Accretion heated atmospheres of X-ray bursting neutron stars

Valery Suleimanov

Universität Tübingen, Germany
Kazan Federal University, Russia

together with

Juri Poutanen, Joonas Nättilä
Tuorla observatory, University of Turku, Finland
Jari Kajava
Tuorla observatory & FINCA, University of Turku, Finland
K. Werner
Universität Tübingen, Germany

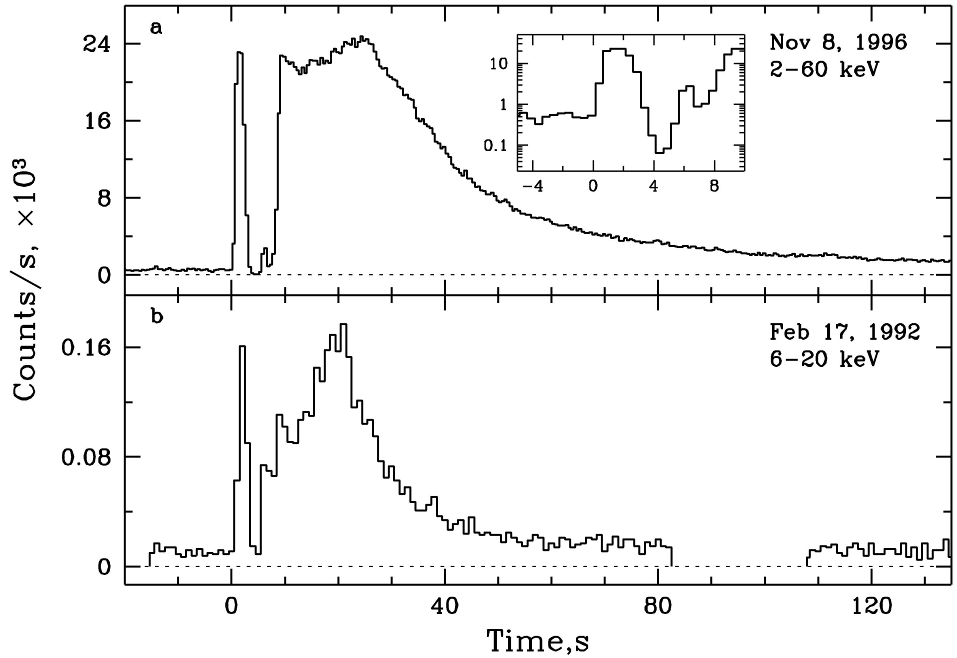
Physics of Neutron Stars
July 14, 2017, St. Petersburg

X-ray bursting neutron stars

- X-ray bursting NSs – LMXBs with thermonuclear explosions at the neutron star surface
- Sometimes close to the Eddington limit during the burst (photospheric radius expansion (PRE) bursts)
- Burst duration ~10 - 1000 sec

Ideal sources for NS masses and radii investigations (important for EOS!!!)

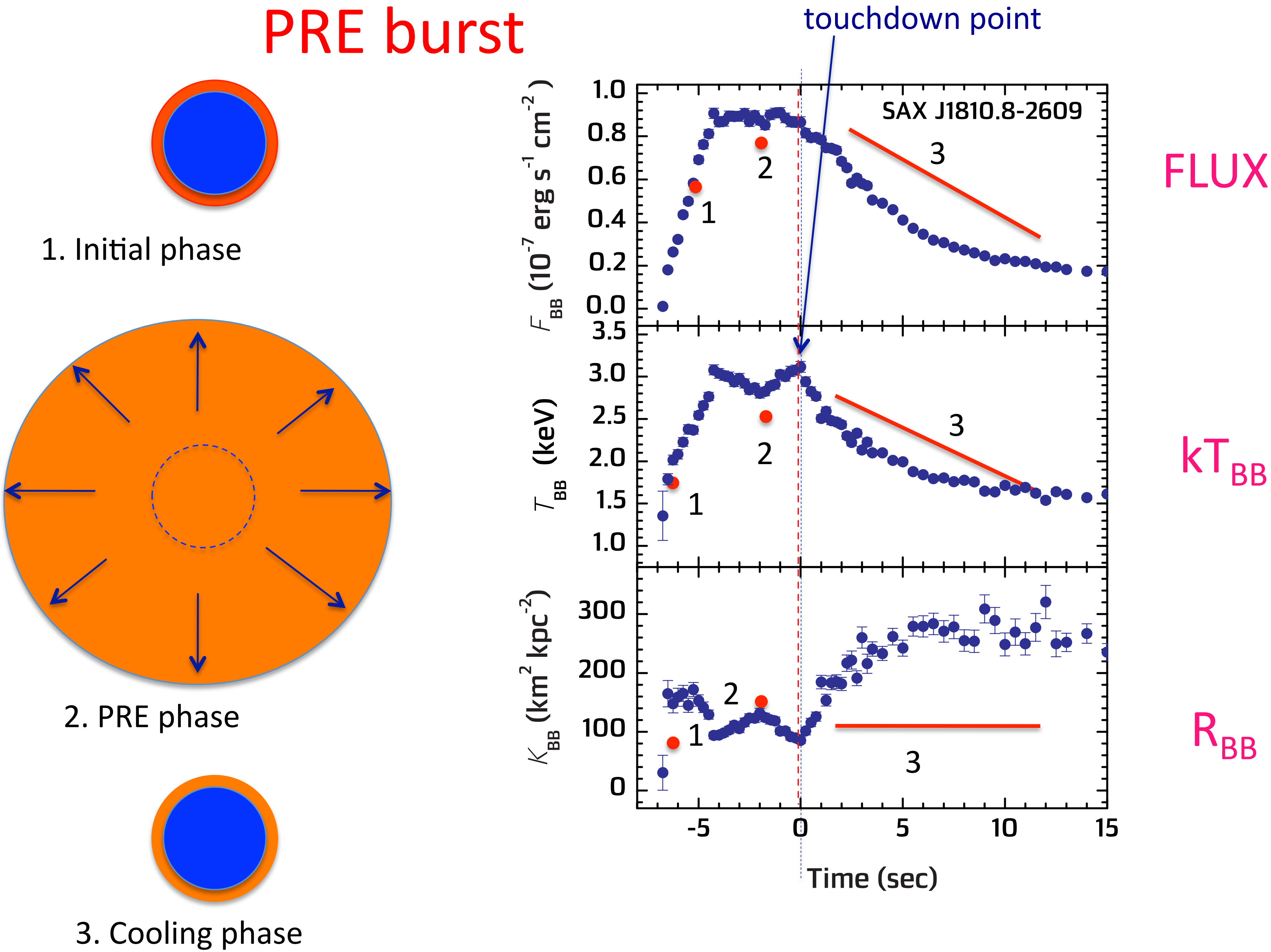
Low Mass X-ray Binary (artist veiw)



4U 1724-307 in Terzan 2

Figure from Molkov et al (2000)

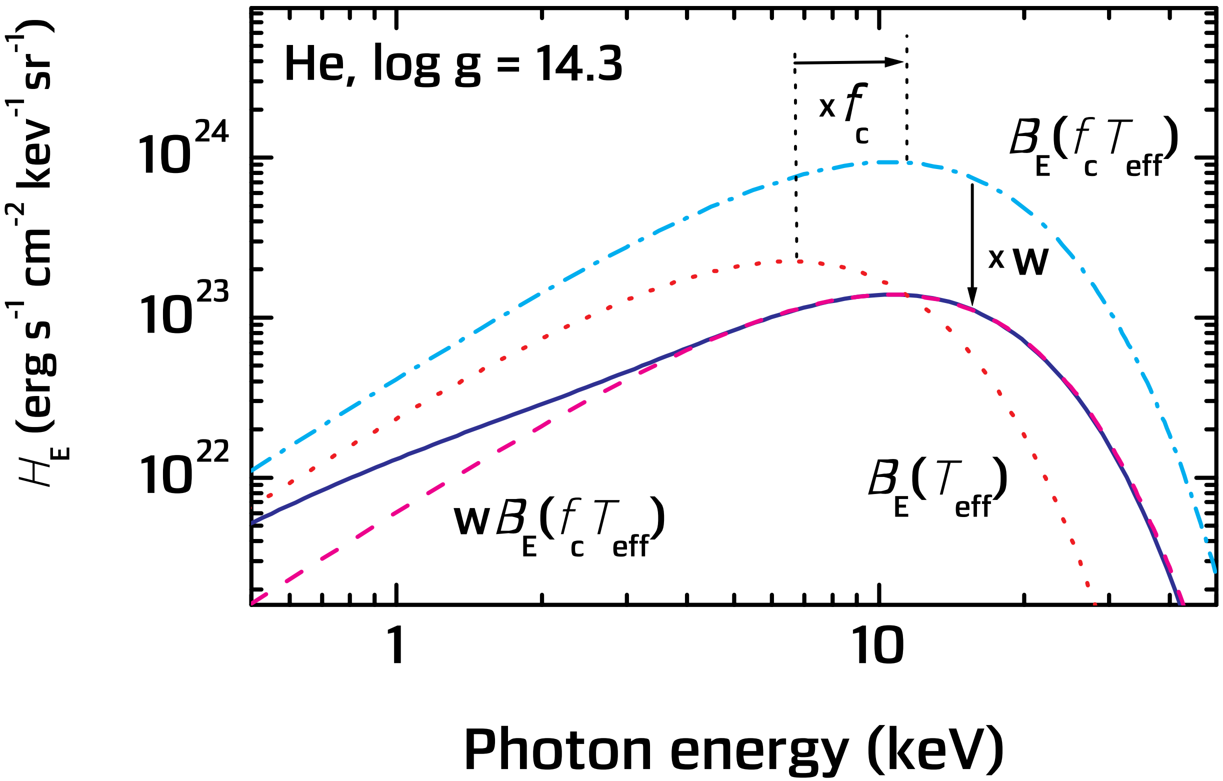
PRE burst



1. Initial phase
2. PRE phase
3. Cooling phase
touchdown point
SAX J1810.8-2609
FLUX
kT_BB
R_BB
F_BB (10^-7 erg s^-1 cm^-2)
T_BB (keV)
K_BB (km^2 kpc^-2)
Time (sec)

Spectrum formation of X-ray bursting NSs

Compton scattering is important !!!



$$F_\nu \approx w\, B_\nu(f_c T_{eff})$$

$f_c > 1$ color correction factor

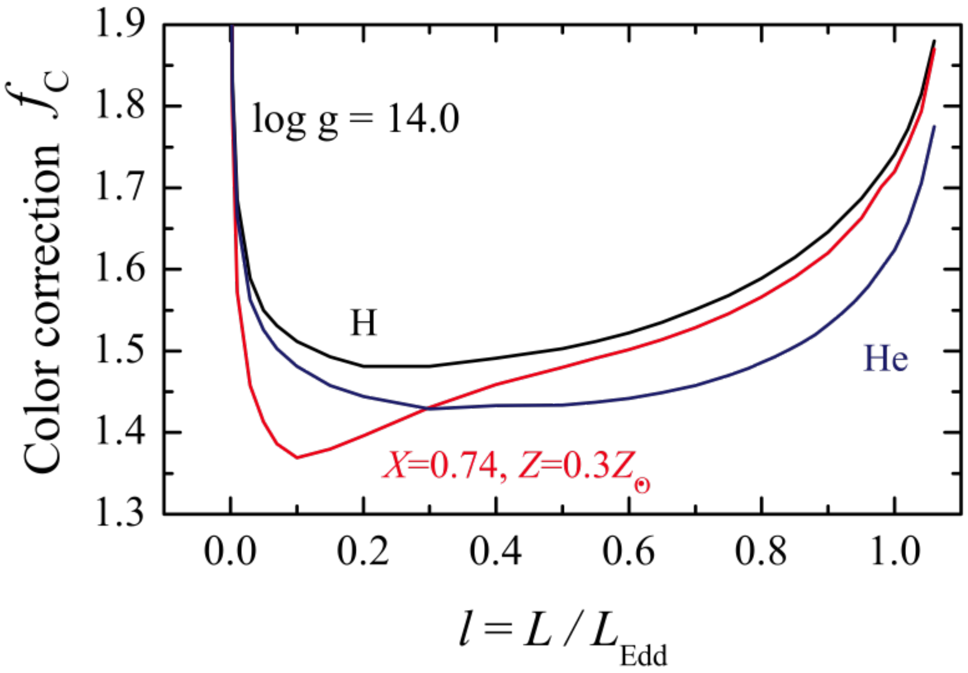
$w \approx f_c^{-4} < 1$ dilution factor

$$F_\nu^{obs} \approx B_\nu(T_{BB}) K = B_\nu(T_{BB})\, w\, \frac{R^2(1+z)^2}{D^2}$$

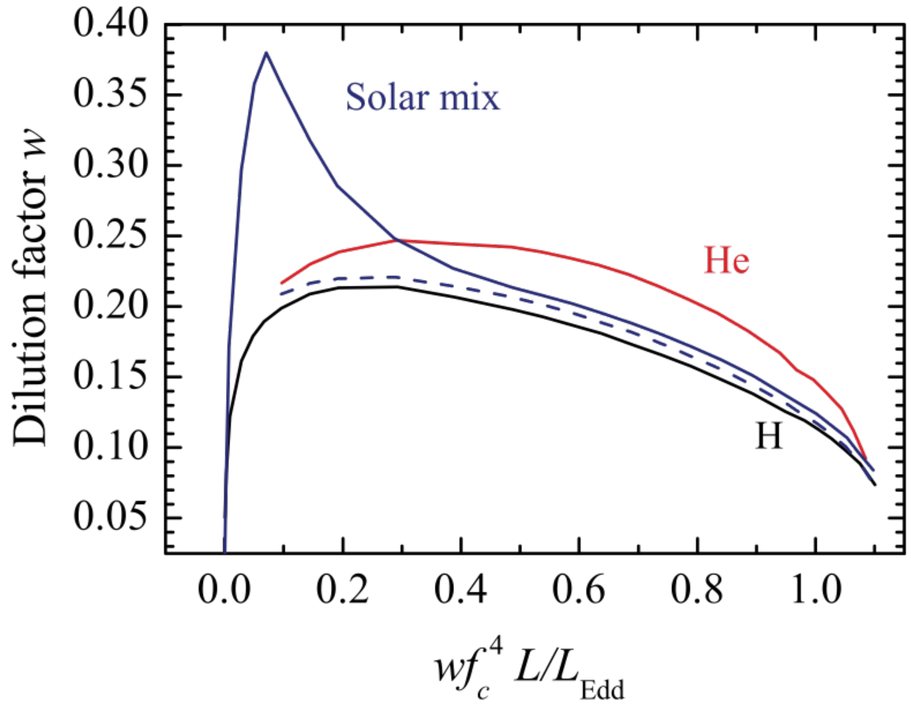
$$T_{BB} = f_c T_{eff} (1+z)^{-1}$$

Model dependences

Computed using undisturbed models of hot NS atmospheres



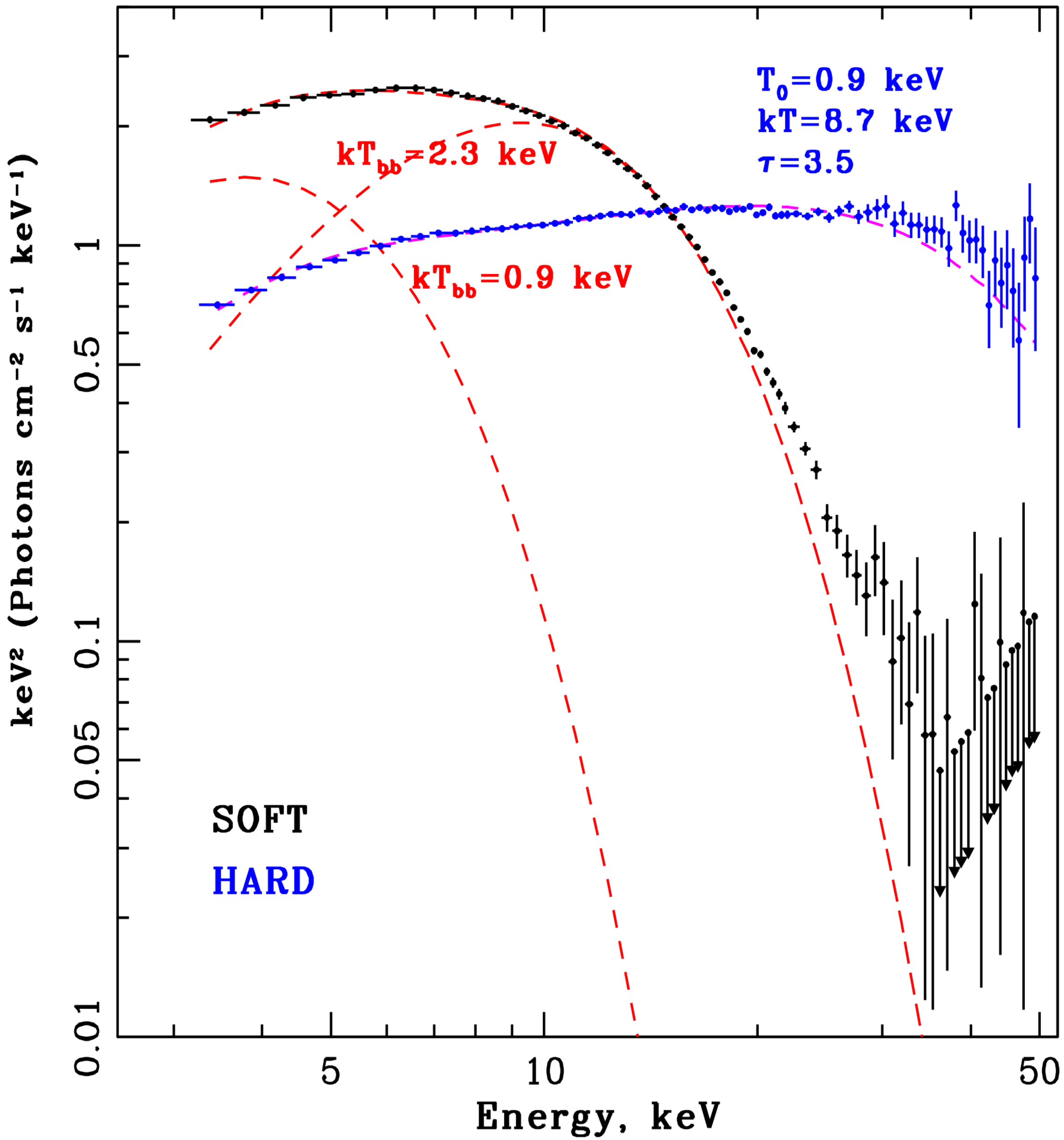
Suleimanov et al. 2011

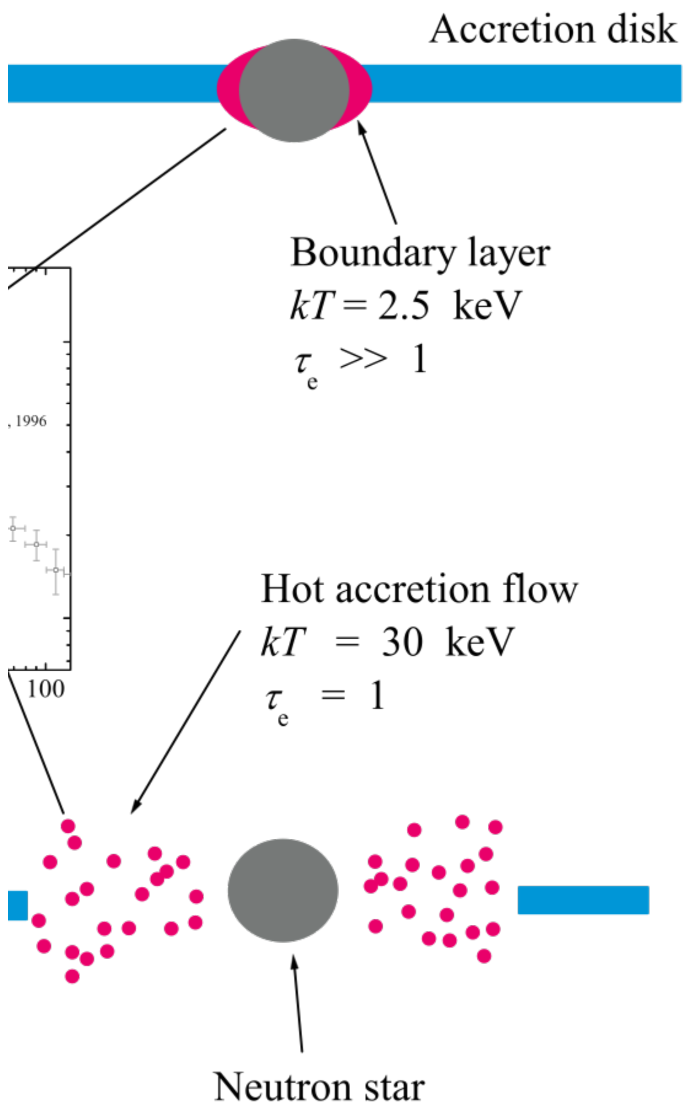


Suleimanov et al. 2017

Ultracompact system 4U 1820-30

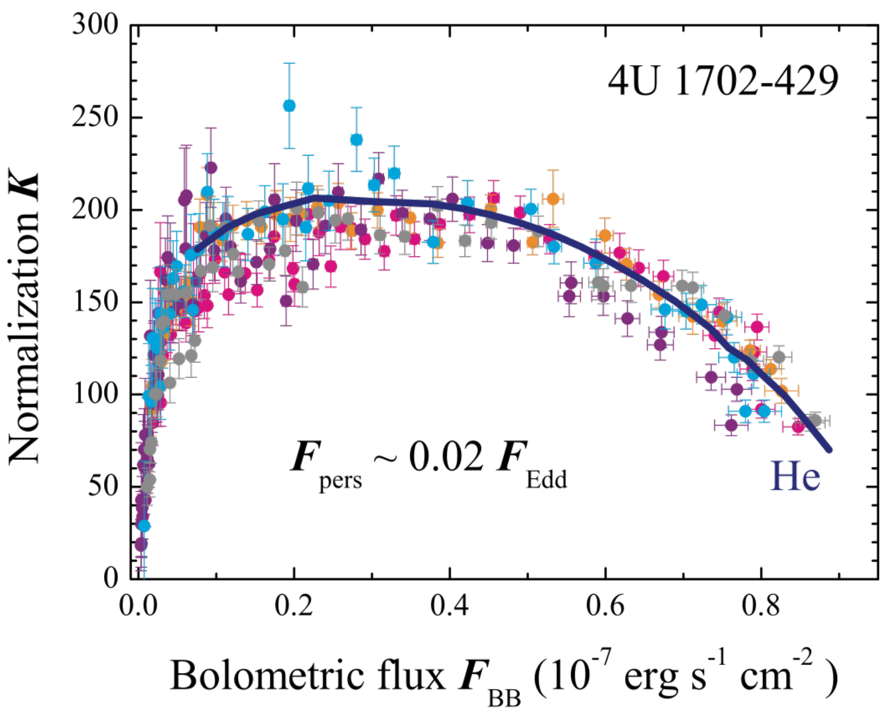
Persistent spectra

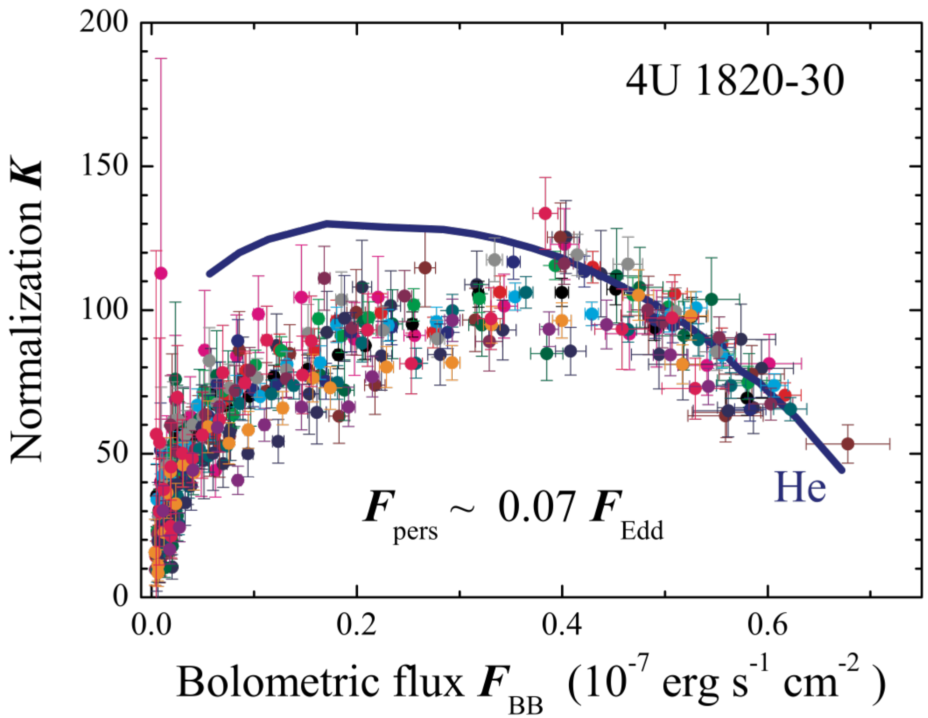




Comparison with observations

Deviation from theory depends on the persistent flux

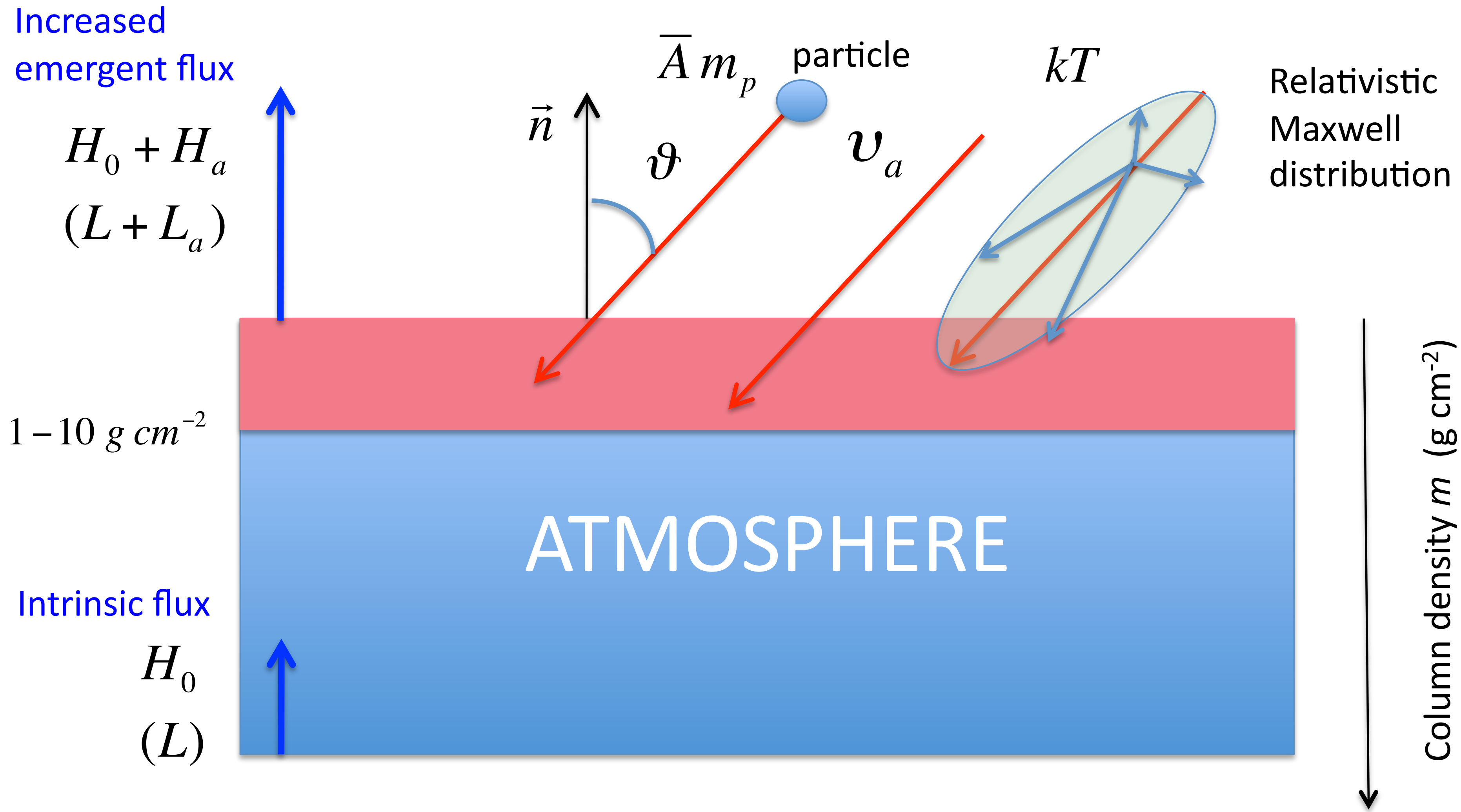




Low persistent flux

High persistent flux

Accretion heated atmospheres



$\dot{m}_a(H_a, \bar{A}\, m_p, \upsilon_a, kT, \vartheta)$ - local mass accretion rate, g s^{-1} cm^{-2}

Accretion heated atmospheres
Short history

Larkin (1960) - fast particle stopping in plasma

Zeldovich & Shakura (1969) – NS surface heated by fast particles

Alme & Wilson (1973) – the fist numerical computations

Bildsten et al. (1992) - analytical description, heavy ions destruction

Turolla et al. (1994) – “hot” solutions (T up to 10^{11} K)
Zampieri et al. (1995) – extension of AW73 computations
Zane et al. (1998) – spectra of “hot” solutions
Zane et al. (2000) – magnetized NS atmospheres heated by particles

Deufel et al. (2001) – application to hard quiescent spectra of LMXBs

Accretion heated atmospheres

Method of computation

The approach and the code used for undisturbed hot NS model atmospheres computations was accepted (Suleimanov et al. 2012)

Additionally

- energy generation in the heated layers $$\frac{dH}{dm} \approx -\dot{m}_a v_a \frac{dv_a}{dm}$$
- ram pressure force $$g_{ram} = \frac{dP_{ram}}{dm} \approx -\dot{m}_a \frac{dv_a}{dm}$$
- electron thermal conductivity (insignificant) $$H_C \approx k_C T^{5/2} \frac{dT}{dm}, \quad \frac{dH_C}{dm} \neq 0$$

$$\frac{dv_a}{dm} \propto v_a^{-3} \rho^{-1} \frac{Z^2}{A}$$

Accretion heated atmospheres

Adopted parameters

Neutron star: $M = 1.5\, M_\odot\,,\quad R = 12\ km,\quad \ell = L / L_{Edd}$

$$\upsilon_{ff} = \left(\frac{2GM}{R}\right)^{1/2} = 1.8 \times 10^{10}\, cm/s \approx\ 0.6\, c$$

$$kT_{vir} = \frac{GM\bar{A}m_p}{3R} \approx \bar{A}\, 61\ MeV\ (6.7 \times 10^{11}\, K)$$

Accretion flow: $\ell_a = L_a / L_{Edd} \qquad \upsilon_a = \eta\, \upsilon_{ff}\,,\quad \eta < 1$

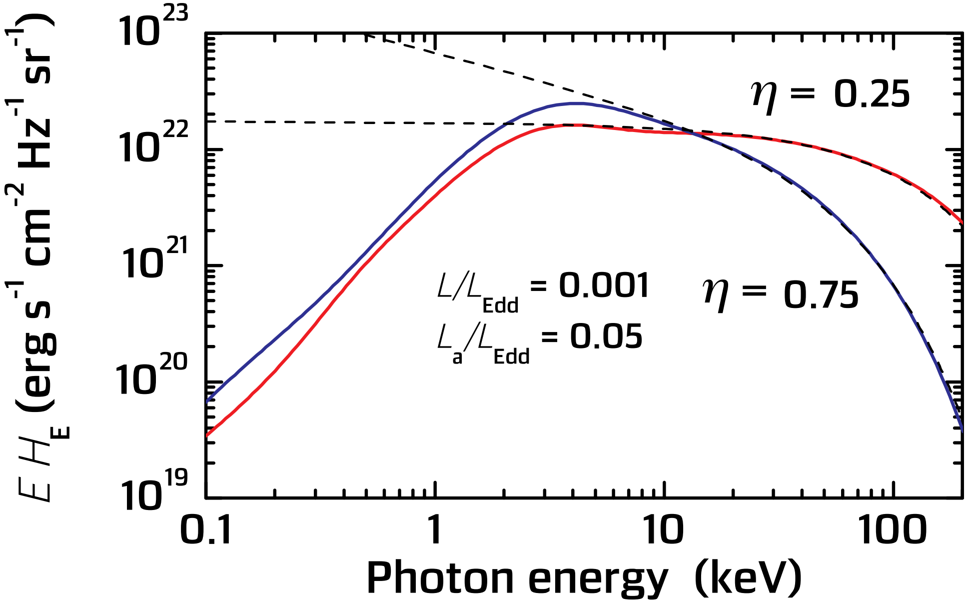
$kT = \chi\, kT_{vir}\,,\quad \chi < 1 \qquad \vartheta$

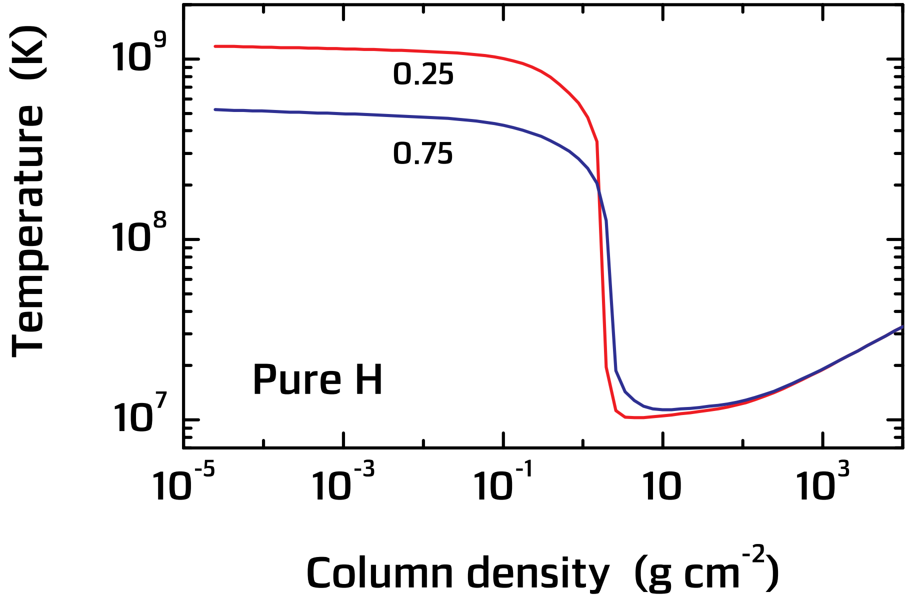
$\bar{A} = 1$ - pure hydrogen $\qquad \bar{A} = 4$ - pure helium

$\bar{A} \approx 1.3$ - solar hydrogen/helium mix

Low luminosity accretion heated atmospheres with various particle velocities η

$$L = 0.001\, L_{Edd} \quad L_a = 0.05\, L_{Edd} \quad \chi = 0.1 \quad \vartheta = 60^\circ$$





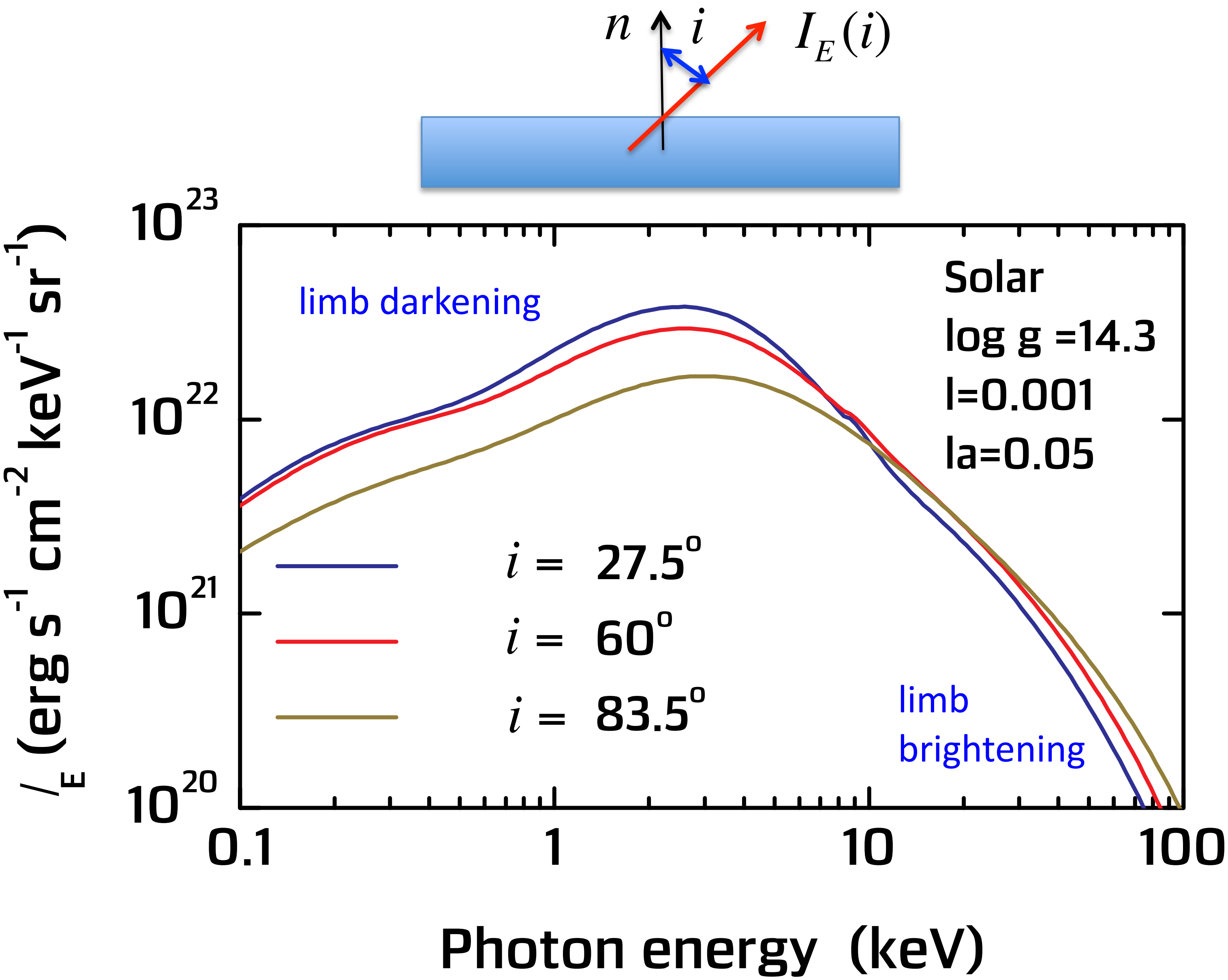
Spectra were fitted with exponential cutoff power law model

$$E^{-\Gamma} \exp(-E / E_{cut})$$

$\Gamma = 2.5 \quad E_{cut} = 43\ keV$ and $\Gamma = 2.01 \quad E_{cut} = 100\ keV$

Accretion heated atmospheres. Fixed parameters.

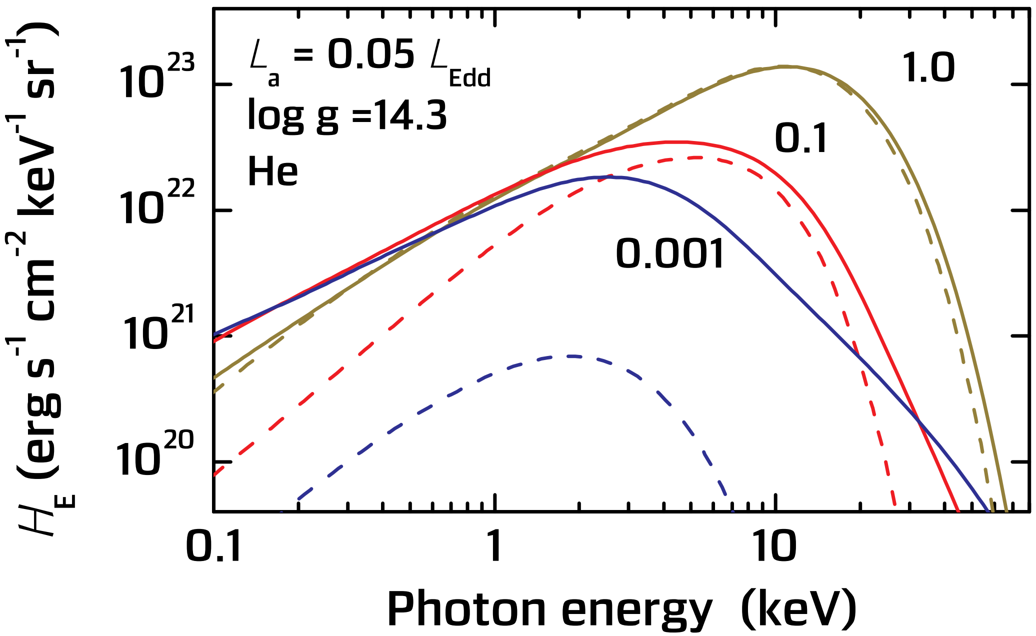
Angular distribution of the emergent radiation

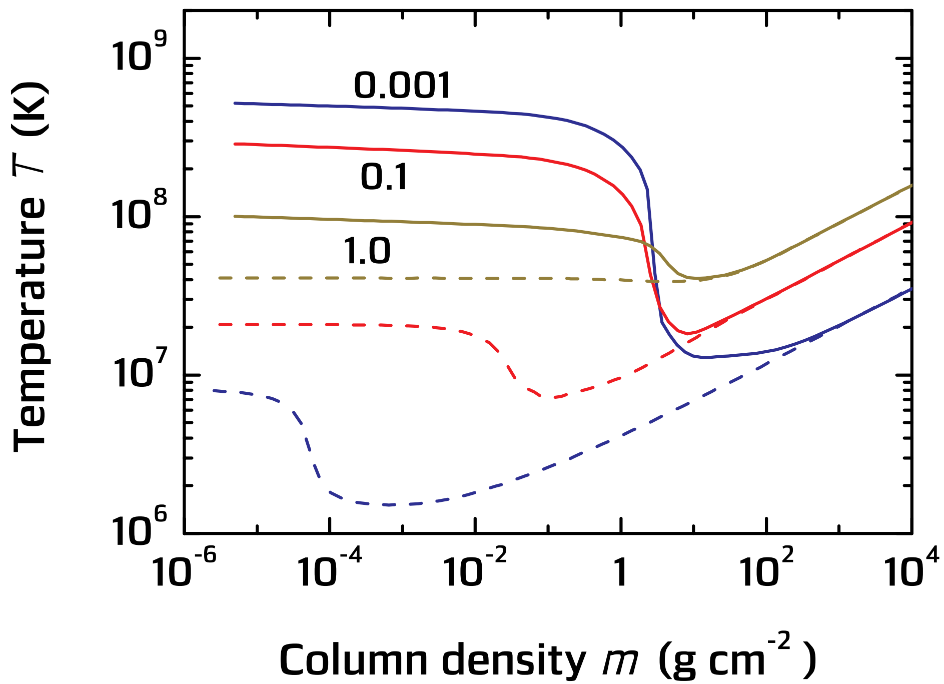


Accretion heated helium atmospheres. Fixed parameters.

Various internal luminosities

$$L_a = 0.05\, L_{Edd} \quad \eta = 0.75 \quad \chi = 0.03 \quad \vartheta = 60^\circ$$

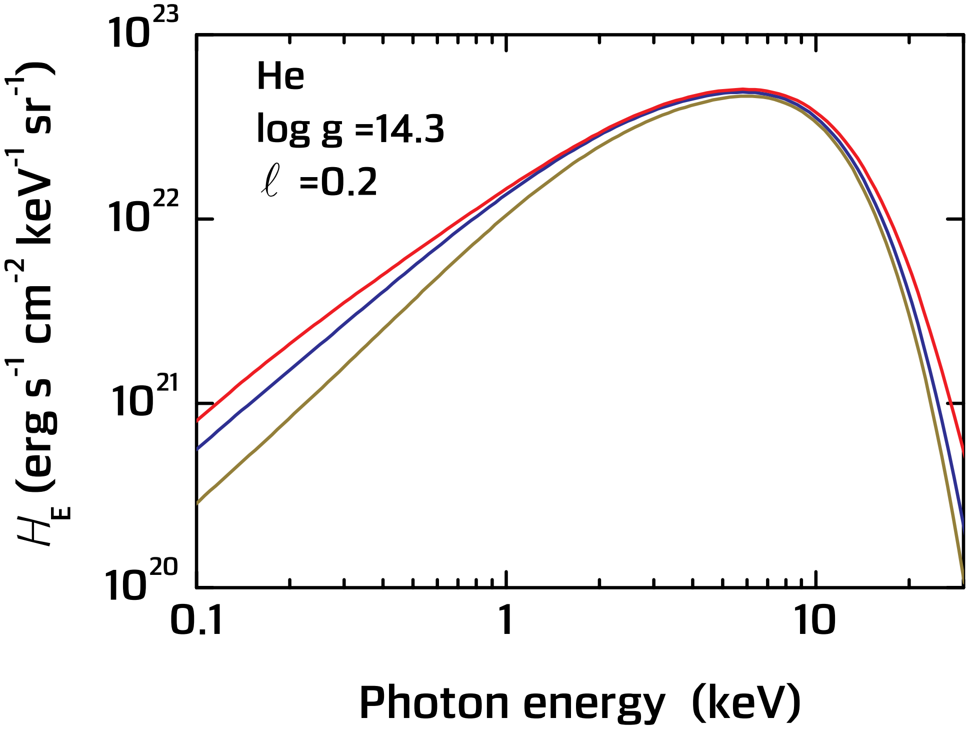


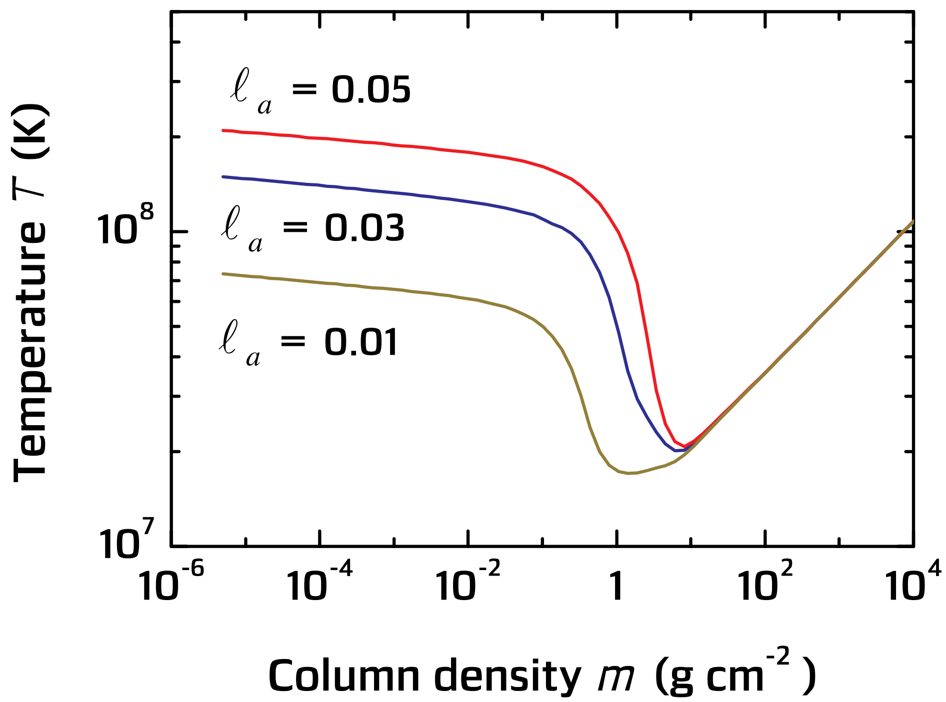


Accretion heated helium atmospheres. Fixed parameters.

Various heat luminosities

$$L = 0.2\, L_{Edd} \quad \eta = 0.75 \quad \chi = 0.03 \quad \vartheta = 60^\circ$$

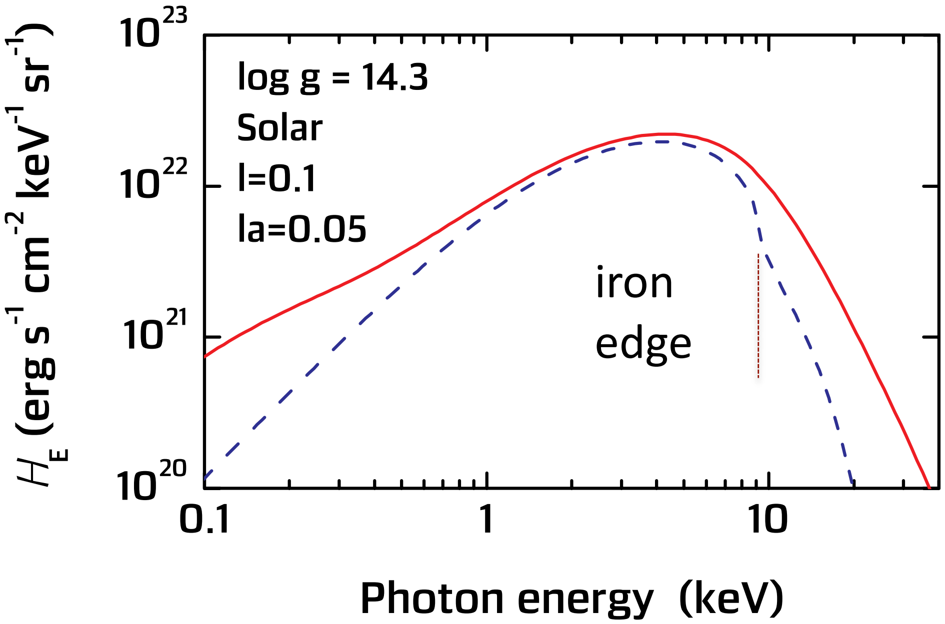


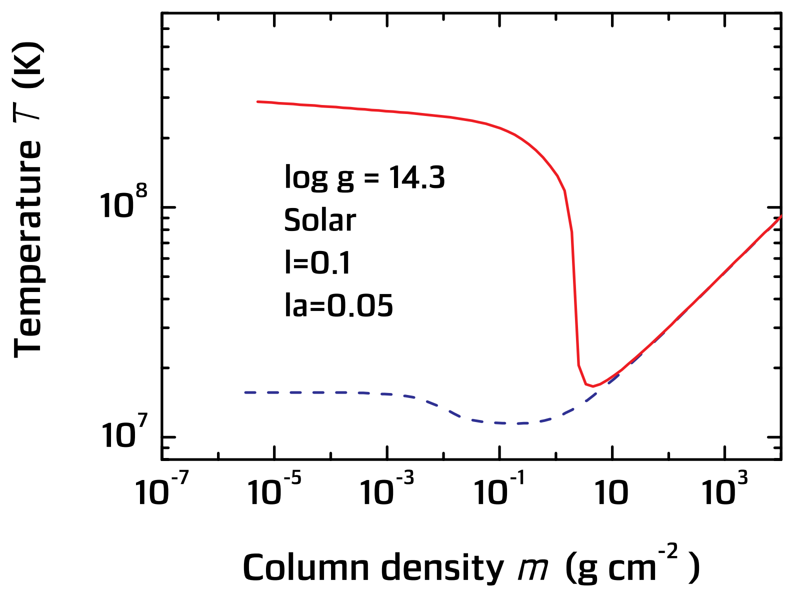


Accretion heated atmospheres with solar composition.

Iron edge disappears in the spectrum

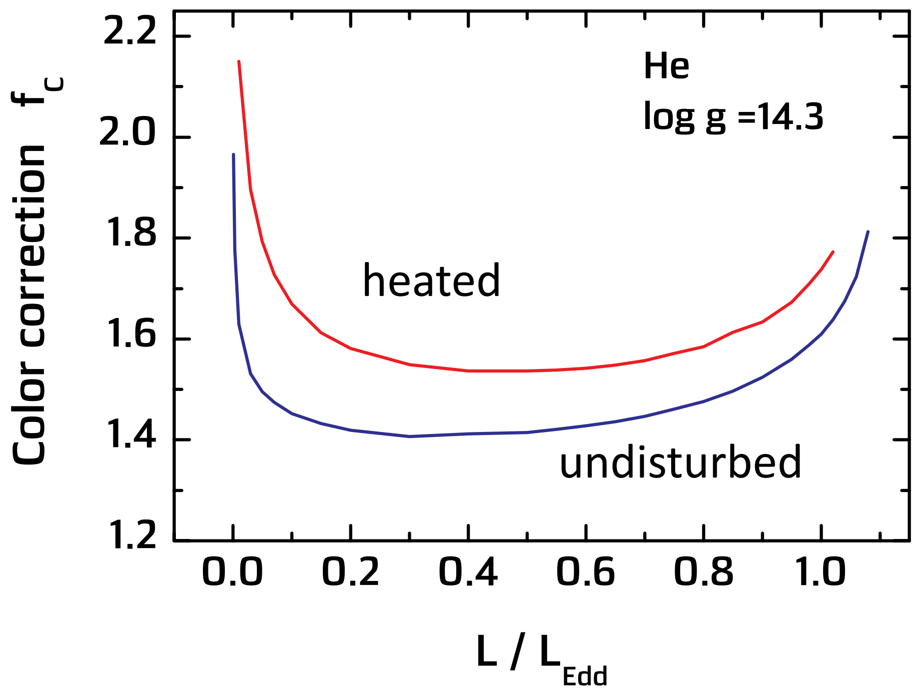
$$L_a = 0.05\, L_{Edd} \quad \eta = 0.75 \quad \chi = 0.03 \quad \vartheta = 60^\circ$$

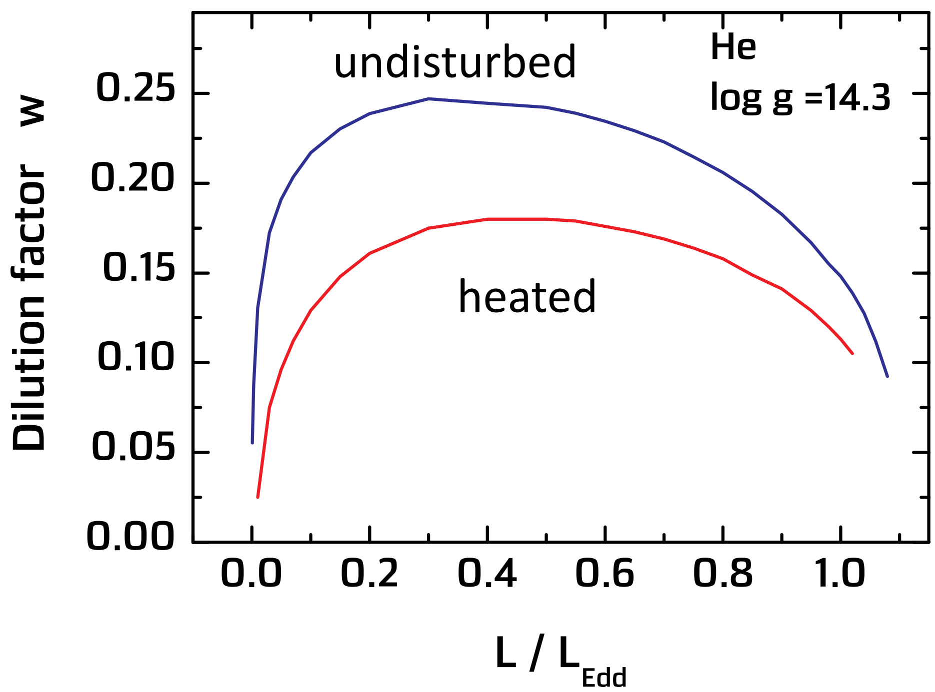




Accretion heated helium atmospheres.

Heated atmospheres less prominent evolution of the model curves at high relative velocities. The color correction values are large for heated atmospheres (corresponding dilution factors are smaller).

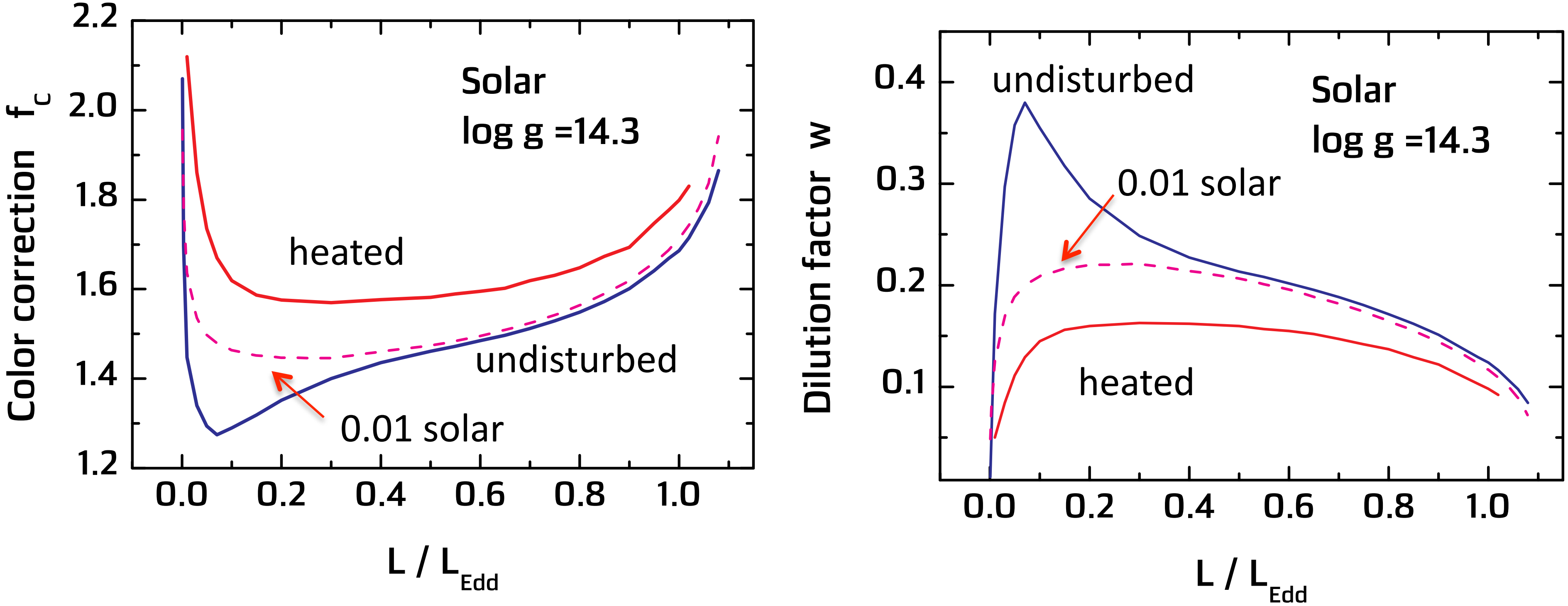




$$L_a = 0.05\ L_{Edd} \quad \eta = 0.75 \quad \chi = 0.03 \quad \vartheta = 60^\circ$$

Accretion heated atmospheres with solar composition.

Heated atmospheres mimic atmospheres of low metal abundances



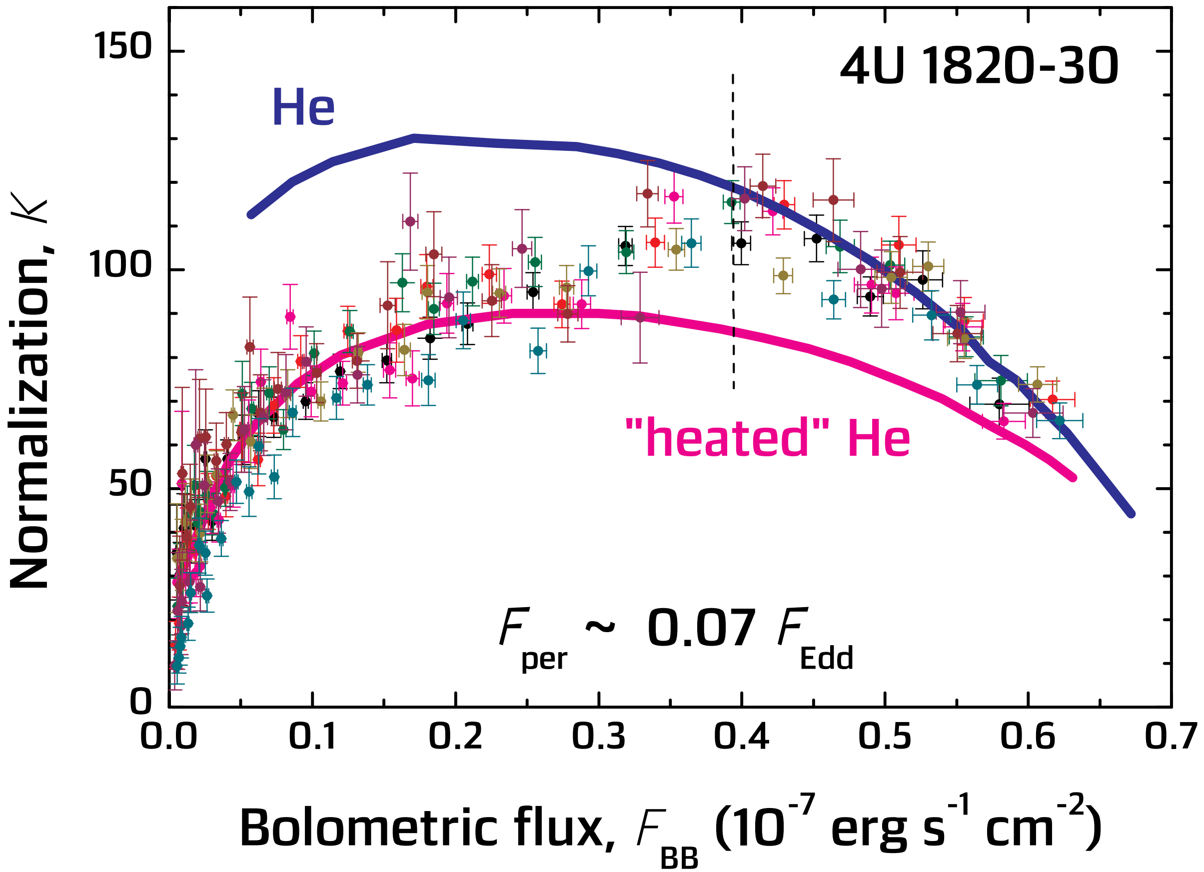
$$L_a = 0.05\, L_{Edd} \quad \eta = 0.75 \quad \chi = 0.03 \quad \vartheta = 60^\circ$$

Burster in ultracompact system 4U 1820 -- 30

Both model curves have the same fitting parameters

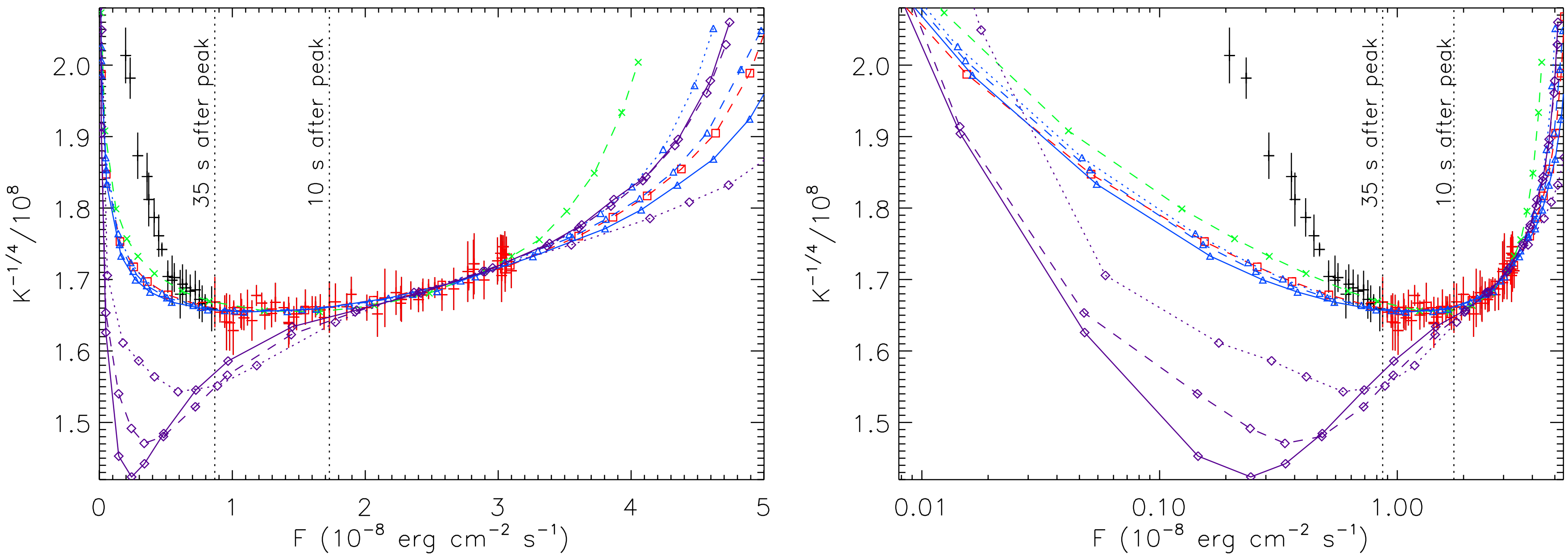
$$F_{Edd} = 0.6 \ \ (10^{-7} \ erg \ s^{-1} cm^{-2})$$

$$\Omega = R^2 (1+z)^2 / D^2 = 500 \ km^2 / (10 \, kpc)^2$$



“Clocked” burster GS 1826 -- 24

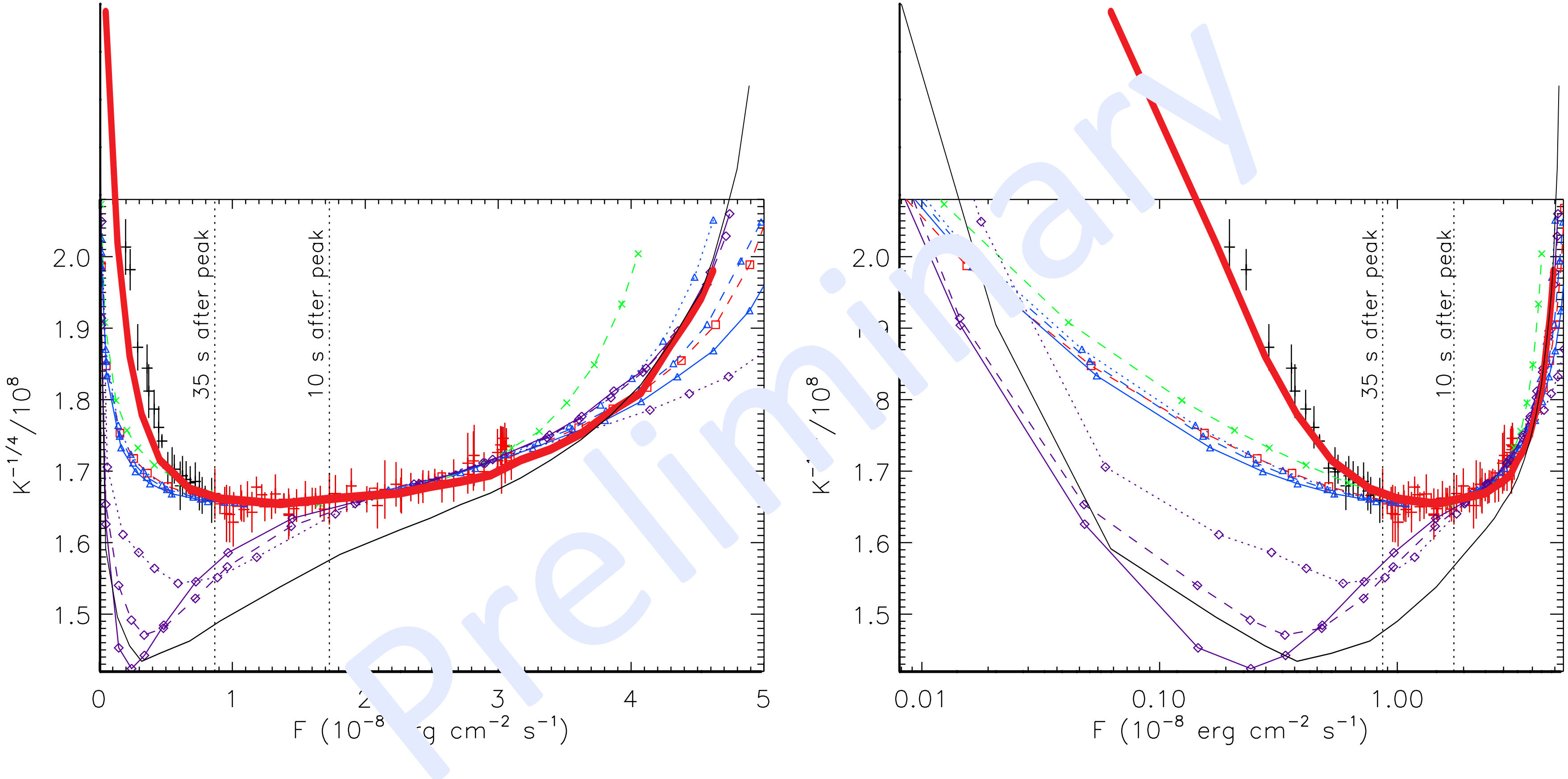
Its atmosphere has to have solar chemical composition (Heger et al. 2007). But the observed curve $K^{-1/4} - F_{BB}$ doesn’t show depression at $L \approx 0.1\, L_{Edd}$ typical for model curves computed for undisturbed atmospheres.



Figures from Zamfir et al. 2012

“Clocked” burster GS 1826 -- 24

But the observed curve well fitted with the “heated” model curves



Figures from Zamfir et al. 2012

Conclusions

A method of accretion heated NS atmospheres was developed.

A number of heated atmospheres was computed and
the dependences on the input parameters were investigated.

The "observed" spectra of heated atmospheres
of X-ray bursting NSs are well fitted with diluted blackbody.

Color correction factors are large for heated atmospheres,
and dilution factors are smaller.

Iron edge disappears in the heated NS atmospheres with
solar abundance of heavy elements.

Model curves $w - w f_c^4 L / L_{Edd}$ are well fitting the observed curves
$K - F_{BB}$ at the later phases of the X-ray bursts.