X-RAYS FROM NEUTRON STAR ATMOSPHERES AT LOW ACCRETION RATES

E. Sokolova-Lapa[1, 2], M. Gornostaev[2], J. Wilms[1], R.Ballhausen[1],
S. Falkner[1], K. Postnov[2], P. Thalhammer[1], F. Fürst[3], F.-W. Schwarm[1],
K. Pottschmidt[4], P. Becker[5], and M. Wolff[6]

[1]Remeis & ECAP [2]SAI MSU [3]ESAC [4]CRESST [5]GMU [6]NRL SSD

Abstract

We present a new model to simulate an energy spectrum of accretion-powered X-ray pulsars at very low accretion rates $\dot{M} \lesssim 5\times10^{15}$ g s^{-1}. We solve the polarized radiative transfer equation in the atmosphere of the neutron star taking into account magnetic Compton scattering and free-free processes. The structure of the atmosphere is obtained assuming energy balance and hydrostatic equilibrium. The model is able to explain the recent faint observations of accreting X-ray pulsars which show untypical bimodal spectral energy distribution with two humps around 5 keV and 30-40 keV. We argue that the high-energy component is the Wien hump due to saturated Comptonization in the hot dense upper layers of the neutron star atmosphere, modified by an imprinted cyclotron line. The low energy blackbody-like component results from the thermal irradiation from the deeper layers of the neutron star atmosphere, transferred by extraordinary photons.

Model description

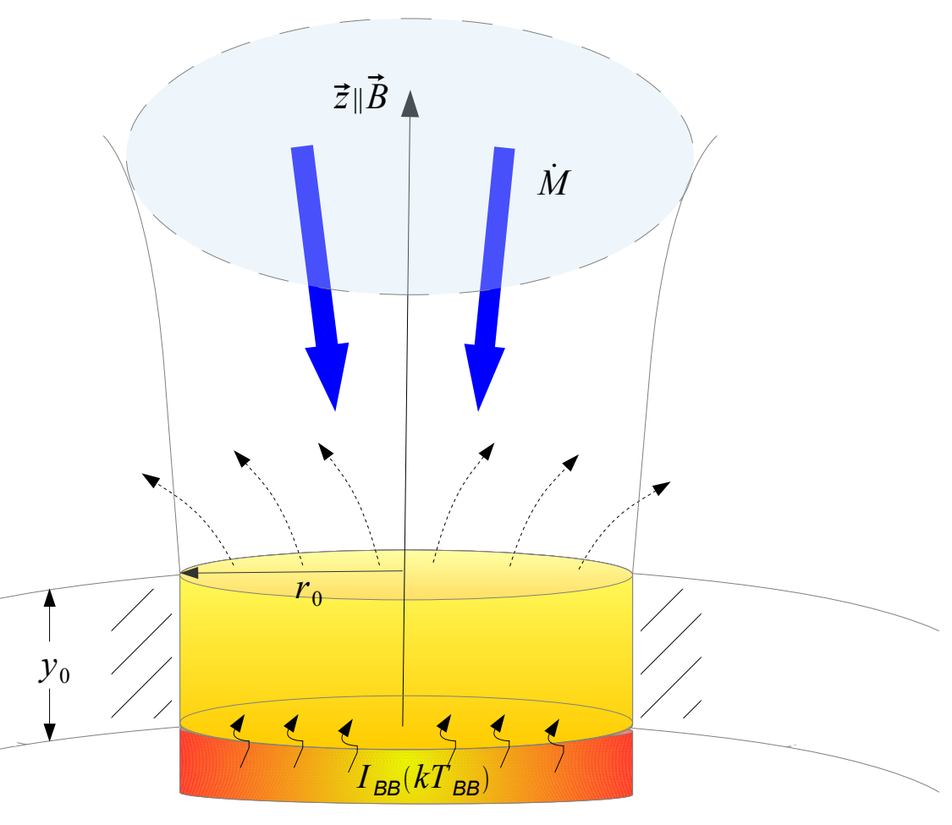

Figure 1: Schematic depiction of the polar cap model.

We consider accretion onto strongly magnetized neutron stars with rates corresponding to low luminosities of $L \lesssim 10^{35}$ erg s^{-1}. At these accretion rates no accretion column is formed. Accreted matter falls freely and the final stopping occurs within a thin layer of the neutron star atmosphere by Coulomb collisions (Harding et al., 1984). We model the emission from the polar cap by solving the polarized radiative transfer in the neutron star atmosphere. We assume a plane-parallel slab of atmosphere with electron temperature and density varying along the z-coordinate parallel to the magnetic field $\vec{B}$ and perpendicular to the surface (see Fig. 1). We tabulated synthetic spectra for a large set of parameter combinations to fit directly to observational data of low luminosity observations of X-ray pulsars. Hereafter we refer to our model as the `polcap` model.

Model parameters

$\dot{M}$ - mass accretion rate
B_0 - surface magnetic field
y_0 - atmosphere depth
r_0 - polar cap radius
$T_{\rm BB}$ - seed photons temperature

Atmosphere structure and radiative transfer

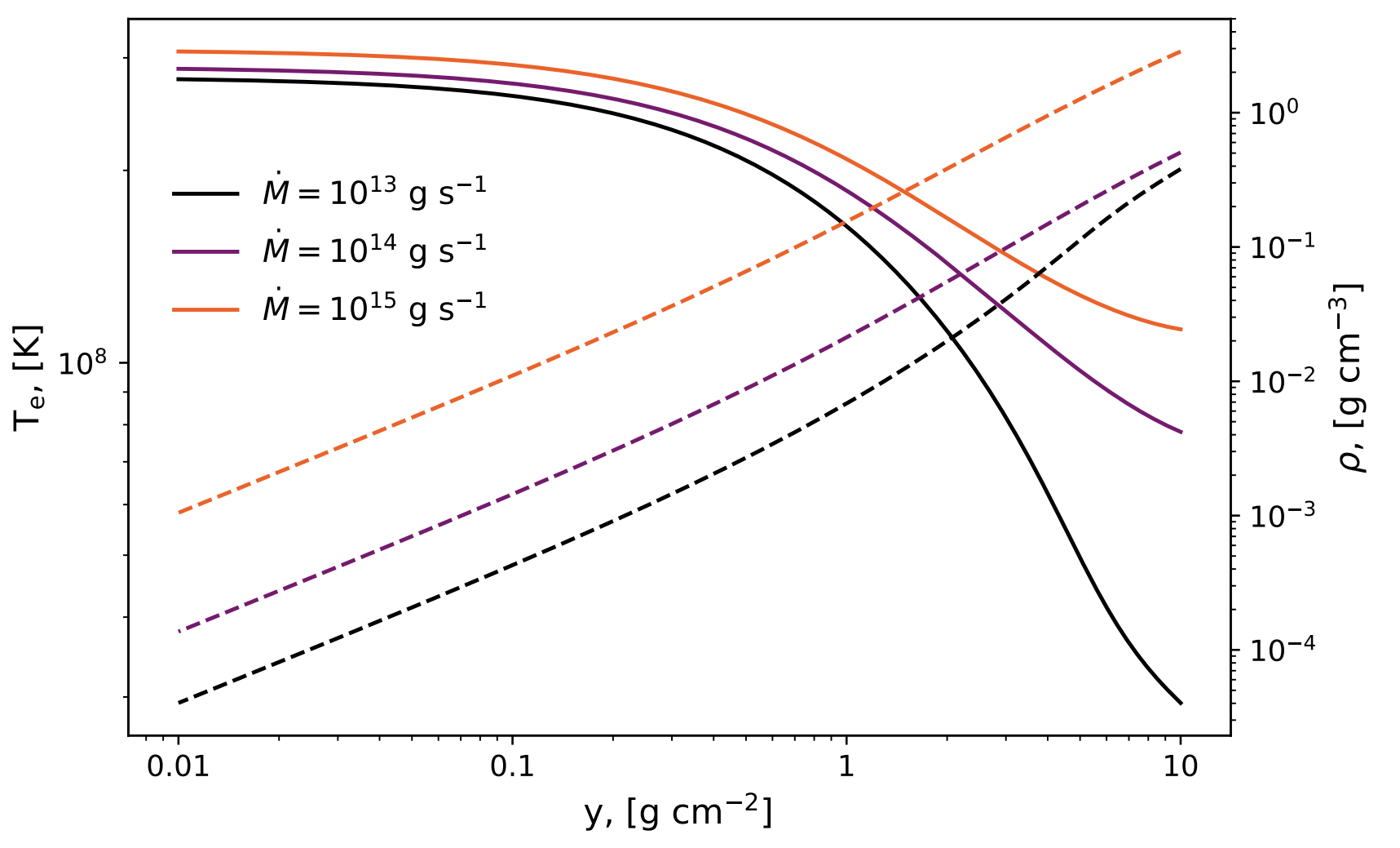

Figure 2: Atmosphere structure for depth $y_0 = 10$ and various $\dot{M}$.

We solve the energy balance and hydrostatic equations together within the neutron star atmosphere applying the approach from Zel'dovich & Shakura (1969). The equation of the energy balance can be written as

$$F_{\rm eff}\rho_{\rm e}/y_0 = \Lambda_{\rm B} + \Lambda_{\rm C}, \qquad (1)$$

where $F_{\rm eff} = L/(4\pi r_0^2)$, L is the luminosity of the polar cap determined by $\dot{M}$, $\rho_{\rm e}$ is the electron density, r_0 is the polar cap radius, $\Lambda_{\rm B}$ is cooling by bremsstrahlung emission and $\Lambda_{\rm C}$ is cooling by Compton scattering.

In highly magnetized plasma of the neutron star atmosphere the radiation propagates in the form of two polarization normal modes which are usually referred to as ordinary (mode 2) and extraordinary (mode 1), which have significantly different scattering cross sections. We solve radiative transfer in two polarization modes

$$\frac{\cos^2\theta}{\kappa}\frac{\partial^2 u}{\partial z^2} - \kappa u + 4\pi \sum_{p'=1,2} \iint \frac{d^2\sigma_{pp'}}{dE' d\mu'}\frac{E}{E'} u \, dE' d\mu' + \alpha_{\rm ff}\bar{u}(E, T_{\rm e}) = 0 \qquad (2)$$

for function $u = \frac{1}{2}(I(E,\mu,p,z) - I(E,-\mu,p,z))$ by the Feautrier method following the approach of Meszaros & Nagel (1985). Here κ is the total opacity, $\alpha_{\rm ff}$ is the free-free absorption coefficient and $d^2\sigma/dE'd\mu'$ is the differential scattering cross section, $\bar{u}(E, T_{\rm e})$ is the equilibrium photon density (Planck). The calculated spectra for two depths of the atmosphere y_0 are shown in the Fig. 3. Note the contribution of the different polarization modes to different energy ranges.

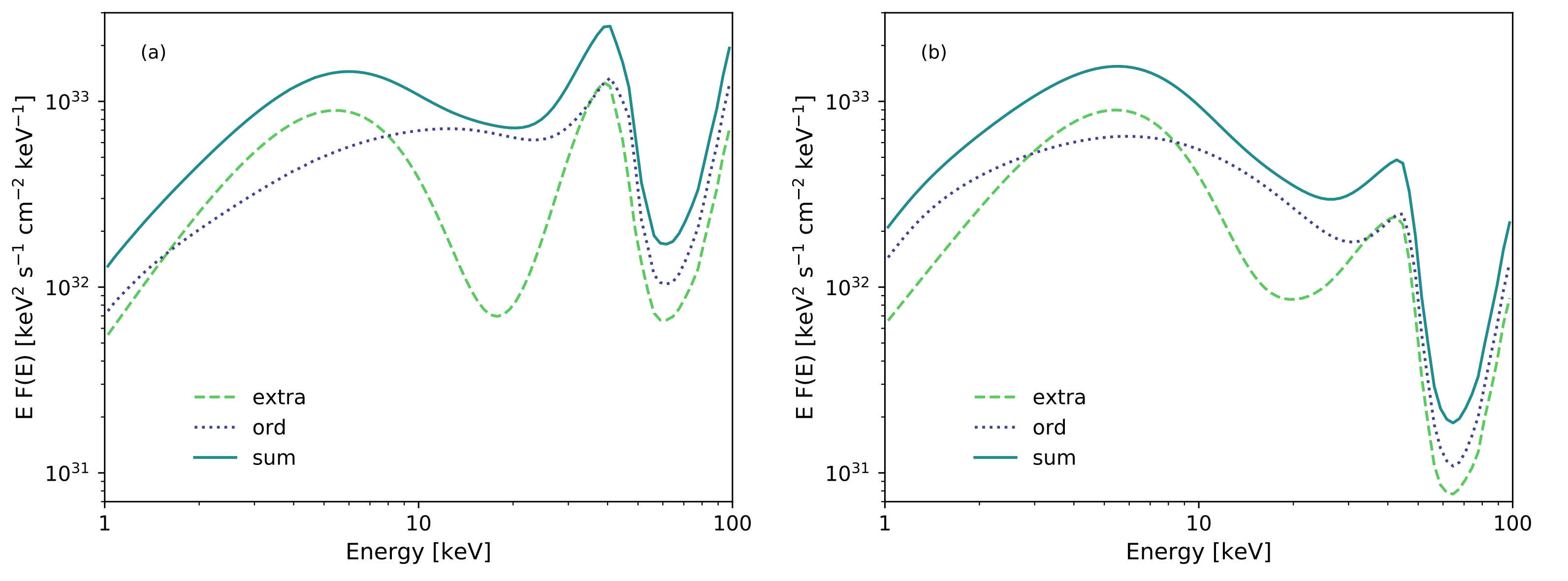

Figure 3: Energy flux from neutron star atmosphere for $\dot{M} = 10^{14}$ g s^{-1}, $B = 7.6\times10^{12}$ G, $r_0 = 10^4$ cm, $kT_{\rm BB} = 1.4$ keV. Atmosphere depth is $y_0 = 6$ g cm^{-2} (a) and $y_0 = 10$ g cm^{-2}(b).

Data analysis and results

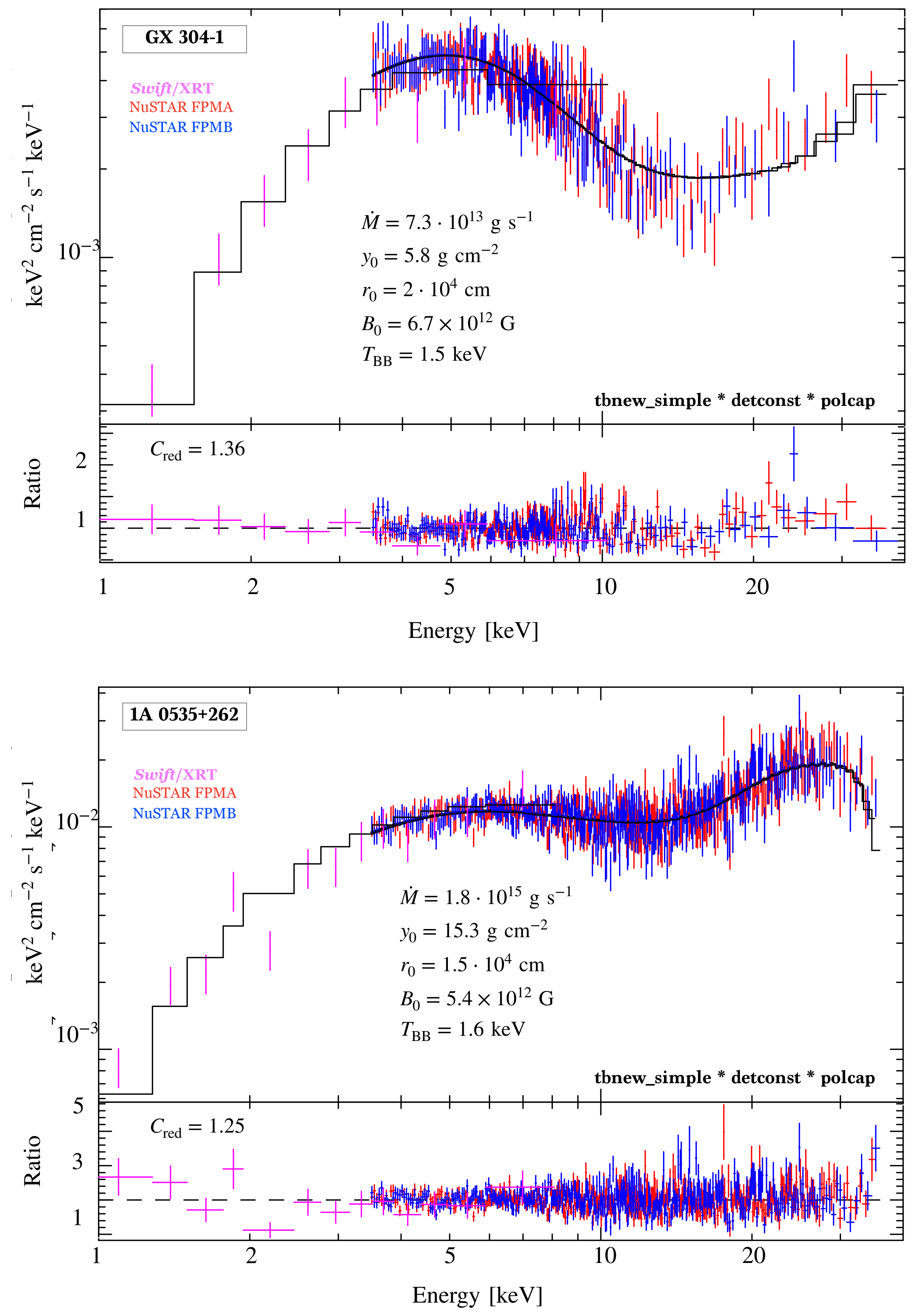

Figure 4: Unfolded phase-averaged spectra of low-luminous observations: GX 304-1 at $L\sim10^{34}$ erg s^{-1} (top) and 1A 0535+262 at $L\sim7\times10^{34}$ erg s^{-1} (bottom). For both observations we assume a gravitational redshift of 0.3 which is an approximately redshift value near the neutron star surface. Absorption was also fixed to the $N_{\rm H} = 1.1\times10^{22}$ cm^{-2}. The red, blue and magenta crosses correspond to the *NuSTAR* FPMA /FPMB and *Swift*/XRT, respectively. The solid black lines show the fit by `polcap` model.

Conclusions and future work

The `polcap` model is presented, it can be used to describe the continuum shape of accreting X-ray pulsars faint observations. We argue that the atypical two-component spectra of such observations can be explained by radiative transfer in two polarization modes in a very hot optically thick medium. As a caveat, we note that the energy balance equation and radiative transfer are solved independently in the current version of the model, which leads to the fact that not all solutions for atmosphere conserve energy. We will implement a more sophisticated scheme to obtain the solution, coupling radiative transfer and the energy balance equation as a next step. The good results shown above, however, are already very promising.

Acknowledgments & References

This work has been partially funded by DFG grant 1830Wi1860/11-1 and RSF grant 18-502-12025.

This research has made use of `ISIS` functions (`ISISscripts`) provided by ECAP/Remeis observatory and MIT (http://www.sternwarte.uni-erlangen.de/isis/).

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