



湘潭大學

XIANGTAN
UNIVERSITY

Long thermonuclear X-ray bursts

Zhaosheng Li (李兆升)

Xiangtan University

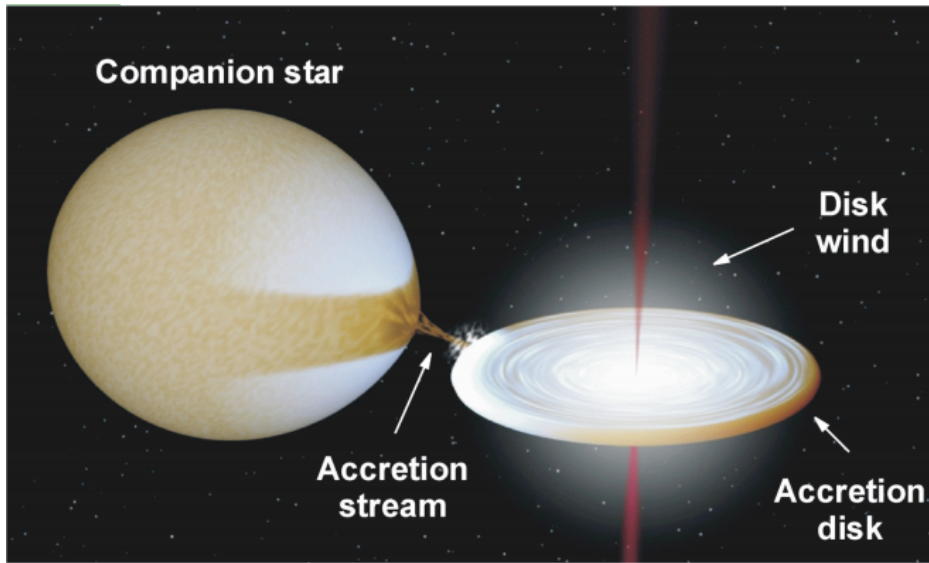
2025.07.02-06

SPSS2025 & FPS14@青島

Outline

- **Low-mass X-ray binary**
- **4U 1850-087**
- **4U 1820-30**
- **Summary**

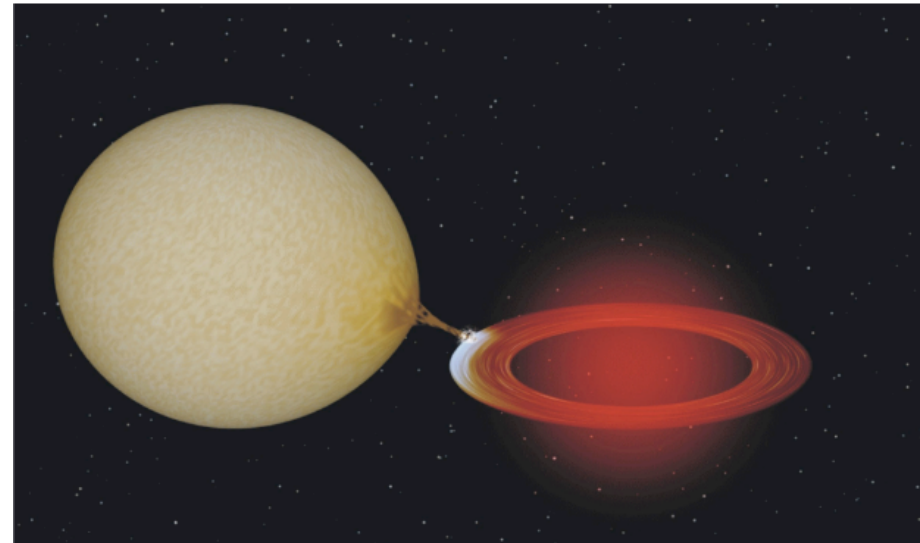
LMXBs



Transient source

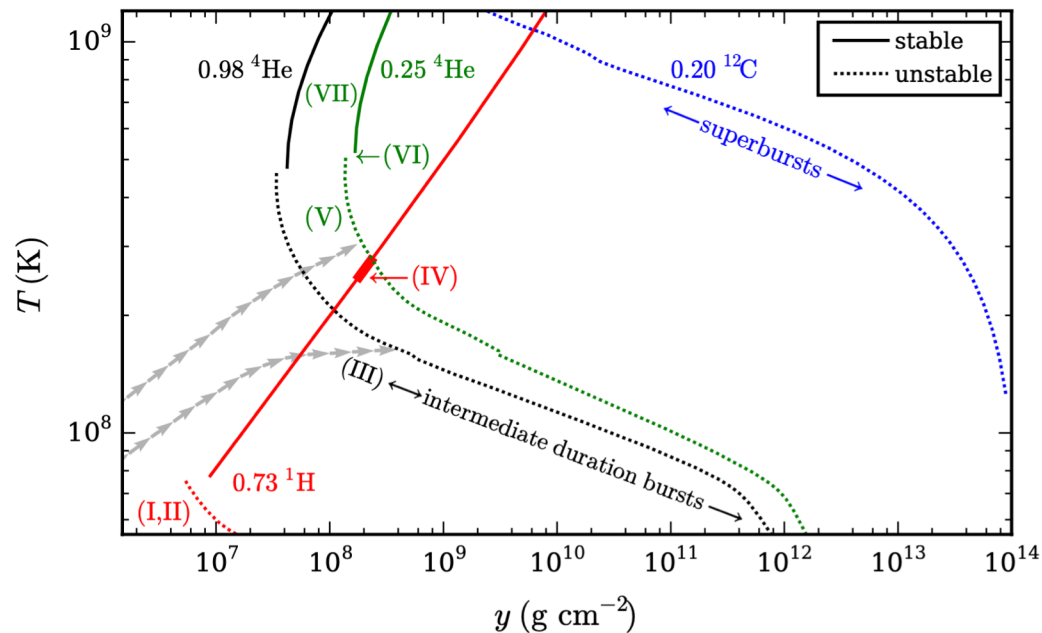
**“Switched on”:
Accretion
induced outburst**

**“Switched off”:
Quiescence**

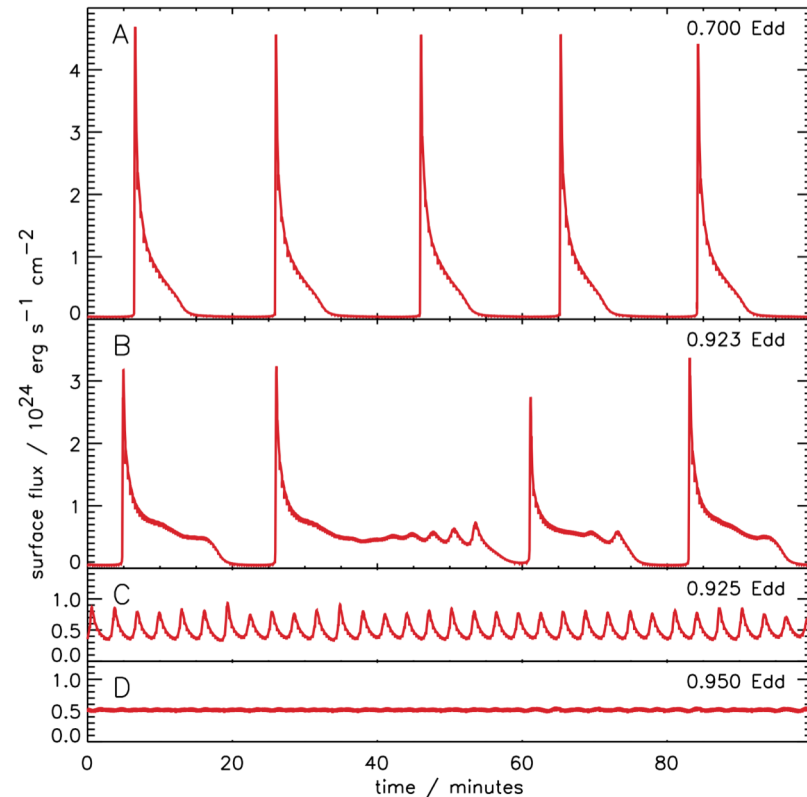


LMXBs: burning process

The accreted matter can be consumed via stable, marginally, and unstable burning



Galloway & Keek 2021



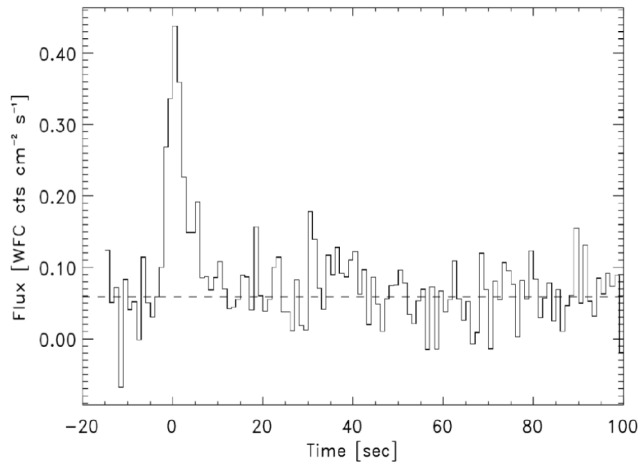
Heger et al. 2007

LMXBs: unstable burning

Normal X-ray burst

H burning via: CNO cycle 6.7 MeV/u

He burning via: $\alpha + \alpha + \alpha \rightarrow {}^{12}\text{C}$ 0.6 MeV/u

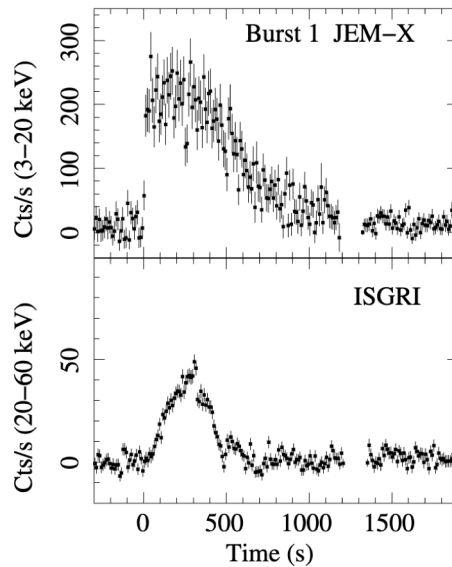


X-ray burst in 4U 1254-69 (In't Zand et al., 2003)

Intermediate-duration

Low accretion rate

Helium burning in deep layer

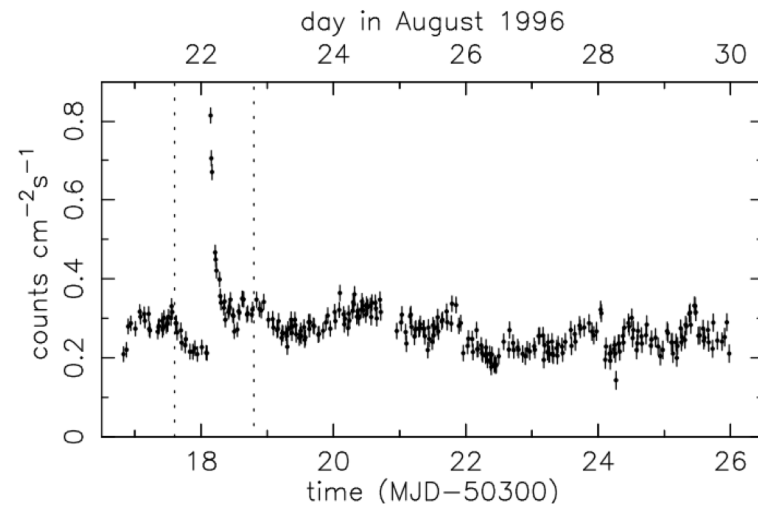


Falanga et al. 2008

Superburst

Carbon burning

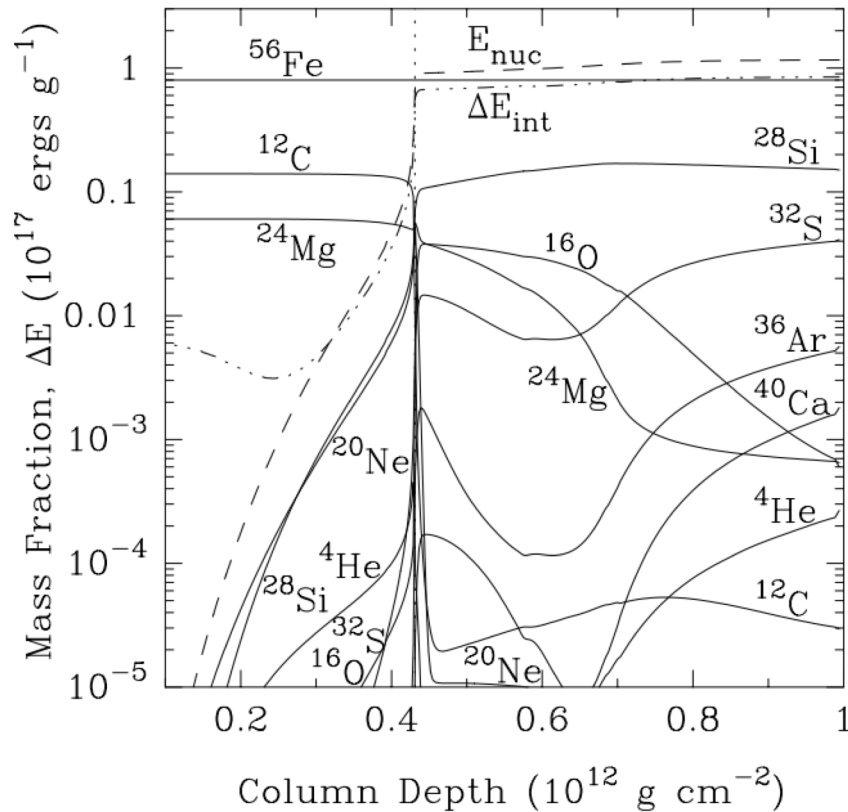
10³ longer, 1/10³ rare, 10³ energetic



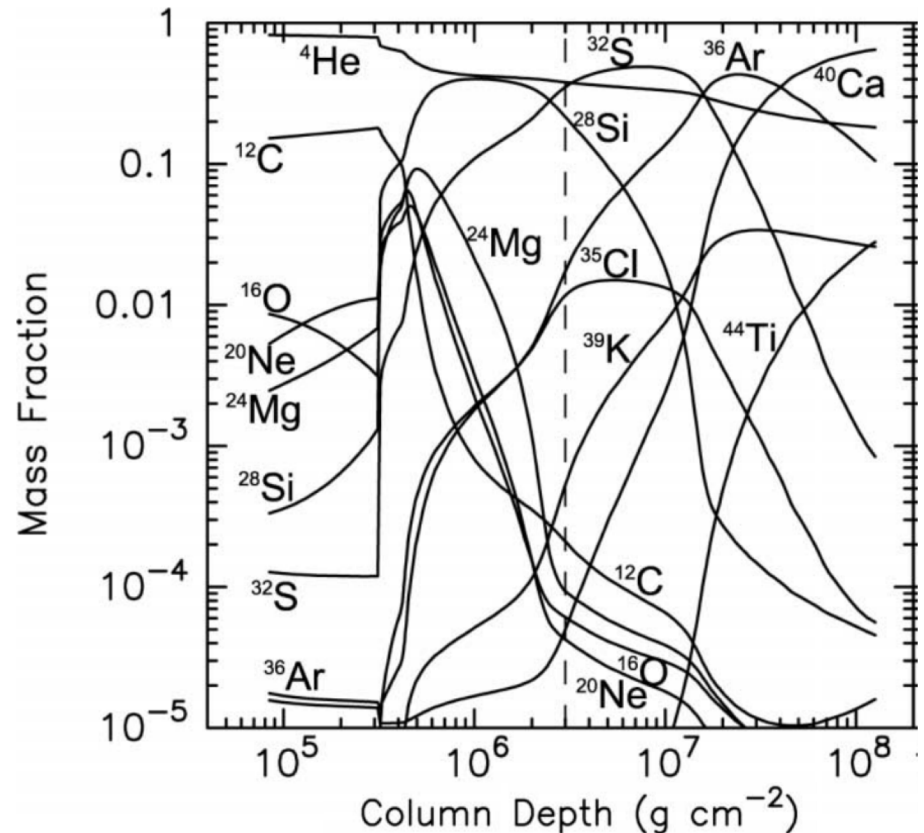
4U 1735-44, Cornelisse et al 2000

LMXBs: unstable burning

Thermonuclear X-ray bursts can generate, C, Fe, Si, S, Ar, Ca, and so on. These elements produce spectral features mainly in soft X-ray band.



Superburst, Weinberg & Bildsten 2007



Helium Burst, Weinberg et al. 2006

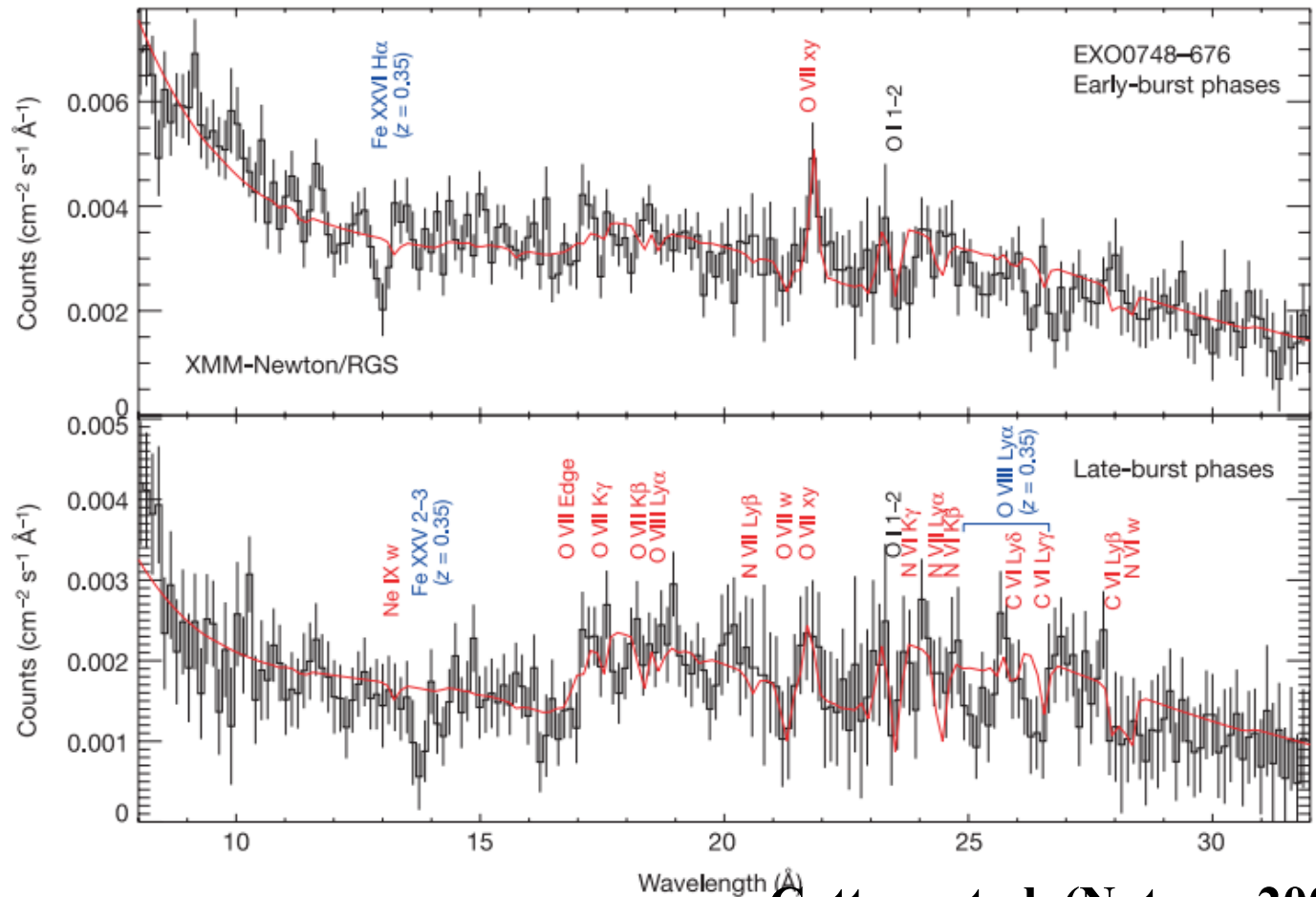
LMXBs: unstable burning

- EXO 0748-676 (XMM-Newton/RGS)

$$1+z(R) = (1 - 2GM_{\text{NS}}/Rc^2)^{-1/2}$$

Z=0.35

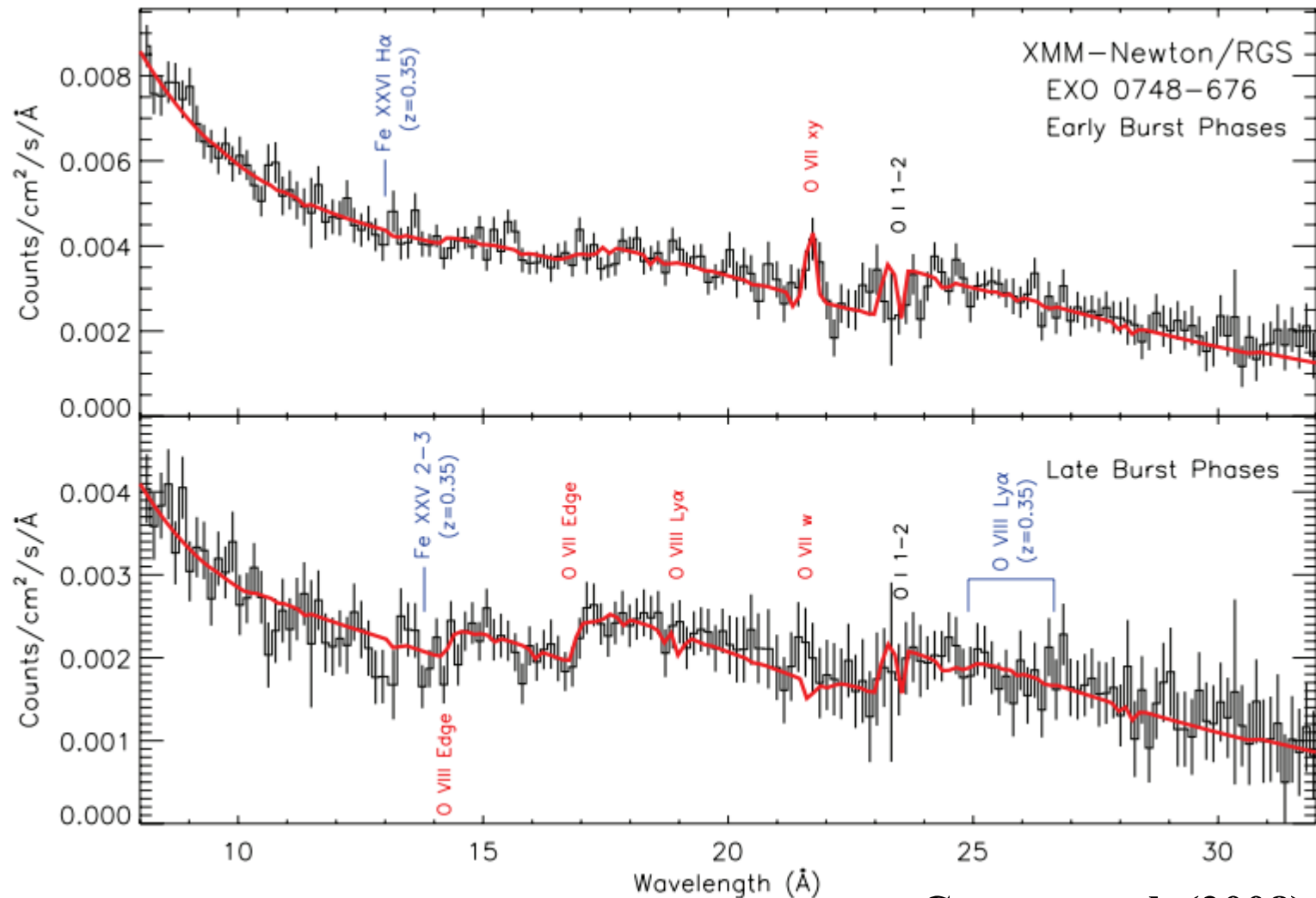
Fe XXVI (H α)
Fe XXV (He-like)
O VIII



Cottam et al. (Nature, 2002)

LMXBs: unstable burning

- None detection of absorption line in EXO 0748-676!

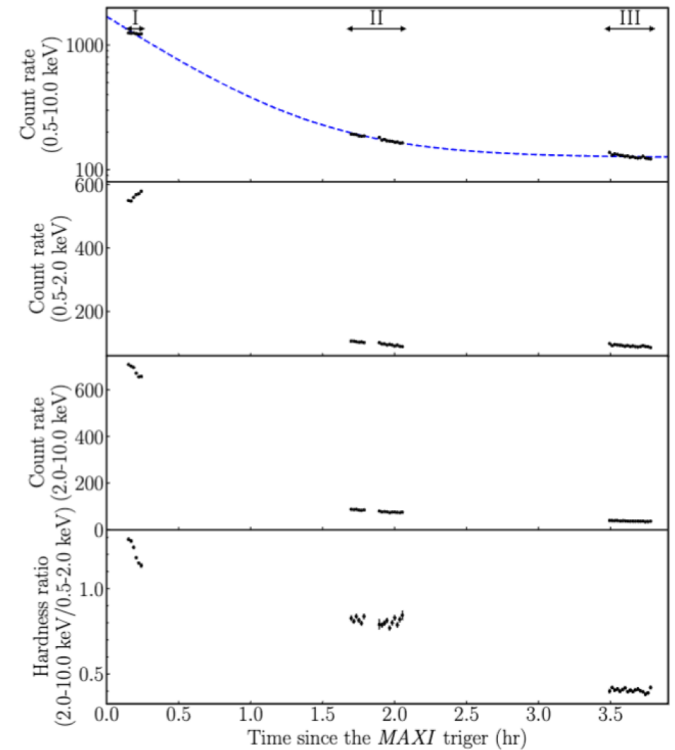
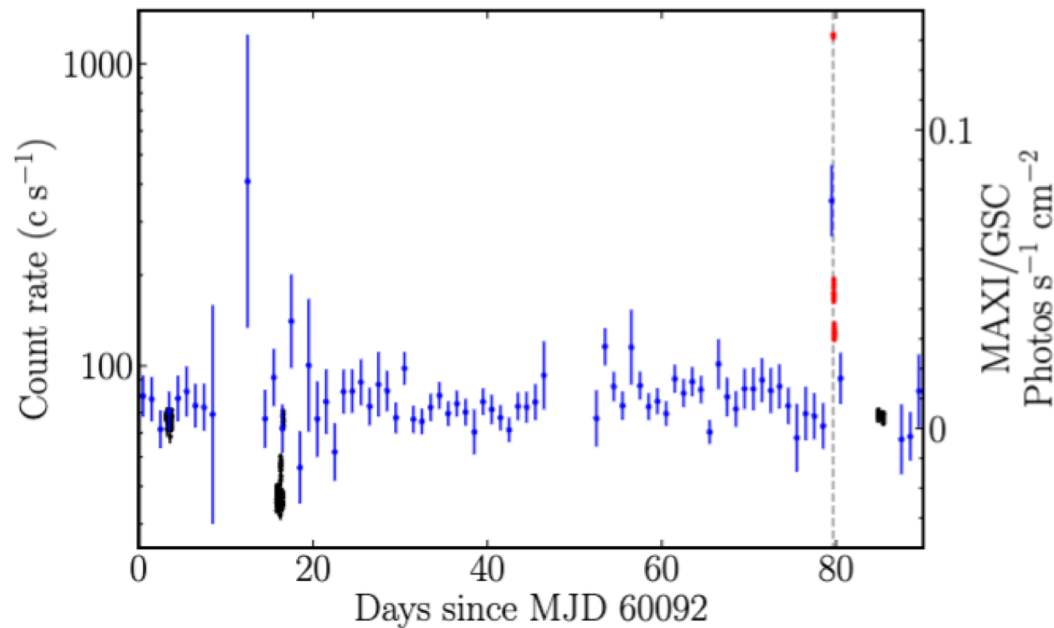


Cottam et al. (2008)

Spectral lines in UCXBs

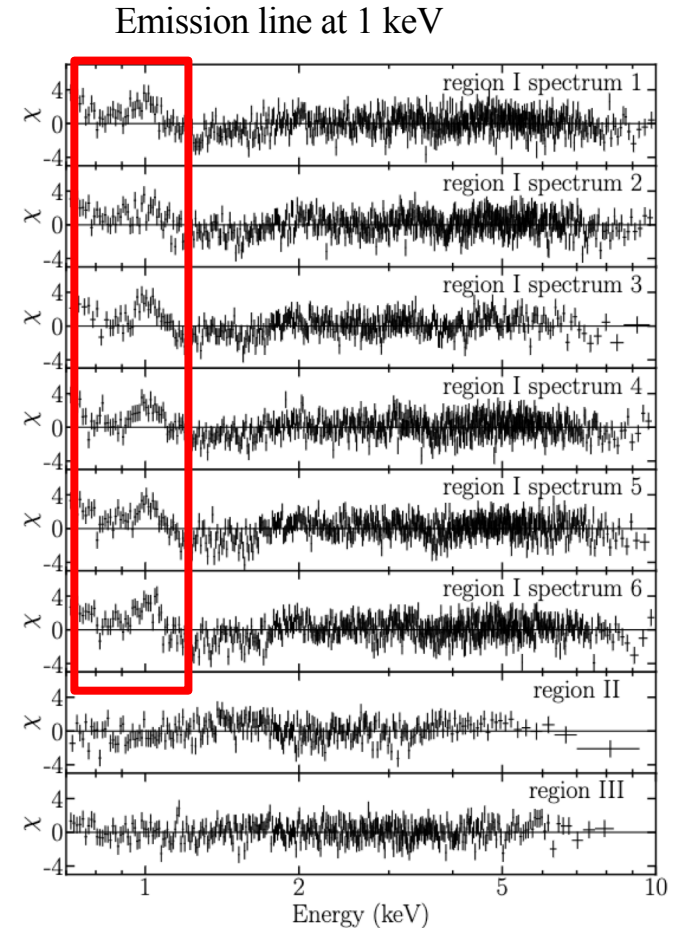
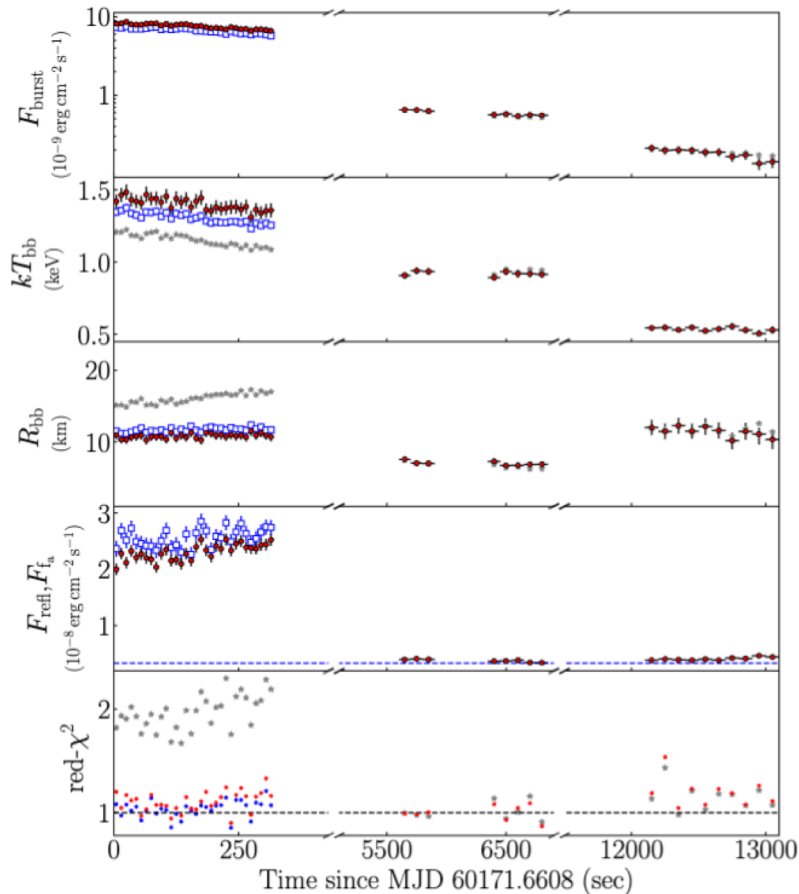
Joint MAXI and NICER observations: all sky survey + large collecting area
4U 1850-087: 1% L_{edd} , UCXB, $P_{\text{orb}} \sim 20.6$ min, MAXI+NICER, $\tau \approx 0.78$ hr,
He burning in deep layer

MAXI+NICER



Spectral lines in UCXBs

4U 1850-087: 1 keV Fe emission line, may from inner accretion disk reflection



Spectral lines in UCXBs

4U 1820-30: Superburst emptied the inner accretion disk, causing the deficit of persistent emission.

$E \sim 3.5e42$ erg

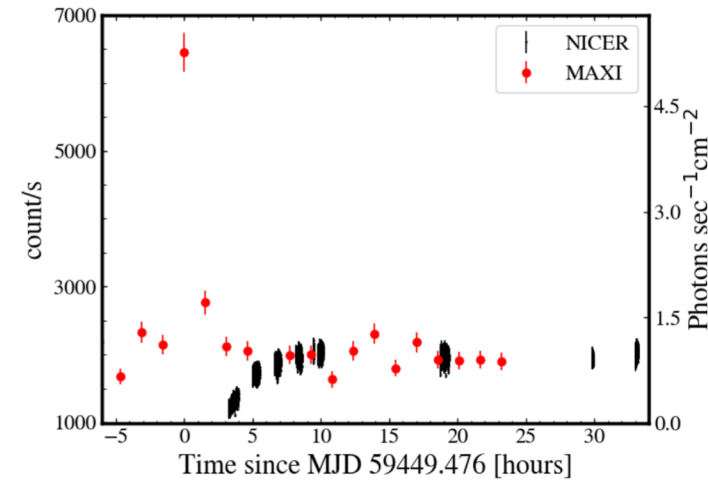


Figure 1. The light curve of the superburst from 4U 1820-30 observed by NICER (with time bin size of 1 s in 0.5–10 keV, black points) in units of counts/s and MAXI (~ 250 s, 2–20 keV, red points) in units of photons $\text{sec}^{-1} \text{cm}^{-2}$.

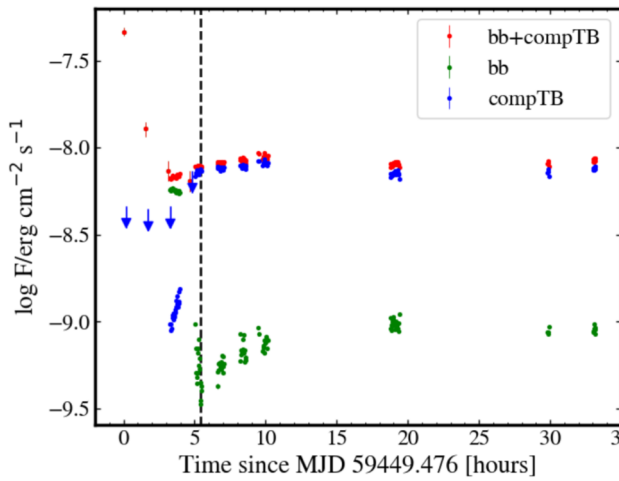
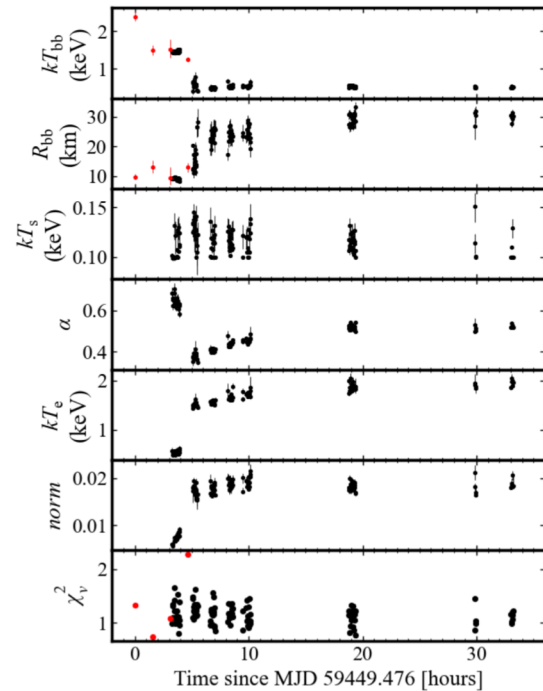


Figure 6. The variation of flux during the entire Obs. Ids 05 and 06. The red, green, and blue points represent the total X-ray, the blackbody, and the Comptonization flux respectively. The dotted line marks the moment of the lowest blackbody flux.



Spectral lines in UCXBs

4U 1820-30: Superburst emptied the inner accretion disk, causing the deficit of persistent emission.

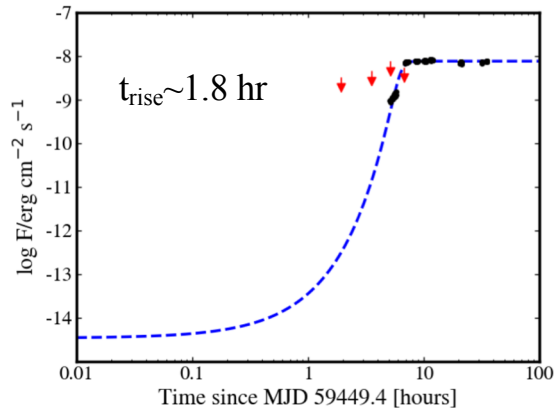


Figure 7. Evolution of the Comptonization flux fitted by the sigmoid model $f(t) = F/(1 + e^{-k(t-t_0)})$. The red (only upper limit) and black points represent the data from MAXI and NICER, respectively.

$$\Sigma = 2.7 \times 10^5 \alpha^{-4/5} \left(\frac{M_{\text{NS}}}{1.4 M_{\odot}} \right)^{-2/5} \left(\frac{\dot{M}}{7.7 \times 10^{17} \text{ g s}^{-1}} \right)^{3/5} \times \left(\frac{D}{8.4 \text{ kpc}} \right)^{6/5} \left(\frac{R}{r_g} \right)^{-3/5} J(R)^{3/5} \text{ g cm}^{-2}, \quad (3)$$

where R denotes the outer radius of the accretion disk, $J(R) = 1 - (6r_g/R)^{1/2}$, $r_g = GM_{\text{NS}}/c^2$, and $\alpha = 0.1$ is the Shakura–Sunyaev viscosity parameter. The accretion rate is $\dot{M} = 4\pi D^2 F/\eta c^2 = 7.7 \times 10^{17} (D/8.4 \text{ kpc})^2 \text{ g s}^{-1}$, where the persistent bolometric flux is $8.2 \times 10^{-9} \text{ erg s}^{-1} \text{ cm}^{-2}$, and the accretion efficiency η is assumed to be 0.1. Based on this model, we estimated the gravitational potential energy, $\sim 6 \times 10^{39} \text{ erg}$, of the disk material located between $6r_g$ and $1000r_g$ under the Schwarzschild metric for an NS with a mass of $1.4 M_{\odot}$ and radius of 10 km. If the peak flux of the superburst

$$t_{\text{visc}} = 0.35 \alpha^{-4/5} \left(\frac{M_{\text{NS}}}{1.4 M_{\odot}} \right)^{8/5} \left(\frac{\dot{M}}{7.7 \times 10^{17} \text{ g s}^{-1}} \right)^{-2/5} \times \left(\frac{D}{8.4 \text{ kpc}} \right)^{-4/5} \left(\frac{R}{1000 r_g} \right)^{7/5} J(R)^{-2/5} \text{ hr}.$$

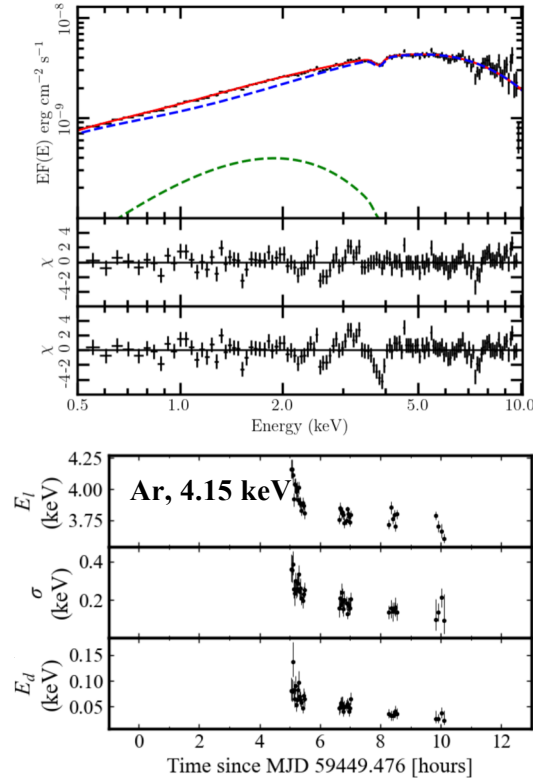


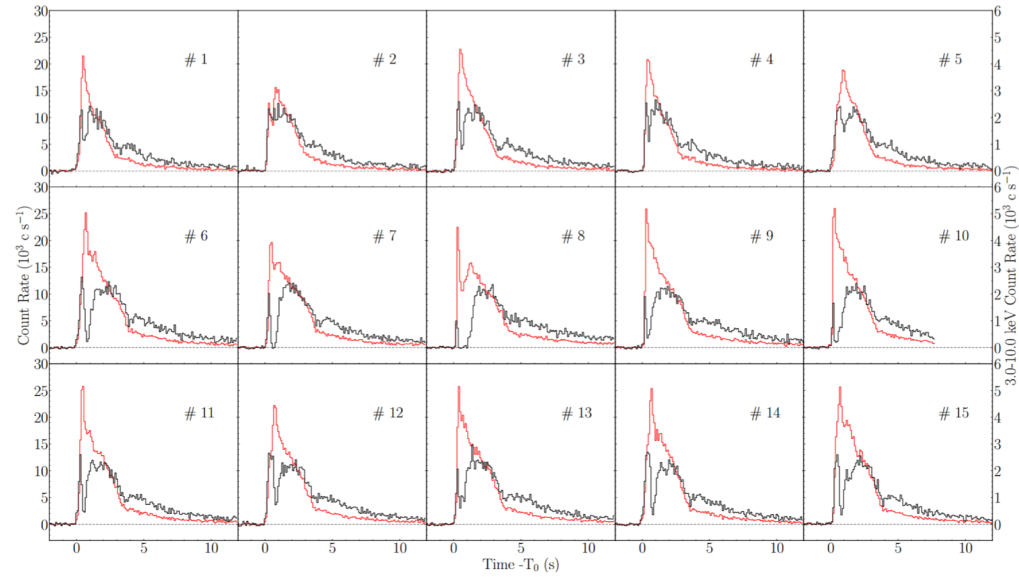
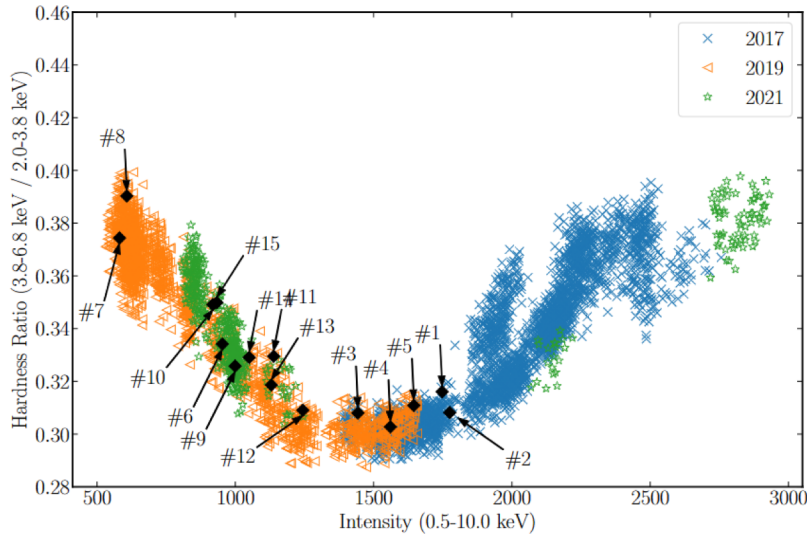
Figure 9. The evolution of the absorption line energy, width, and depth.

Peng, [Li](#), et al. 2025, ApJ

Spectral lines in UCXBs

4U 1820-30: UCXB, $P_{\text{orb}} \sim 11$ min, He donor, low $N_{\text{H}} \sim 2E21$

Bursts were occurred at low accretion rate.



Red: 0.5-10 keV, 0.1 s bin; Black: 3-10 keV, 0.1 s bin.

Fig. 2. Hardness-intensity diagram (HID, *top panel*) and color-color diagram (CCD, *bottom panel*) of 4U 1820-30 from the NICER observations. The blue crosses, orange triangles, and green stars represent the data observed in 2017, 2019, and 2021, respectively. All bursts are removed, and each point represents a segment of 64 s. The HID and CCD of the persistent emission before each X-ray burst are shown as filled black diamonds. For each panel, from left to right, the spectra evolved from the hard island state to the soft banana state.

Spectral lines in UCXBs

4U 1820-30: 1 keV emission (Fe L shell), 1.6 keV (Fe, Mg XI, Cr XXIV), 3 keV absorption lines (He-like S XV)

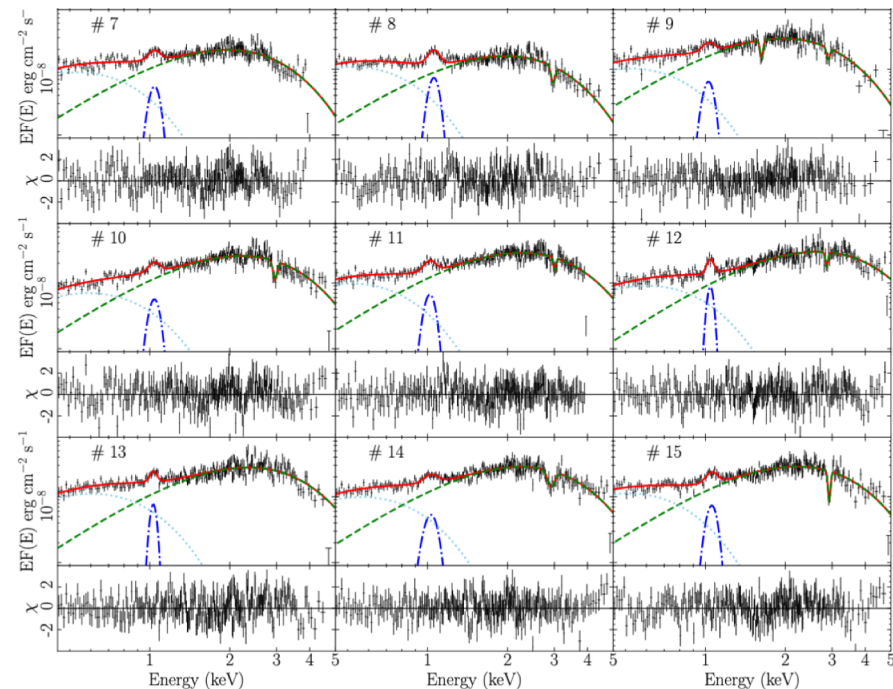
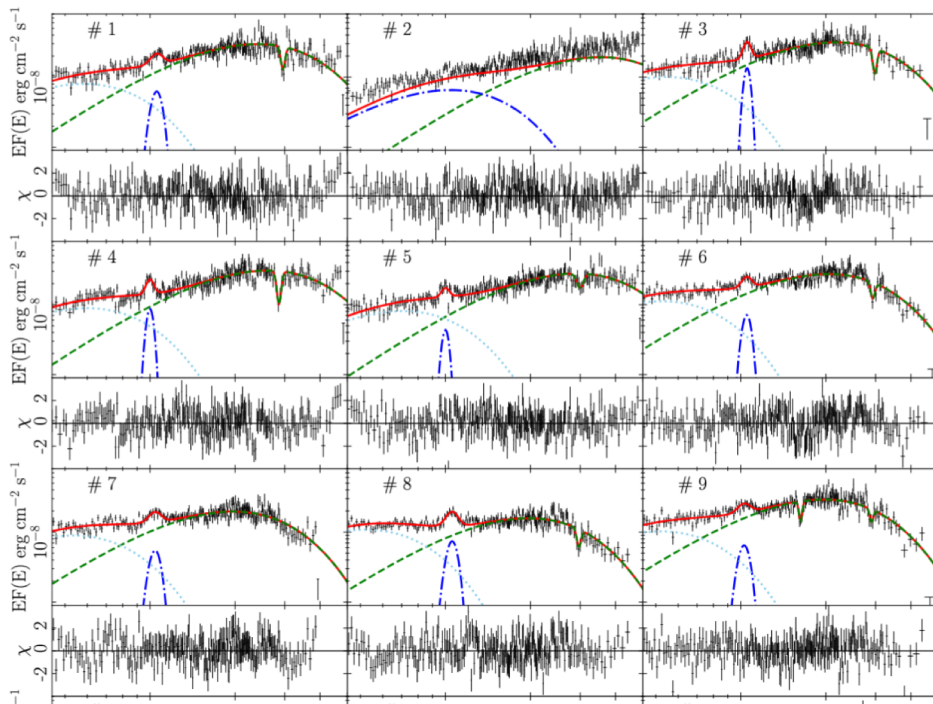


Fig. 4. The unabsorbed spectra extracted during the PRE phase for all bursts in 0.3–5 keV. The red solid lines are the best-fitting model, including the continuum and spectral lines if necessary. The residuals of the best fit model to the data are plotted in bottom panels.

MC estimates the significance of lines

- (1) Fit the real spectrum with line
- (2) Simulate M spectra based on model
- (3) Fit the simulate spectra w/without line
- (4) $p=1-N/M$

Yu , Li, et al. 2025, A&A

Spectral lines in UCXBs

**4U 1820-30: the 1 keV line may from Fe L-complex,
can be resolved by HUBS, at the peak, 10, 000 cts/s in 0.1-2 keV**

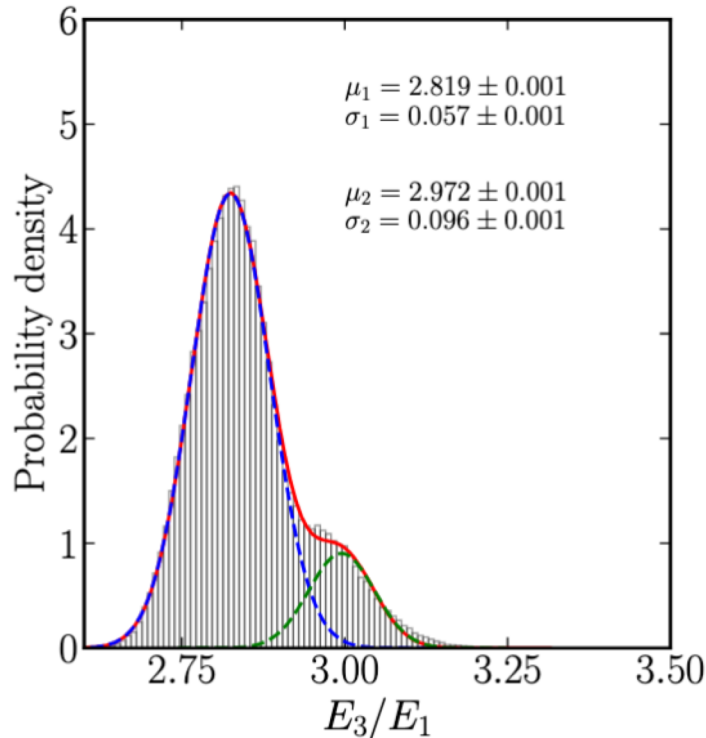


Fig. 9. The ratios of centroid energy between E_3 and E_1 at the same time. The distributions are well fitted by two Gaussian function. The main peak at 2.819, and secondary at 2.972.

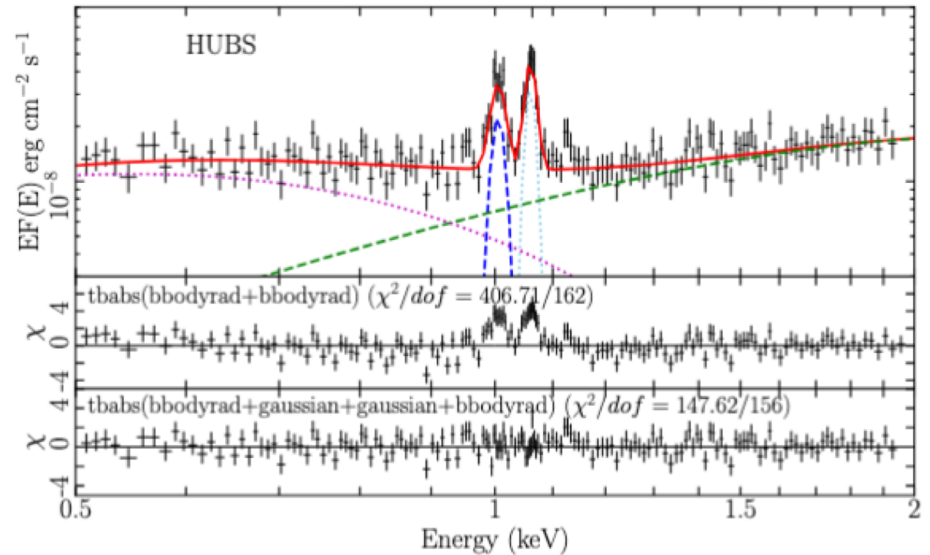


Fig. 10. Mock *HUBS* X-ray spectrum with the continuum parameters from burst # 8 and two additional narrow emission lines. The best fitting model is $Tbabs \times (bbodyrad + gaussian + gaussian + bbodyrad)$. The dashed lines represent the two Gaussian lines. The best-fit model is plotted as red solid line. The burst blackbody and disk blackbody components are shown in pink and green dotted lines, respectively.

Summary

- **4U 1850-087**
 - **1 keV emission line, from disk reflection**
- **4U 1820-30**
 - **1, 1.6, 3, and 4.15 keV spectral lines during bursts/superbursts**
 - **HUBS can resolve 1 keV lines**
- **EP can detect more long bursts**

Thank you!