On the dependence of the X-ray continuum variations with luminosity in accreting X-ray pulsars

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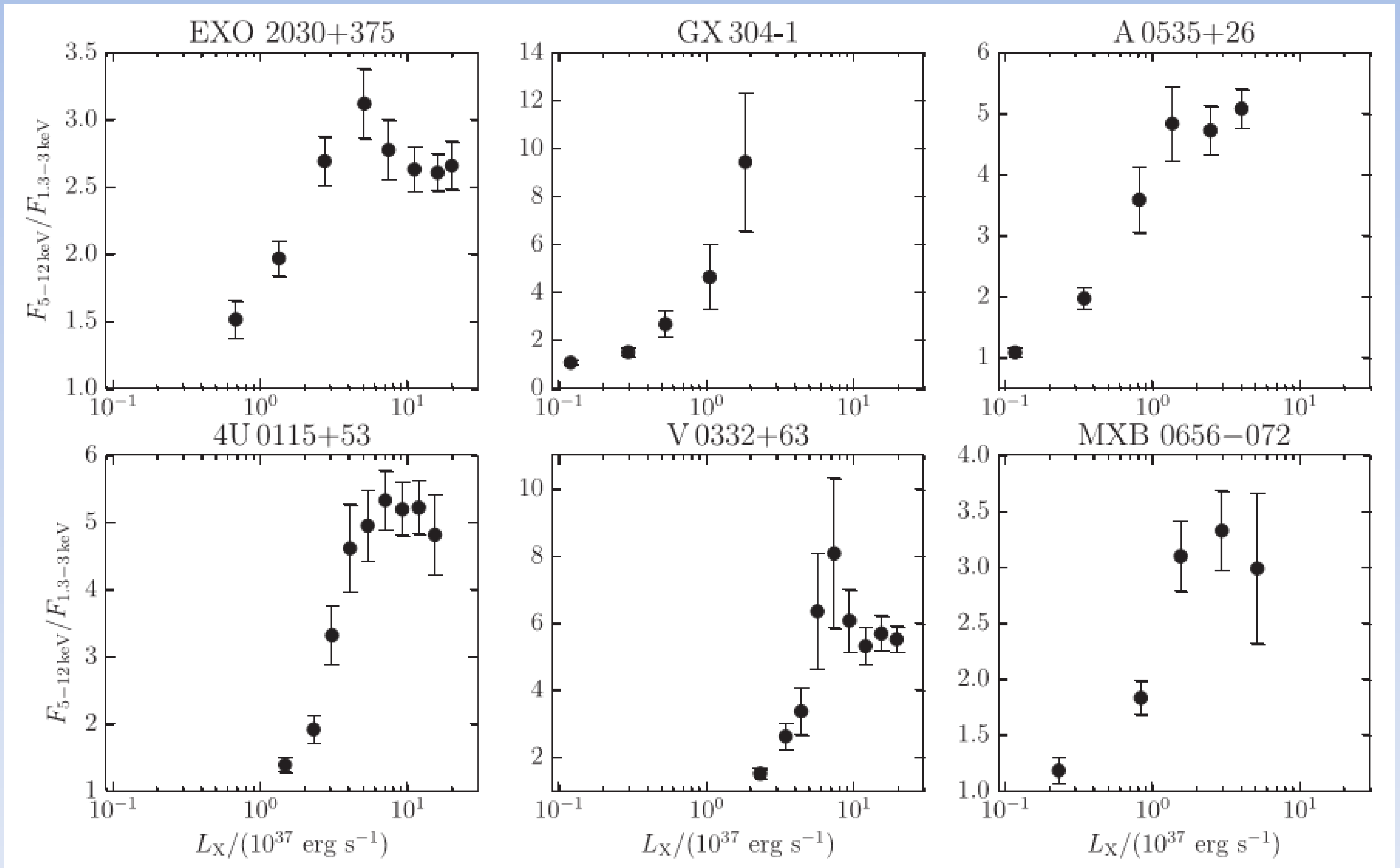
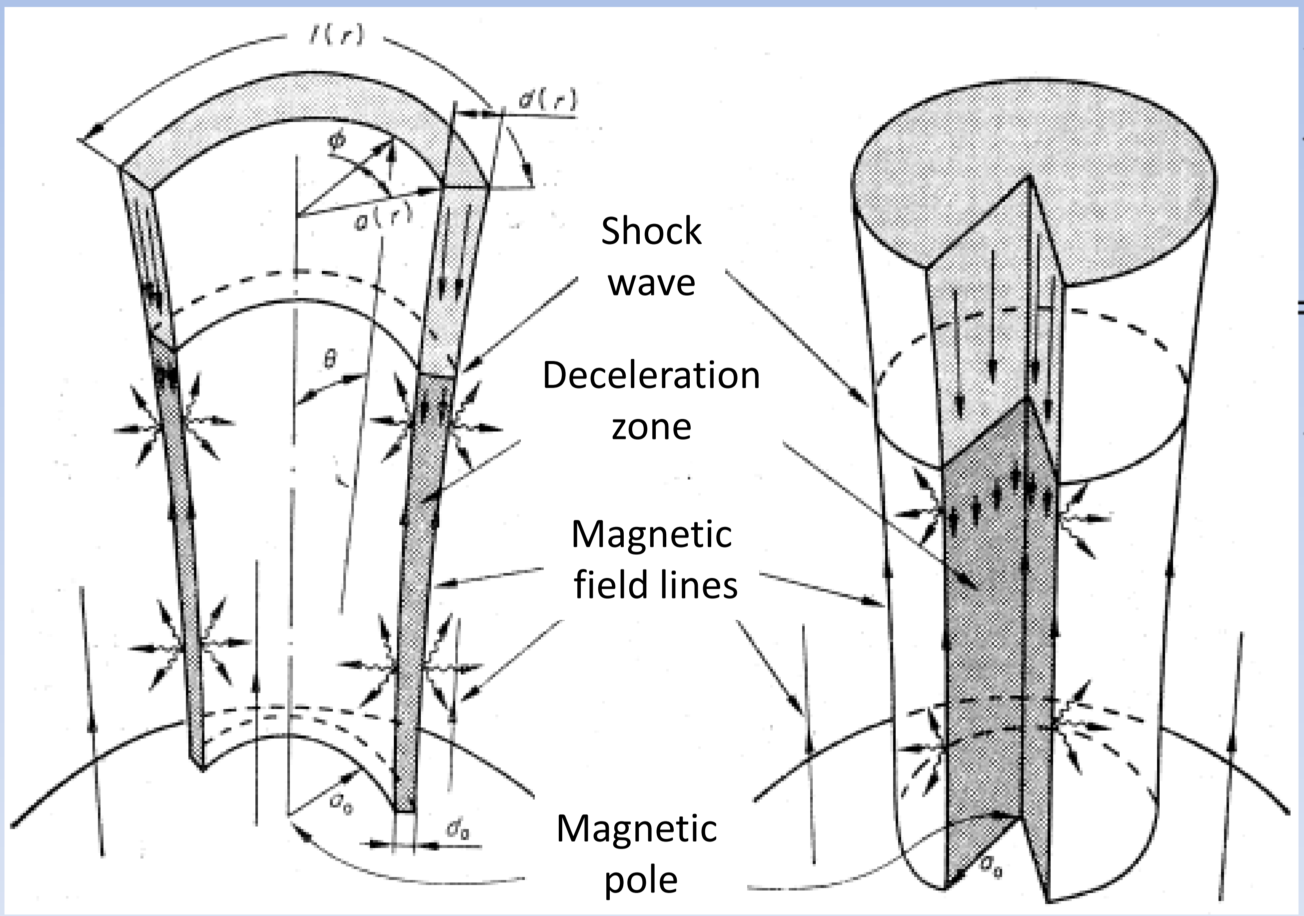
Introduction. Observations

- The dependence of the X-ray continuum hardness with luminosity studied using data from all-sky monitors such as *RXTE*/ASM (D. Klochkov, E. Laplace; Postnov et al. 2015)



Two models of the accretion columns. Boundary conditions



$v(\infty) = 10^{10}$ cm/s

$v(0) = 0$

$F_r(a_0) = F_r(a_0 + d_0) = = \frac{2}{3} cU$

$\dot{M} = 1 \div 8 \times 10^{17}$ g/s

Basko M. M., Sunyaev R. A., 1976, MNRAS, 175, 395

Basic equations

- The steady-state momentum equation for accretion braking by the radiation with energy density U reads

$$(\mathbf{S} \cdot \nabla)\mathbf{v} = -\frac{1}{3}\nabla U.$$

Here $\mathbf{S} = \rho\mathbf{v}$ is the material flux.

- The mass continuity equation

$$S = \rho v = \mathrm{const}$$

- The energy equation

$$\nabla \cdot \mathbf{F} = -\mathbf{S} \cdot \nabla \left(\frac{v^2}{2}\right).$$

- The radiative transfer equation in the diffusion approximation is

$$\frac{c}{3\kappa\rho}\nabla U = -\mathbf{F} + \frac{4}{3}U\mathbf{v}.$$

Basic equations

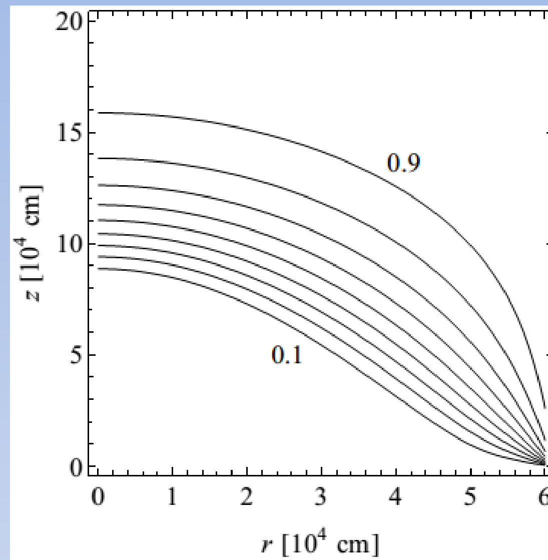
$$K_T\left[\frac{\partial^2 Q}{\partial \tilde{r}^2}+\frac{1}{\tilde{r}}\frac{\partial Q}{\partial \tilde{r}}\right]+K_{\|}\left[\frac{\kappa_T}{\kappa_{\|}}\frac{\partial^2 Q}{\partial \tilde{z}^2}-8\frac{\partial}{\partial \tilde{z}}\left(\sqrt{Q}-Q\right)\right]-\frac{\partial Q}{\partial \tilde{z}}=0,$$

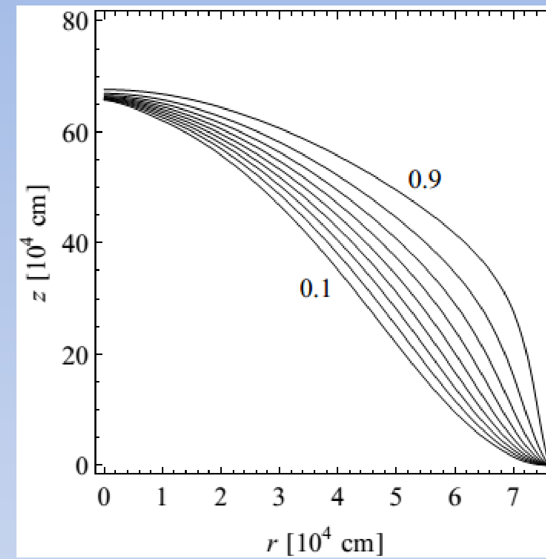
$$K_T=\left(1+\frac{v_0}{6c(1-\sqrt{Q})}\left|\frac{\partial Q}{\partial \tilde{r}}\right|\right)^{-1},\ K_{\|}=\left(1+\frac{\kappa_T}{\kappa_{\|}}\frac{v_0}{6c(1-\sqrt{Q})}\left|\frac{\partial Q}{\partial \tilde{z}}\right|\right)^{-1}.$$

$$Q=\left(\frac{v}{v_0}\right)^2,\quad \tilde{r}=\frac{\kappa_T S r}{c},\quad \tilde{z}=\frac{\kappa_T S z}{c}.$$

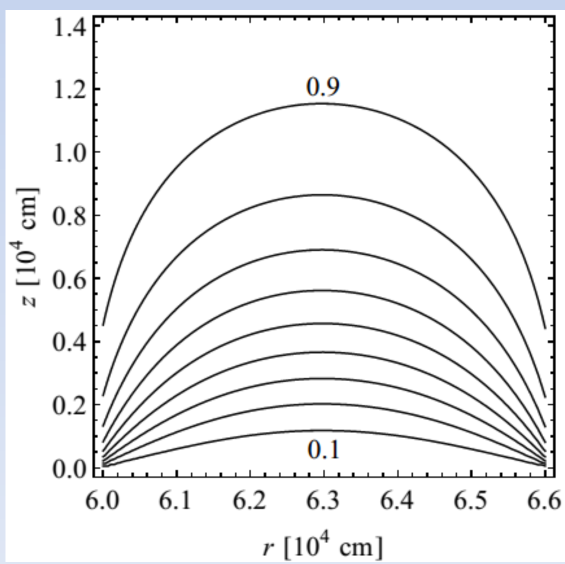
The lines of equal $Q = \left(\frac{v}{v_0}\right)^2$. $\dot{M}_{17} = \dot{M}/_{10^{17}\ \mathrm{g/s}} = 1; 5$

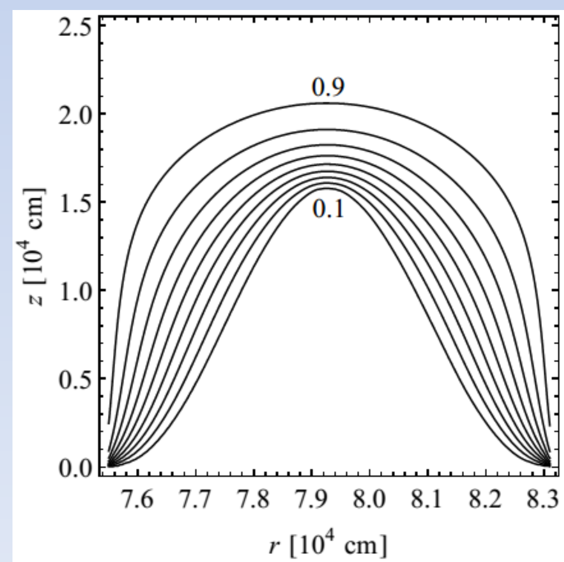
- For the filled-column geometry





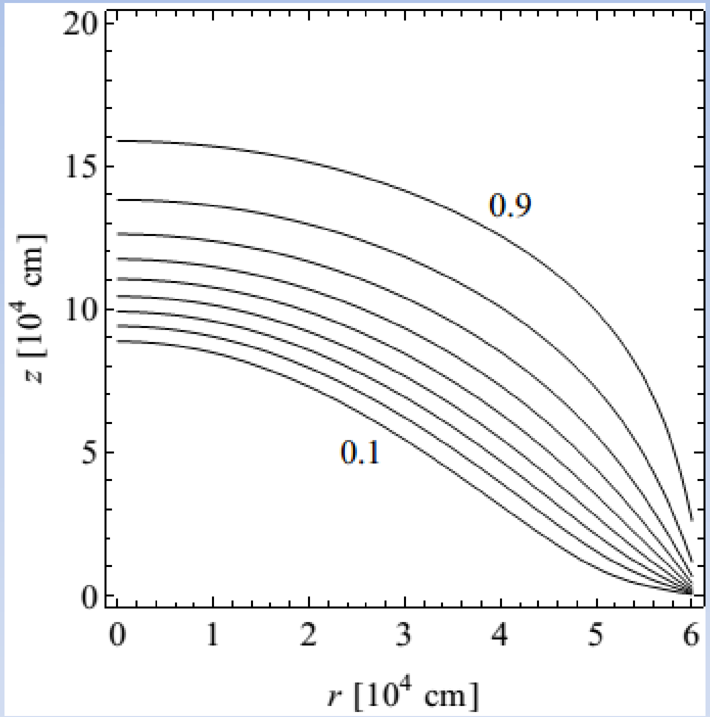
- For the hollow-column geometry with wall thickness $0.1r_0$; r_0 is the radius of corresponding filled column

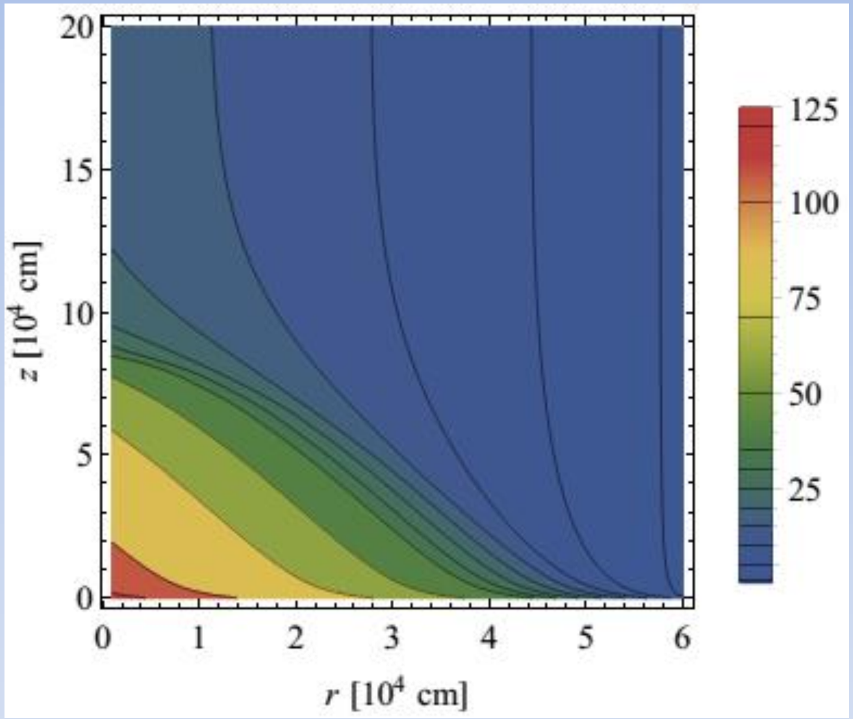




The lines of equal optical depth

- The filled column, $\dot{M}=10^{17}$ g/s

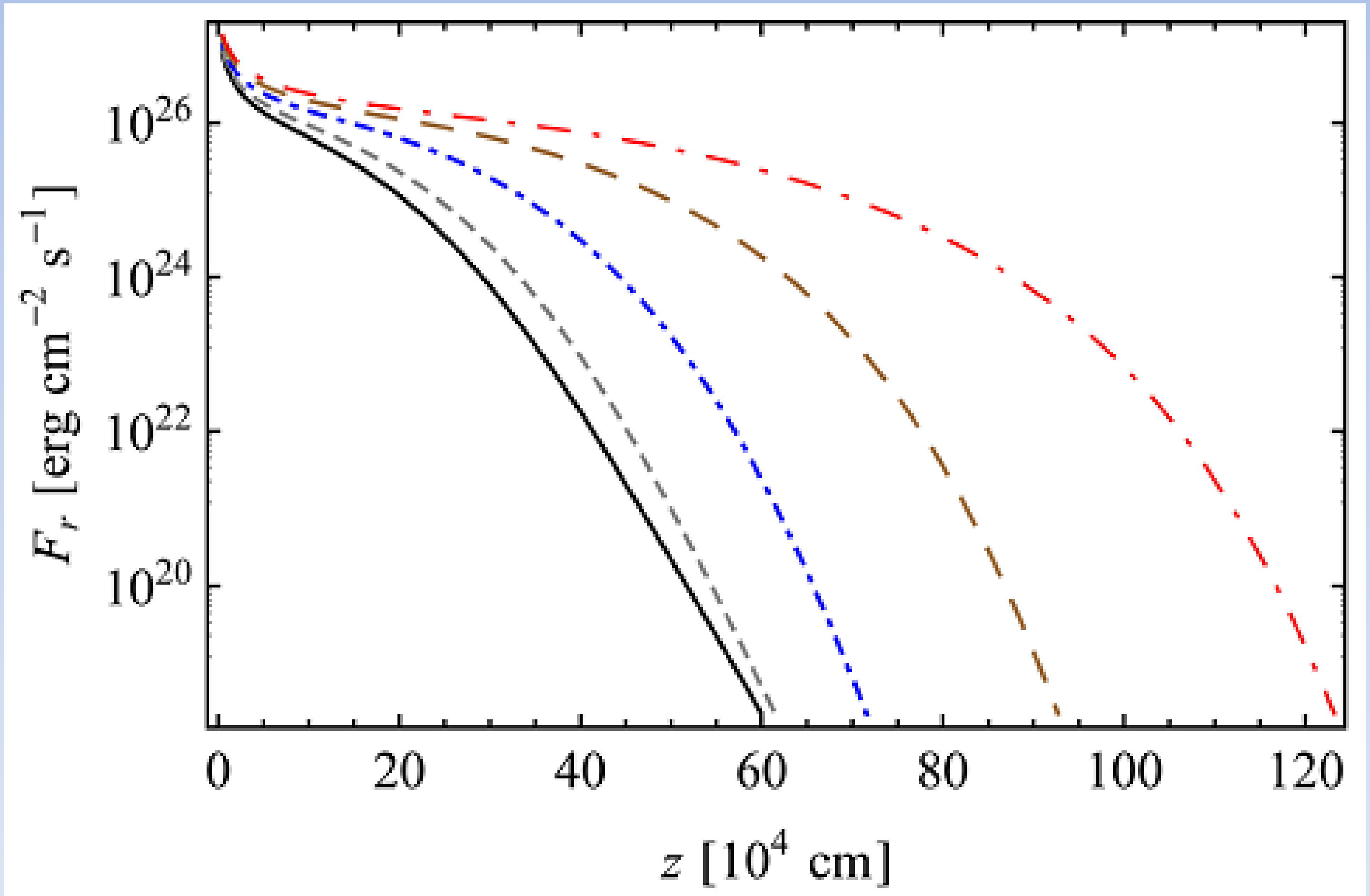




The radial energy flux F_r ($\tau \approx 1$, z) calculated along the height of a filled-cylinder column at different mass accretion rates

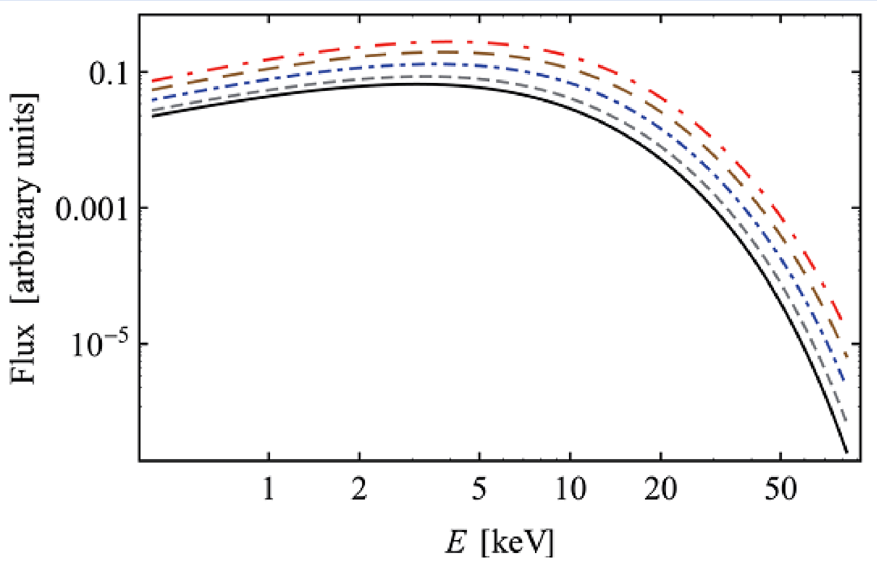
- The lines from bottom to up correspond to $\dot{M}_{17} = 2, 3, 5, 8, 12$, respectively.

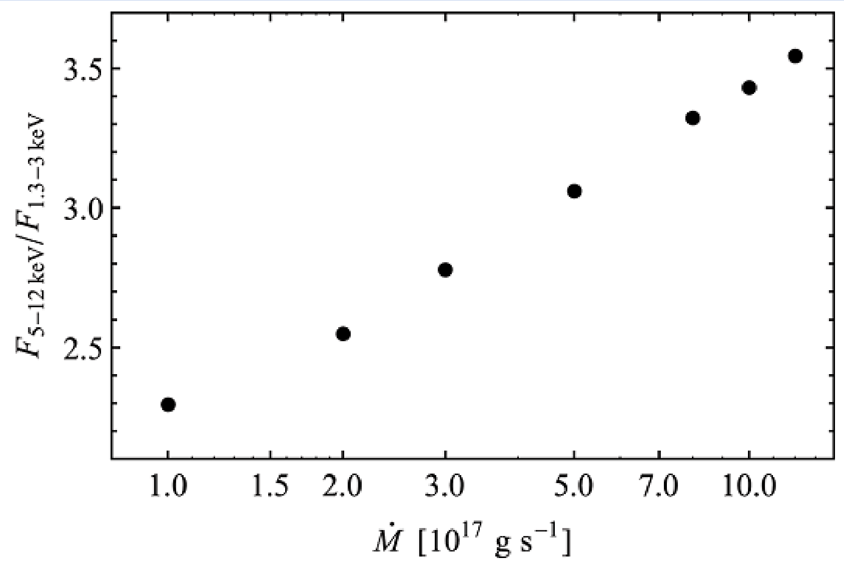
$\dot{M}_{17} = \dot{M} / 10^{17}\ \mathrm{g/s}$



Spectra of accretion columns

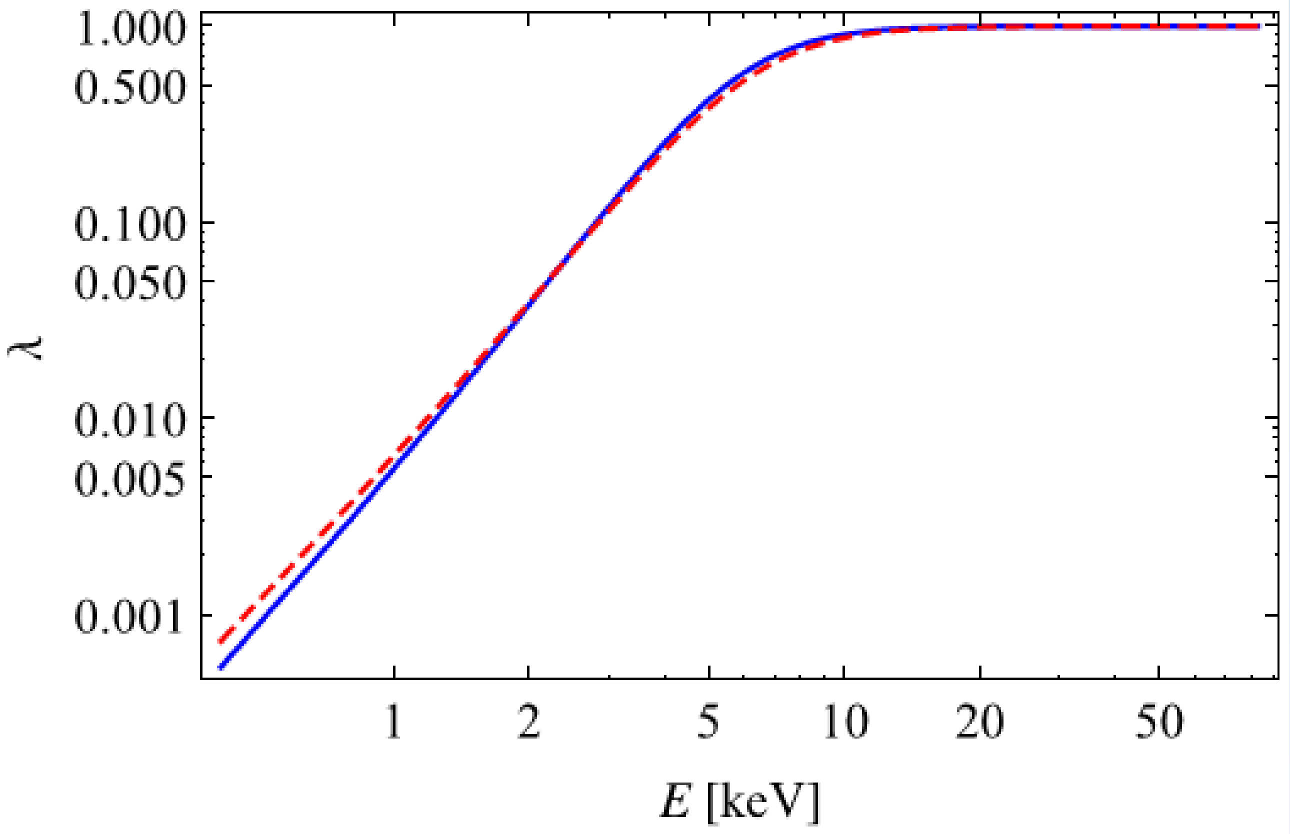
- Left: the spectrum of sidewall emission from optically thick filled-cylinder accretion column, as seen by the local observer, for mass accretion rates $\dot{M}_{17} = 2, 3, 5, 8,$ and 12 (from bottom to up, respectively)
- Right: the spectral hardness ratio HR as a function of mass accretion rate





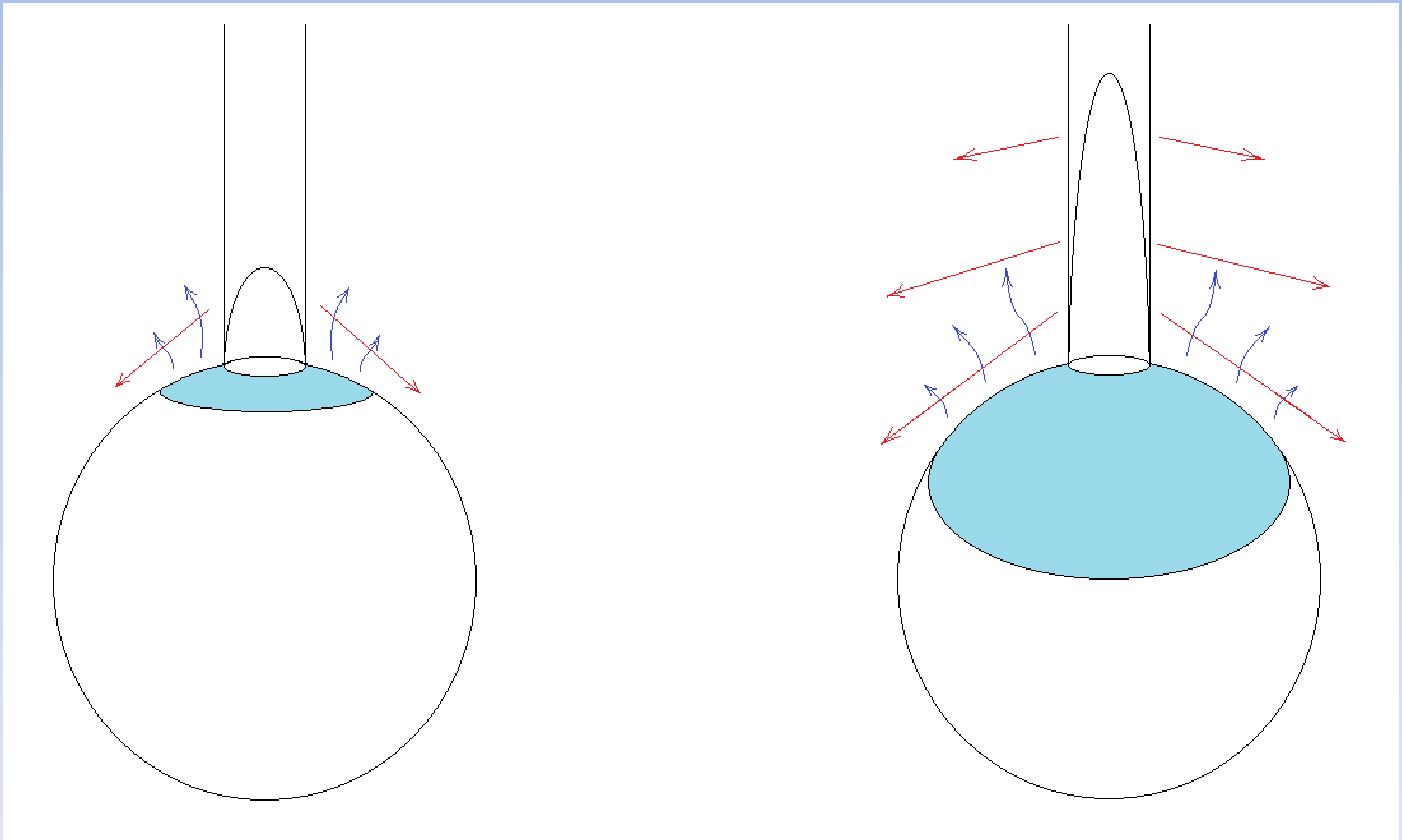
The single-scattering Compton X-ray albedo from a NS atmosphere with strong magnetic field

- The electron number density is $n_e = 5 \times 10^{25}$ cm^{-3}, electron temperature $T = 3$ keV, magnetic field $B = 3 \times 10^{12}$ G, photon incident angle to the magnetic field $\pi/4$. Extraordinary and ordinary photon spectra are shown by the solid and dashed lines, respectively. The cyclotron line is ignored



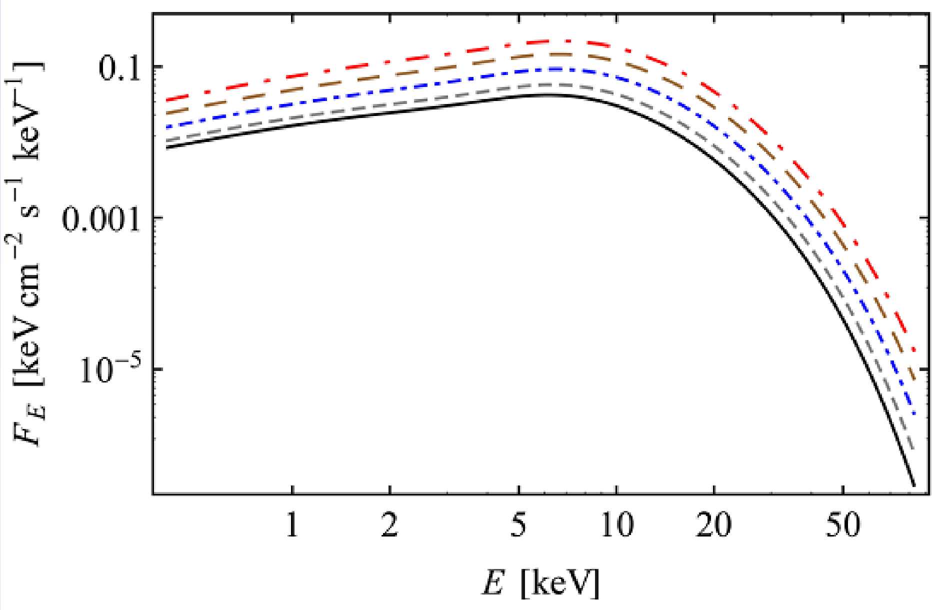
Reflection from the neutron star

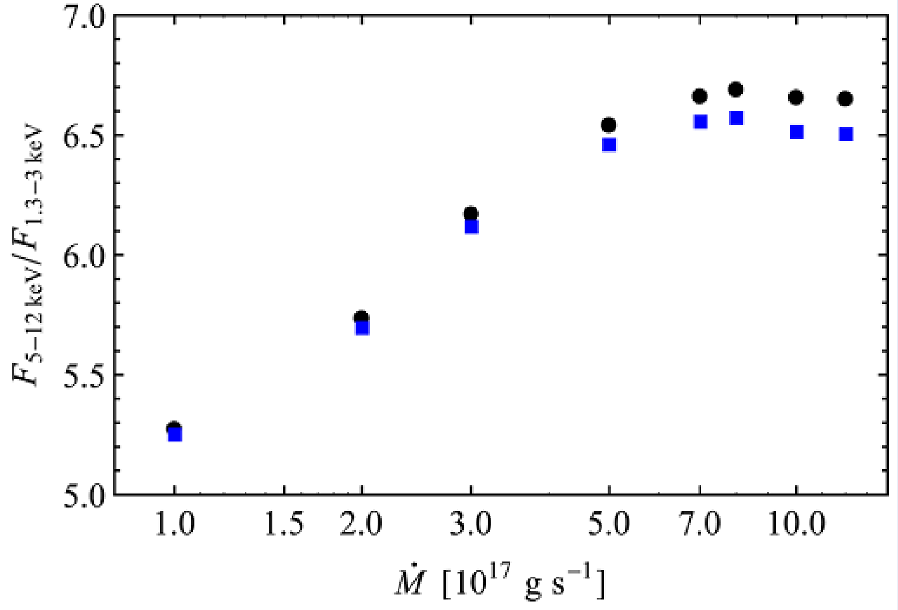
- Contribution of the reflected component in the total spectrum decreases with increasing of accretion rate



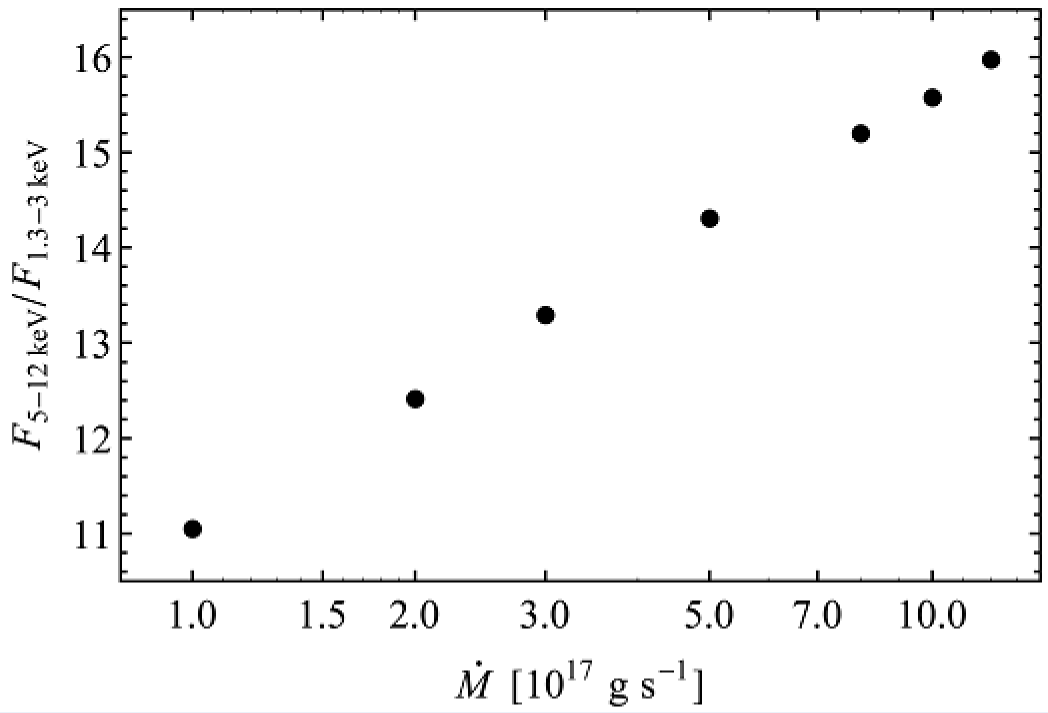
Spectra of accretion columns with taking into account the radiation reflected from the neutron star atmosphere

- Left: the total spectrum of direct sidewall and reflected from the NS atmosphere from the optically thick filled accretion column for mass accretion rates $\dot{M}_{17} = 2, 3, 5, 8,$ and 12 (from bottom to up, respectively)
- Right: the hardness ratio HR of the total spectrum. Shown are calculations for the NS radius $R_{\rm NS} = 10$ km (squares) and $R_{\rm NS} = 13$ km (circles)





Hardness ratio of the total emission (direct plus reflected from the NS atmosphere) from a hollow-cylinder accretion column as a function of mass accretion rate $\dot{M}$



Conclusions

- The results show the difference between structures in one-dimensional and two-dimensional approaches to the solution
- Changing of the height of the optically thick structure significantly affects on the dependence of the x-ray hardness with luminosity
- "Saturation” can be explained not by the transition to the regime of radiation domination, but changing of the parameters of a column in this regime
- In the frame of this model, the saturation of the spectral hardness in the case of a hollow-cylinder geometry of the accretion column can be achieved at much higher accretion rates (roughly, scaled with the relative thickness of the column wall), because the characteristic height of the column in this case is correspondingly smaller than that of the filled column

References

- Postnov K.A. et al., 2015, MNRAS, 452, 1601