Radiative transfer in the neutron star atmosphere: reflection model

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Abstract

We present a new model for calculating the reflection of the radiation from the neutron star surface illuminated by the accretion column for high-mass X-ray binaries. We calculate the trajectories of photons emitted from the column onto the neutron star surface considering the gravitational light bending to obtain the external boundary condition for radiative transfer simulation in the neutron star atmosphere. The equation of the radiative transfer is solved using the Feautrier method for two photon polarization modes with partial angle and frequency redistribution, taking into account the possibility of the mode conversion. The resulting spectrum is treated as the additional to the direct column one flux component. The intention of the model is to investigate the effects of reflection from the neutron star surface on the spectral shape of X-ray pulsars.

Rationale

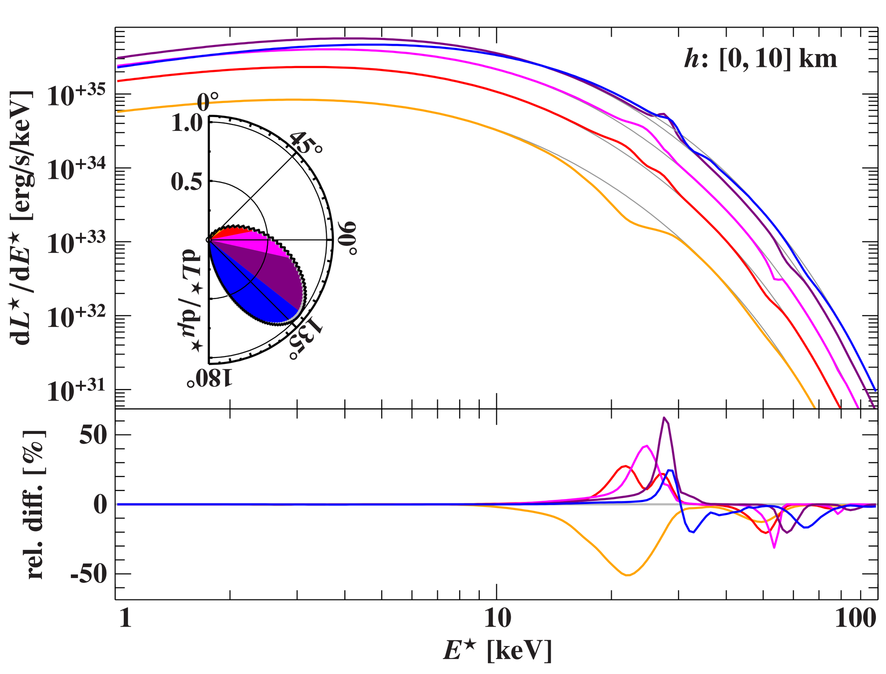

Fig. 1: Accretion column emission profile in the NS rest frame

Lyubarskii & Syunyaev (1988) showed that the radiation emitted from the accretion column is strongly beamed toward the neutron star (NS) surface due to relativistic aberration caused by the bulk velocity. Fig. 1 shows the beamed emission profile of the accretion column (Falkner et al. 2018) using the continuum of Postnov et al. (2015), cyclotron line calculated by Schwarm et al. (2017) and the light bending code by Falkner et al. (2018).

Reflection from the NS surface should be taking into account if one wants to study the spectrum characteristics of X-ray pulsars (Poutanen et al. 2013). Postnov et al. (2015) showed that the reflected component can explain the softness of the spectra in the low energy band. Finally, the broad line-like feature in the spectra of some sources (known as "10 keV feature") may result from the photon redistribution in the NS atmosphere.

Reflection model

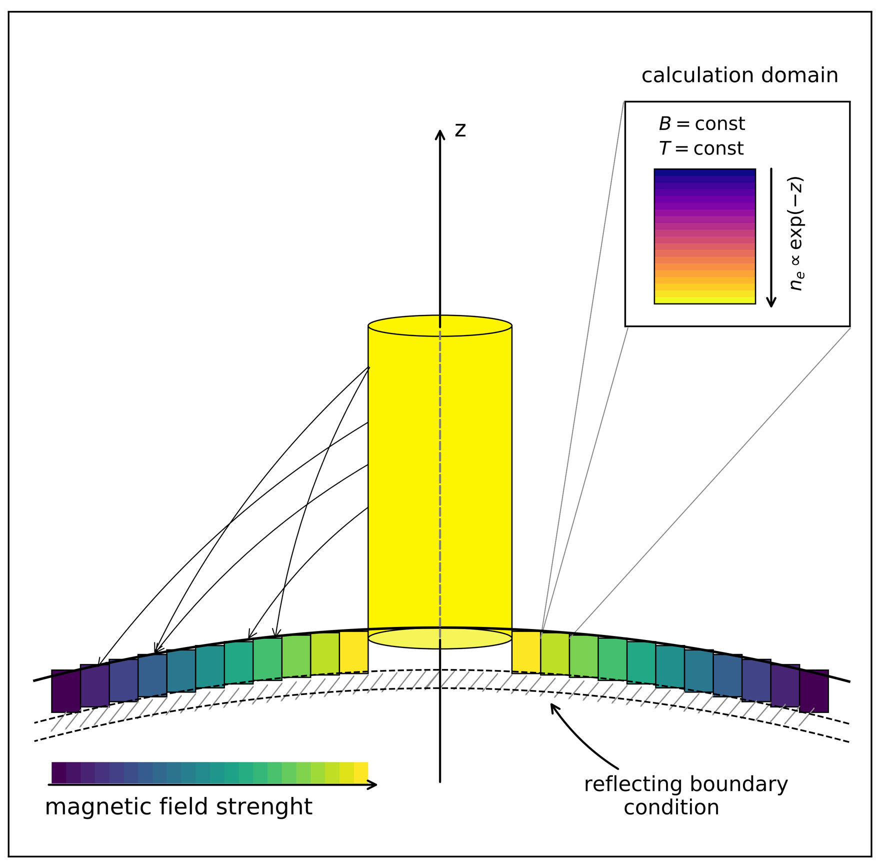

Fig. 2: Reflection model

The NS atmosphere is represented as a thin hydrogen layer divided into individual computational domains of constant B-field and electron temperature, with exponential distribution of the electron density (Fig. 2). The atmosphere is illuminated by the accretion column taking gravitational light bending into account. This irradiation is used as the internal boundary condition for radiative transfer calculation using the Feautrier method (Meszaros & Nagel 1985).

The result can be used as the reflected spectrum itself or as the input continuum for cyclotron line (Schwarm et al. 2017). We assume the temperature to be constant along the NS surface. The temperature $kT_{\mathrm{e}} \approx 2$ keV is obtained by assuming that all kinetic energy thermalizes: $v^3\rho/2 = \sigma_{\mathrm{B}} T_{\mathrm{e}}^4$.

Aknowledgments & References

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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Photon trajectories

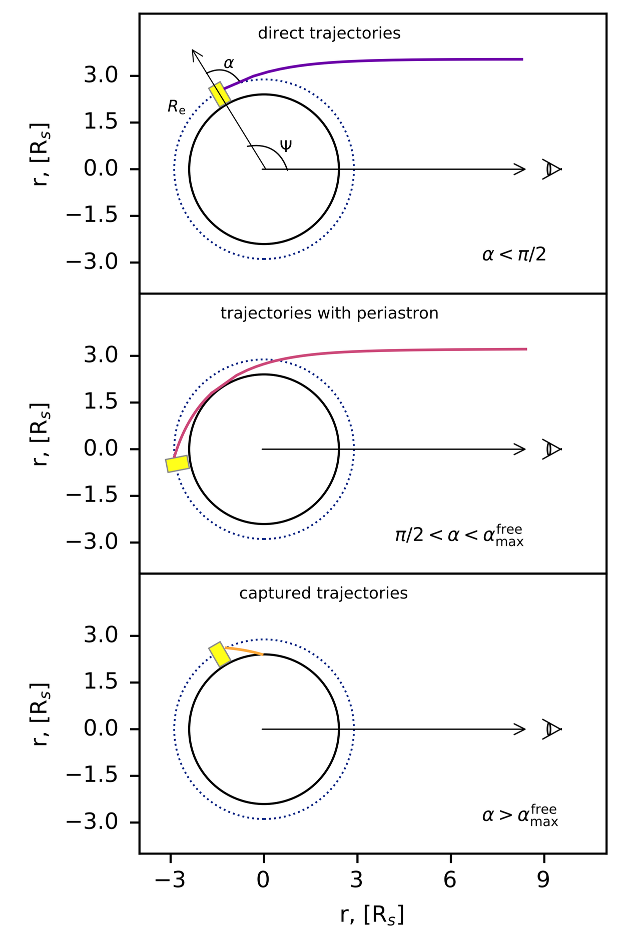

Fig. 3: Types of photon trajectories in the NS gravity field.

Illumination of the neutron star surface by accretion column emission is calculated taking into account relativistic light bending (Fig. 4). The principal types of photon trajectories are presented in the Fig. 3. There are two types of photon trajectories which can hit the surface: the captured ones and trajectories formed when photons are emitted at an angle within $[\alpha_{\min}^{\mathrm{ref}}(R_{\mathrm{e}}), \alpha_{\max}^{\mathrm{free}}(R_{\mathrm{e}})]$, where

$$\alpha_{\min}^{\mathrm{ref}} = \pi - \arcsin\left(\frac{R_{\mathrm{NS}}}{R_{\mathrm{e}}}\sqrt{\frac{1-R_{\mathrm{NS}}}{1-R_{\mathrm{e}}}}\right) \tag{1}$$

is the minimal emission angle to hit the NS and

$$\alpha_{\max}^{\mathrm{free}} = \pi - \arcsin\left(\frac{3\sqrt{3}}{2}\frac{1}{R_{\mathrm{e}}}\sqrt{1-\frac{1}{R_{\mathrm{e}}}}\right), \tag{2}$$

R_{e} - emission radius calculated from the NS center. As it seen from Fig. 5, $\alpha_{\min}^{\mathrm{ref}}$ is always smaller than $\alpha_{\max}^{\mathrm{free}}$. These two types of trajectories have to be treated in different ways.

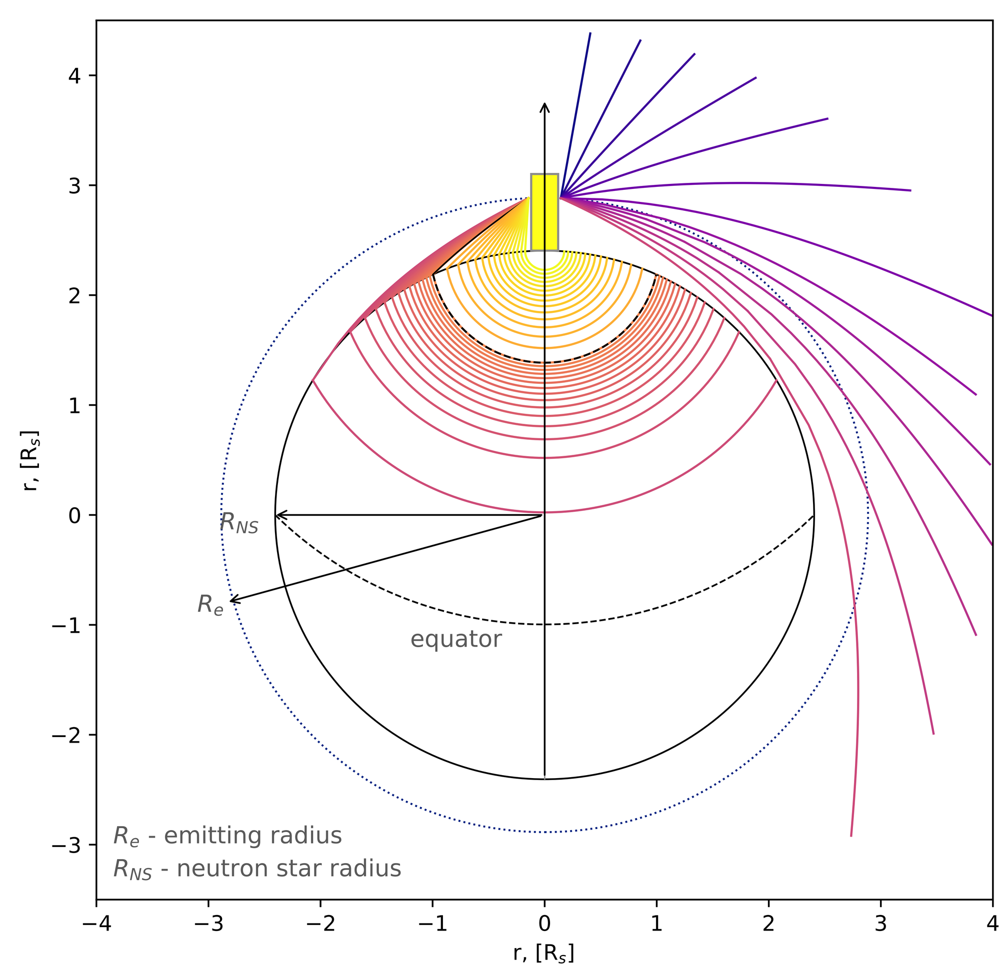

Fig. 4: Photon trajectories in the gravitational field of the neutron star

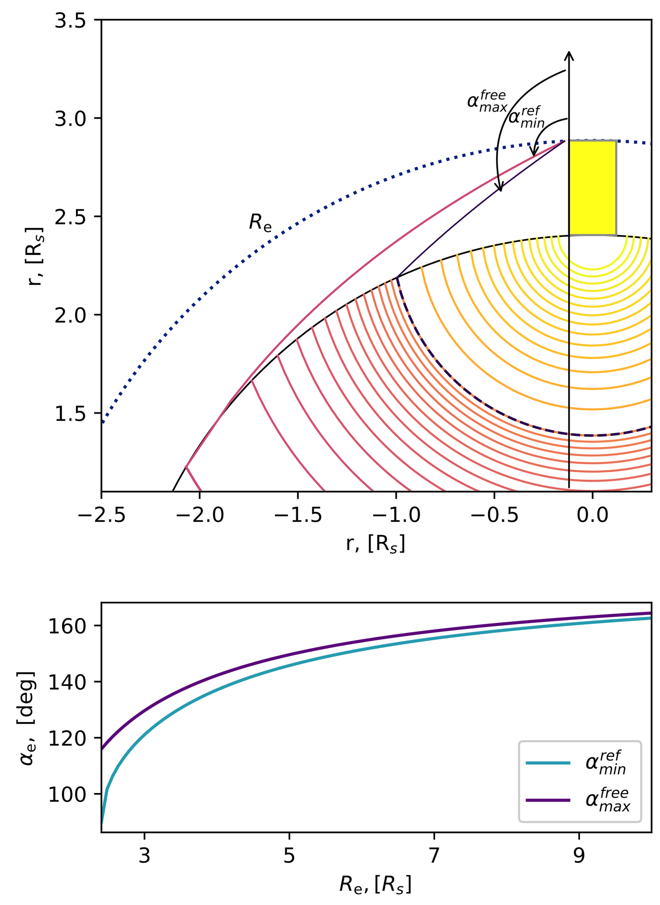

Fig. 5: top: trajectories hitting the surface, bottom: $\alpha_{\max}^{\mathrm{free}}$ and $\alpha_{\min}^{\mathrm{ref}}$ behaviour .

Radiative transfer

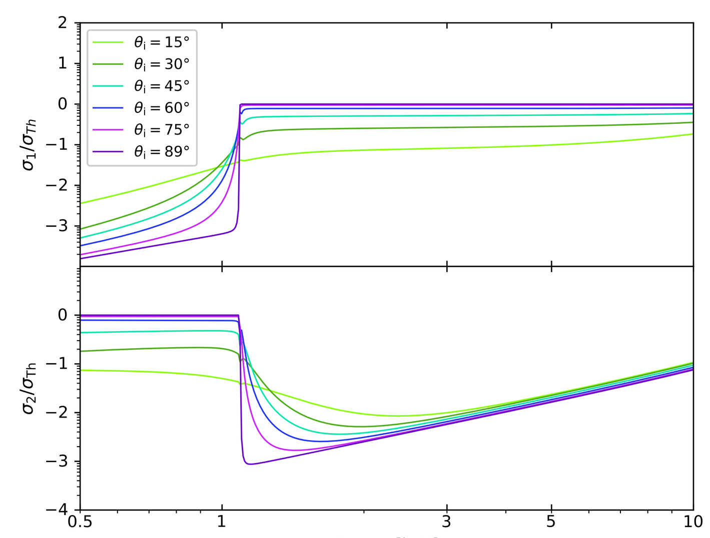

Fig. 6: Scattering cross sections with mode conversion.

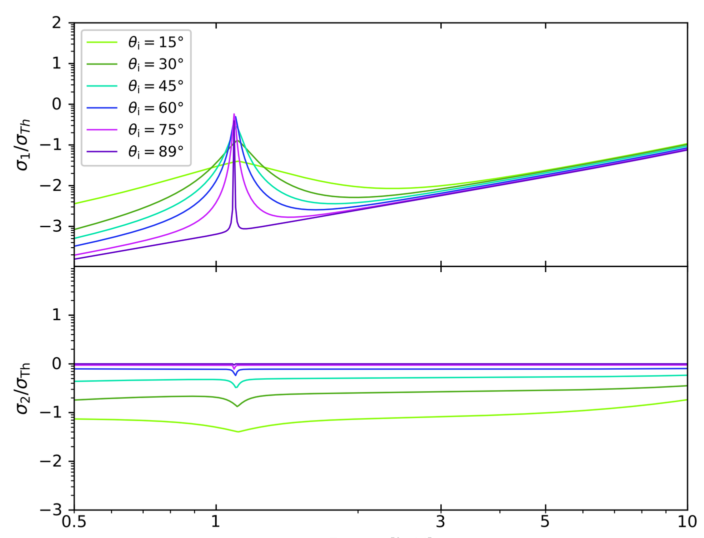

Fig. 7: Same as Fig. 6, but without mode conversion.

We solve the radiative transfer in the NS atmosphere using the Feautrier method. The opacity of the atmosphere includes free-free absorption and Compton scattering for highly magnetized plasma (Nagel 1981) for two polarization modes (ordinary e_2 and extraordinary e_1), taking into account partial energy and frequency redistribution. Ho & Lai (2003) showed that the adiabatic conversion of the polarization modes can affect the shape of the spectrum. To study this effect, we use the photon polarization modes in non-relativistic limit derived by Nagel (1981) which includes both the effects of the highly magnetized plasma and vacuum polarization.