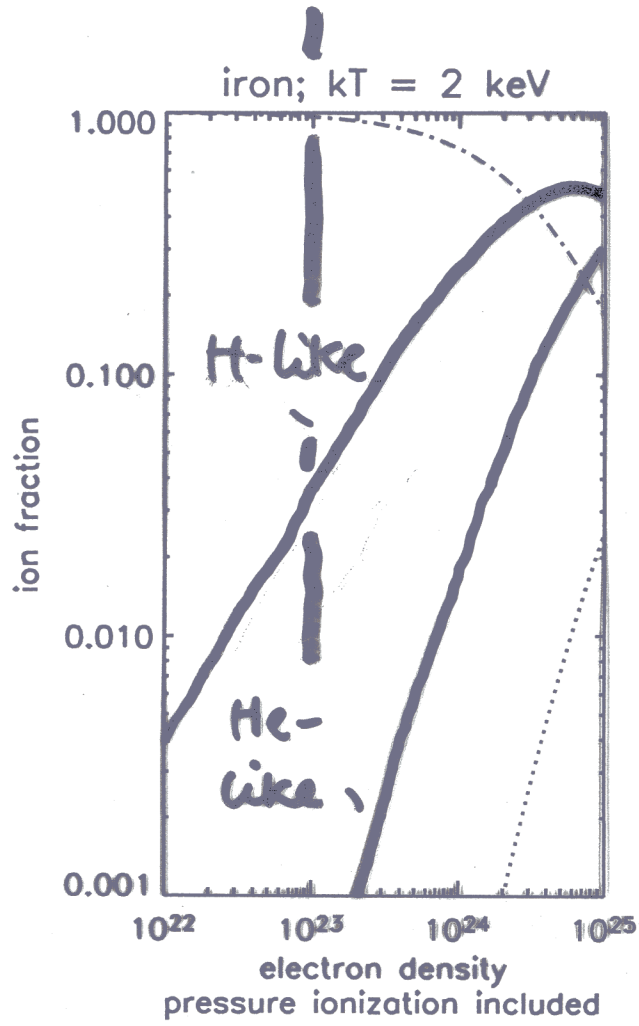
PHOTOSPHERIC SPECTROSCOPY OF X-RAY BURSTS: 30 BURSTS FROM LMXB 0748-676 WITH XMM/RGS



Cottam & al., '03

$\boxed{\text{Fe XXVI, XXV } n = 2\text{-}3 : z = 0.35}$

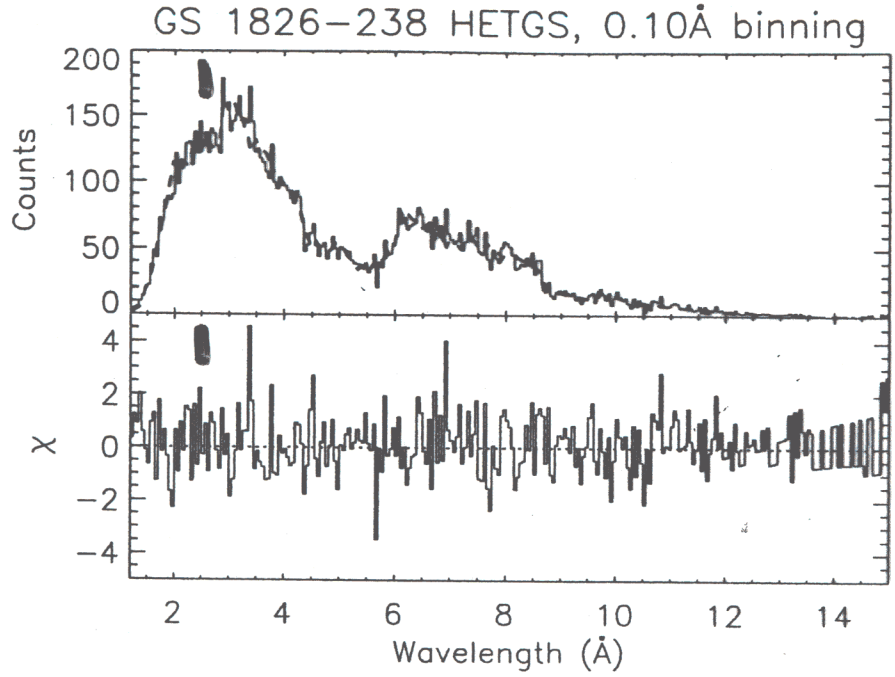




SAHA IONIZATION BALANCE,

$kT = 1\text{-}2$ keV

$n_e = 10^{22} - 10^{25}\ cm^{-3}$

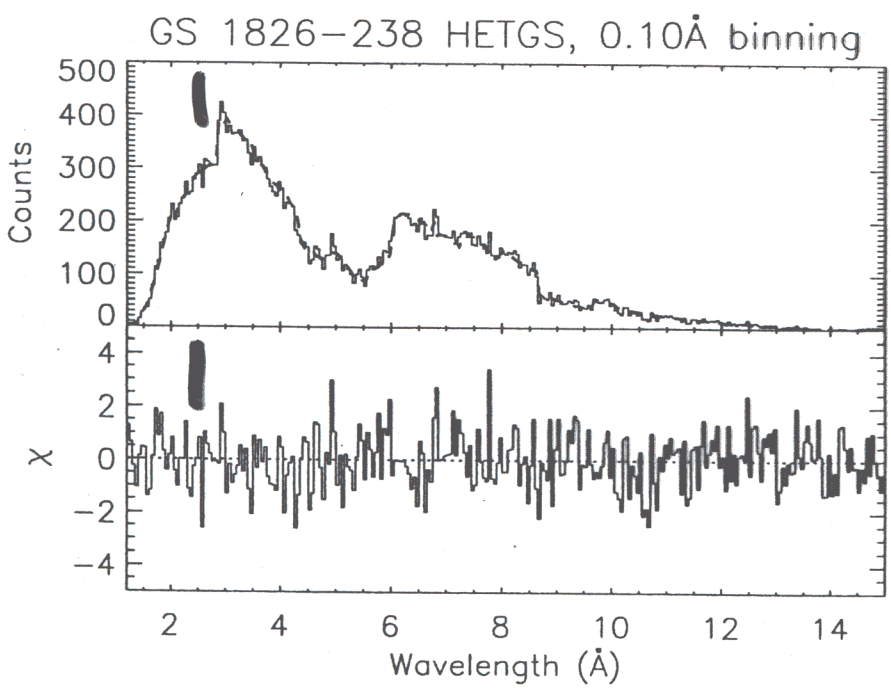


six BURSTS FROM GS 1826-238; Chandra HETGS

peak

Figure 1: *Top: Chandra* HETGS spectrum of the peaks of the six bursts observed from GS1826-283 in August 2002. A continuum model was fit to the data, consisting of a simple blackbody with cold absorption. *Bottom:* Residuals from the blackbody continuum. No significant absorption features are found near the locations of known ionic edges or resonance lines.

courtesy Herman Marshall (MIT)

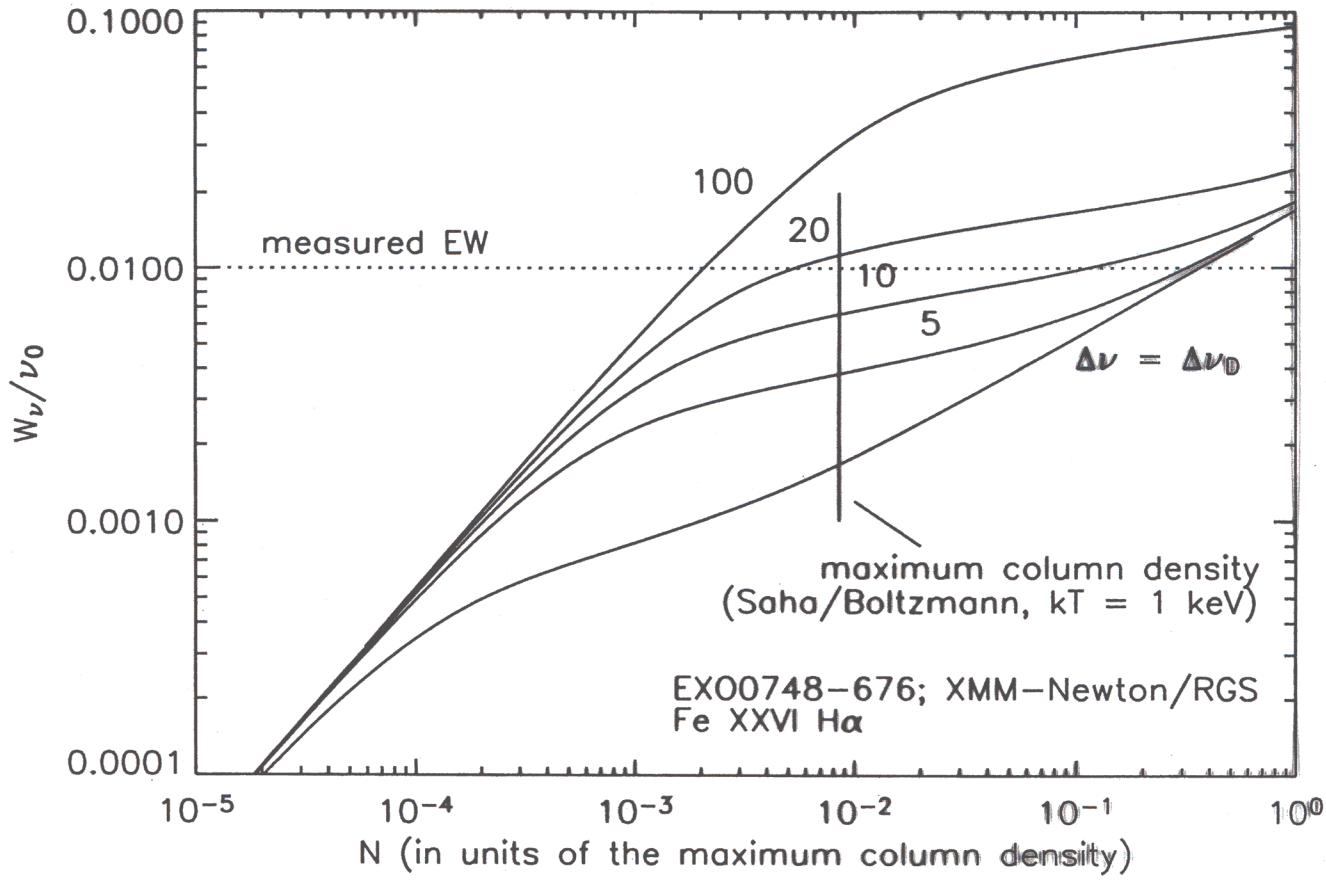


—: Fe XXVI Lyα, z = 0.35

tail

Figure 2: Same as fig.1 but for the tails of the bursts, defined as starting 25 s from the beginning of the burst and lasting for 105 s each burst. The continuum model is a simple blackbody absorbed by neutral gas in the interstellar medium. No significant edges are found in the residuals. There are no absorpion features at any of the expected Fe Lα or Hα wavelengths.

EW, Fe XXVI Hα



Do the observed line <u>strengths</u> make any sense?

- Calculate EW ($N_{Fe XXVI}$), assuming ALL gas above $\tau_{es} = 1$ absorbs ⇒ UPPER limit to EW
- do this for $\Delta\nu_{core} = \Delta\nu_D$: UNDERpredict EW by order of magnitude!