Puffy disc is a numerical model, expected to capture the properties of the accretion flow in X-ray black hole binaries in the luminous, mildly sub-Eddington state. We fit the kerrbb and kynbb spectral models in XSPEC to synthetic spectra of puffy accretion discs, obtained in general relativistic radiative magnetohydrodynamic simulations, to see if they correctly recover the black hole spin and mass accretion rate assumed in the numerical simulation. We conclude that neither of the two models is capable of correctly recovering the puffy disc parameters, which highlights a necessity to develop new, more accurate spectral models for the luminous regime of accretion in X-ray black hole binaries. We propose that such spectral models should be based on the results of numerical simulations of accretion.

KEYWORDS:
black hole physics, accretion, accretion discs, magnetohydrodynamics (MHD), radiative transfer, scattering, X-ray: binaries

1 | INTRODUCTION

Black hole (BH) accretion is commonly described using a geometrically thin and optically thick disc model (Novikov & Thorne, 1973; Shakura & Sunyaev, 1973). This simple analytic framework proved to be extremely useful and capable of reproducing observed thermal spectra of X-ray black hole binary (XRB) systems with luminosities $L \sim 0.1 L_{\text{Edd}} < 0.3 L_{\text{Edd}}$, where $L_{\text{Edd}}$ is the Eddington luminosity (McClintock, Narayan, & Steiner, 2014). Nevertheless, the basic analytic models predict violent instabilities in the radiation pressure-dominated regime (Shakura & Sunyaev, 1976), which is inconsistent with observations. These issues are addressed in the numerical magnetohydrodynamic models, where thermal and viscous stability appear to be a consequence of the pressure support from the magnetic field (Sadowski, 2016). The corresponding numerical models, referred to as puffy discs (Lančová et al., 2019), are computationally very expensive, precluding detailed mapping of spectral properties across the model parameter space. Hence, it is interesting to quantify errors and biases of existing spectral fitting tools, when interpreting synthetic spectra of puffy discs as a proxy of luminous XRB system with $L \gtrsim 0.3 L_{\text{Edd}}$ for which geometrically thin disc approximation fails. In Wielgus et al. (2022) we have demonstrated biases of the kerrbb (Li, Zimmerman, Narayan, & McClintock, 2005), incorporating a thin disc of Novikov & Thorne (1973) and slimbh (Straub et al., 2011), incorporating a slim disc of Abramowicz, Czerny, Lasota, & Szuszkiewicz (1988) spectral models. In this work, we test the...
2 | THE PUFFY DISC MODEL

The puffy disc is a model of accretion based on numerical General Relativistic Radiative Magnetohydrodynamic (GRRMHD) simulations of plasma infalling onto a stellar mass BH. The simulations were performed using the KORAL code (Sadowski, Narayan, McKinney, & Tchekhovskoy 2014, Sadowski, Narayan, Tchekhovskoy, & Zhu 2013, Sadowski et al. 2017), which evolves the general relativistic equations for conservation of mass, momentum, and energy on a logarithmic 3D spherical grid, under ideal MHD approximation. The radiation field is evolved using the M1 closure scheme (Levermore 1984, Sadowski et al. 2013), an approximation assuming existence of a frame of reference in which radiation is isotropic. The numerical GRRMHD framework allows for a physically self-consistent treatment of accretion with the presence of a magnetic field, dynamically important radiation, and effects such as turbulent transport of angular momentum, advection, and outflows. Hence, GRRMHD simulations may provide a reliable model of accretion disc spectra even in the luminous regime, in which analytic models fail to reproduce observations.

The puffy disc is a result of the simulation of accretion flow in the innermost region, where radiation pressure strongly dominates over gas pressure, in a mildly sub-Eddington regime, in which thermal stability is supported by the magnetic pressure (Sadowski 2016). Our GRRMHD simulations were performed for a non-spinning (spin $a_s = 0$) stellar mass BH of $M = 10 M_\odot$ (where $M_\odot$ is the solar mass). The particular simulation discussed in this work has a mass-accretion rate $\dot{M} \approx 0.6 M_\odot\,s^{-1}$.

The puffy disc model is specific for its vertical structure separating a geometrically thin dense core, which resembles a standard thin disc, and a geometrically thick puffy region sandwiching the core, see Figure 1. The puffy region, distinguishing this model from the analytic solutions, is mildly optically thick, strongly magnetized, and extends up to the height of the elevated photosphere. The puffy region contributes significantly to the total mass accretion rate in the system. The funnel region near the axis is optically thin, and filled with hot and rarefied out-flowing plasma.

\footnote{Here $M_\text{edd} = L_\text{edd}/(c^2)$ is defined using the thin disc efficiency $\eta = 0.057$ and the Eddington luminosity $L_\text{edd} = 1.25 \cdot 10^{38} M/M_\odot\,\text{erg}\cdot\text{s}^{-1}$. Throughout this work, we are using the gravitational radius $r_g = GM/c^2$ as a unit of length.}

FIGURE 1 The cross-section of a puffy disc averaged over time and azimuthal angle, showing the color map of density in the background, clearly separating the high-density core (C), the puffy region (P) and the funnel (F). Grey arrows indicate the gas momentum flow, the white continuous lines are the isolines of optical depth $\tau$ (the photosphere is located at $\tau = 1$ and the white dashed lines near the equatorial plane show the density scale-height of the disc. Pink, orange and yellow contours are the gas temperature lines of $10^7$, $10^8$, and $10^9$ K (0.9, 8.6, and 86.7 keV) respectively.

2.1 | Synthetic Observations of the Puffy Disc

The elevated optically thick photosphere and magnetized puffy region roughly resemble a warm slab corona (Gronkiewicz & Różańska 2020, Zhang et al. 2000), distinguish puffy discs from analytic models in the sub-Eddington regime and influence the observable features of the system by scattering the photons emitted in the core region. The dominant effect on the apparent observed luminosity, absent in the standard thin disc models, is the obscuration of the innermost region by the geometrically thick puffy region at high inclinations. At low inclinations, on the other hand, the puffy region collimates the radiation, leading to super-Eddington apparent isotropic luminosities (Wielgus et al. 2022).

In order to obtain synthetic spectra we post-processed results of the GRRMHD simulations using the HEROIC code (Narayan, Zhu, Psaltis, & Sadowski 2016, Zhu, Narayan, Sadowski, & Psaltis 2015), which solves a complete radiative
transfer problem on a time-averaged simulation output. We created .fits files with the synthetic puffy disc spectra, assuming a distance of 10 kpc and 10% uncertainties in the measured energy distribution. In this work we used the synthetic data to simulate an observation and fit the data using the fakeit function in XSPEC. We then used the Kerrbb and kynbb to fit the simulated observations and obtain the estimates of the system parameters.

A detailed description of the puffy disc GRRMHD model and its properties can be found in Sadowski (2016) and Lančová et al. (2019). The discussion of the observational features of puffy discs and details of the procedures employed to interpret synthetic observations within the XSPEC framework are given in Wielgus et al. (2022).

3 | SPECTRAL MODELING AND ANALYSIS

3.1 | Spectral Modeling

The Kerrbb spectral model (Li et al., 2005) describes the spectrum of a geometrically thin and optically thick Keplerian disc around a Kerr BH, employing curved spacetime ray-tracing and accounting for the relativistic effects (light bending, self-irradiation or returning radiation, gravitational redshift, frame dragging, and Doppler boost) on the observed spectrum. The total power is calculated as a sum over black-body annuli with the radial temperature profile following Novikov & Thorne (1973). The model assumes the inner edge of the accretion disc located at the innermost stable circular orbit \( r_{isco} \) (\( r_{isco} = 6 r_g \) for the Schwarzschild case, and decreases with the BH spin).

Similar to Kerrbb, kynbb also relies on the ray-tracing algorithms to compute the transfer functions for the tables used in the model for photon paths in Kerr space-time, describing a Novikov & Thorne (1973) accretion disc. It is a local model developed as an extension to the KY2 package by Dovčiak et al. (2004). In contrast to Kerrbb, kynbb offers an option to define the inner disc radius \( r_{in} \) either as a free parameter or fixed at a certain value other than \( r_{isco} \), computing the spectra starting from either \( r_{isco} \) or a preferred \( r_{in} \) value. Hence, kynbb model can produce spectra of a truncated disc. For this work, we assumed \( r_{in} \geq r_{isco} \). One can choose to calculate the spectrum only for a range of disc radii. Additionally, one also has the freedom of including polarization calculations but it is not used in this work. In addition to the thermal disc component, for both Kerrbb and kynbb fits we include the nthcomp thermal Comptonization model to account for the up-scattering of the accretion disc seed photons to higher energies (Zdziarski, Johnson, & Magdziarz, 1996; Zycki, Done, & Smith, 1999) in the puffy region, see FIGURE 1.

![FIGURE 1](https://projects.asu.cas.cz/stronggravity/kyn/)

3.2 | Spectral Analysis Results

For the analysis of the synthetic puffy disc spectra the HEASOFT (v.6.29), package XSPEC (v.12.12) (Arnaud, 1996) and PyXspec, a Python interface to the XSPEC is used. Each spectra are generated for inclination angles of \( \theta = 10^\circ, 20^\circ, 30^\circ, 60^\circ, 70^\circ, \) and \( 80^\circ \) measured from the rotational axis.

Throughout the analysis, the BH mass, inclination angle, and distance (normalization parameter of kynbb) are fixed.

![FIGURE 2](https://heasarc.gsfc.nasa.gov/xanadu/xspec/python/html/)
to their respective values used in the GRRMHD simulations while electron and seed photon temperatures (\(T_e\) and \(T_{bb}\), respectively) and the photon index \(\Gamma\) in nthcomp are set free to vary. For simplicity, we refer to each model (kerrbb+nthcomp and kynbb+nthcomp) by the specific model of the thermal component. With each model, the convolution model cflux in XSPEC is used to calculate \(L_{\text{Disc}}/L_{\text{Edd}}\) for the energy range of 0.01-100.0 keV.

First, the spectra are analyzed using kerrbb, with BH spin \(a_\ast\) and \(\dot{M}\) as free parameters additional to the nthcomp parameters. We then replaced kerrbb by kynbb with \(r_{\text{in}}\) as an additional free parameter representing the inner edge of the disc. Low inclination angles produced reduced \(\chi^2 (\chi^2 / \text{d.o.f.} < 0.92 \text{ with kerrbb and } 1.28 < \chi^2 / \text{d.o.f.} < 1.37)\) with kynbb while the obtained values exceeded 2.0 for higher inclination angles, with larger residuals observed in both models. We present the fitted values of parameters obtained from kerrbb with free \(a_\ast\) and \(\dot{M}\) in comparison with additional free \(r_{\text{in}}\) in FIGURE 2 and the synthetic spectra and residuals in ratios obtained from the fitting procedure with both models in the top panel of FIGURE 3 for \(\theta = 10^\circ\) and bottom panel for \(\theta = 60^\circ\).

3.3 Effect of the Disc Inner Edge Position

The second panel from the bottom in FIGURE 2 shows the obtained value of \(r_{\text{in}}\) for varying inclination angle \(\theta\) assumed for the calculations. At low inclination the kynbb model indicates a preference for a truncated disc, with \(r_{\text{in}} > 6r_g\), while the fitted spin values are large and positive. On the other hand, for higher inclinations, \(r_{\text{in}}\) moves closer to the \(r_{\text{isco}}\) corresponding to the obtained \(a_\ast\), resulting in higher energy of the thermal component. With higher inclination, the kerrbb thermal component has to be compensated by stronger nthcomp component even in the low energy bands, however, in the kynbb case, the thermal component is reproducing the thermal part of the puffy disc spectra well and Comptonization is prominent only in the higher energy bands. This provides more consistent (yet still inaccurate) spin outputs than the kerrbb case, see the bottom panel of FIGURE 2.

When tested with spectra obtained from RXTE (Rossi X-Ray Timing Explorer) observations of GRO J1655-40 (Yilmaz et al., in preparation), both kerrbb and kynbb performed almost identically in measuring the spin and disc temperature when \(r_{\text{in}} = r_{\text{isco}}\) is assumed in both models. There is a significant mismatch between the results when the \(r_{\text{in}}\) is set as a free parameter in kynbb for the same mass accretion rates, due to the non-zero torque assumption at \(r_{\text{in}} \neq r_{\text{isco}}\). This assumption becomes much more important as one approaches the ISCO and eventually reaches the horizon. While this does not produce a significant difference in model parameters in FIGURE 2 and model components in FIGURE 3 for lower inclination angles, there is a slight shift in the thermal component of the continuum to higher energies for higher inclination angles. This can be explained with parameter degeneracy between \(r_{\text{in}}\) and \(a_\ast\). For larger inclinations, it becomes more
we investigated whether there exists an effective $r_{\text{in}}$ that would allow to interpret puffy disc spectra within the kynbb model framework, correctly estimating the BH spin parameter. Based on our findings the answer to this question appears to be negative. Our conclusions are consistent with those recently found by Wielgus et al. (2022) – the available spectral fitting models fail to correctly interpret synthetic spectra of puffy discs and to recover the assumed value of the BH spin. In order to address these issues a new spectral model, using results obtained from GRRMHD simulations, and interpolating on a grid of numerical models, should be developed. A complete analysis should necessarily involve simulation of puffy discs around BHs with non-zero spin. However, the progress is limited by the immense computational costs of the GRRMHD simulations ($\sim 10^7$ CPU hours). Hence, we have focused so far on the stability considerations (Sadowski 2016) and the comparison of different mass accretion rates (Lančová et al. 2019), leaving investigations of the spin impact for the future work. A spectral model mapped on GRRMHD simulations across varying system parameters, including spin, could enable us to extend the continuum fitting method to more luminous sources and thus provide new valuable insight into studies of luminous XRBs.

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FIGURE 4 Values of the time component of gas four-velocity ($u_{t}^{\text{sim}}$) and angular momentum ($\ell_{t}^{\text{sim}}$) on the equatorial plane from the simulation compared to the Novikov-Thorne (NT) disc values at $r_{\text{isco}}$.
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