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BEYOND THE STANDARD MODEL OF THE DISC–LINE SPECTRAL PROFILES FROM BLACK HOLE ACCRETION DISCS

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Abstract. The strong gravitational field of a black hole has distinct effects on the observed profile of a spectral line from an accretion disc near a black hole. The observed profile of the spectral line is broadened and skewed by a fast orbital motion and redshifted by a gravitational field. These effects can help us to constrain the parameters of a system with a black hole, both in active galactic nuclei and in a stellar-mass black hole. Here we explore the fact that an accretion disc emission can be mathematically imagined as a superposition of radiating accretion rings that extend from the inner edge to the outer rim of the disc, with some radially varying emissivity. In our work, we show that a characteristic double-horn profile of several radially confined (relatively narrow) accretion rings or belts could be recognized by the planned instruments onboard future satellites (such as the proposed ESA Large Observatory for X-ray Timing).

Keywords: black hole physics, accretion discs, galactic nuclei.

1. Introduction

An observation of spectral lines from the inner regions of an accretion disc around a black hole, both in active galactic nuclei (AGN) [1, 2] and in Galactic black holes [3, 4], gives us information about matter in extreme conditions. These spectral lines are broadened and skewed by a fast orbital motion and redshifted by a strong gravitational field.

According to the standard scenario [5, 6], line emissivity is assumed to be a simple power-law of the radius. With a typically moderate inclination angle of the source, a broad profile is formed with an extended red wing and a dominant well-defined blue peak. However, the radial emissivity of an astrophysically realistic accretion disc cannot be a simple smooth function of the radius. Instead, it is expected to have peaks of enhanced emissivity occurring at particular radii, e.g. due to localized irradiation by magnetic flares [7, 8].

We address the question whether the emission excesses on top of the standard emission profile can be resolved in observed spectra and used to further constrain the black hole spin to better precision. We discussed in [9] whether the proposed Large Observatory for X-ray Timing (LOFT), [10, 11], will have the necessary capability to reconstruct the parameters from a model spectrum. We produced artificial data with appropriate properties and then we analyzed them by using a preliminary response file for LOFT.

Two scientific instruments form the payload of the satellite: LAD (Large Area Detector) with a large effective area (designed to reach $\simeq 12\,\mathrm{m}^2$) and the energy resolution should be about 200–300 eV; and WFM (Wide Field Monitor), which will observe about 50 % of the sky available to the LAD in the same energy band at any time.

In this paper, we compare the results obtained in [9] and discuss how variability of the background can affect the spectrum. Correct modeling of the background is crucial for the success of the measurements, because LOFT does not contain any telescope that could measure the background from the neighborhood of the observed object.

2. Model spectrum and analysis by LOFT

2.1. Test case

We took our fiducial model (Figure 1, left panel) from [9]: it was

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phabs * (powerlaw + 4 * kyrline),
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i.e., a photo-absorbed power-law continuum and four line components blurred by relativistic effects (we used XSPEC v. 12.6.0). One of the `kyrline` components originates over the entire disc surface, and it has been fixed to its default parameters ($r_{\mathrm{ISCO}} \le r \le 400$, radial emissivity index $\alpha = 3$).

We set the model parameters to: $a = 0.93$ (rapidly spinning Kerr black hole in prograde rotation), $i = 30\,\mathrm{deg}$ (moderate inclination typical for the Seyfert 1 nucleus) and three rings of width $0.5 r_{\mathrm{g}}$ at the positions $r_1 = 3 r_{\mathrm{g}}$, $r_2 = 4 r_{\mathrm{g}}$ and $r_3 = 6 r_{\mathrm{g}}$. We produced the simulated spectrum (Figure 1, right panel) by assuming a source flux of approximately 1.3 mCrab ($\simeq 3 \times 10^{-11}\,\mathrm{erg/cm^2}$ in the energy range 2–10 eV), a photo-absorbed power-law continuum (photon index $\Gamma = 1.9$, hydrogen density $n_{\mathrm{H}} = 4 \times 10^{21}\,\mathrm{cm^{-2}}$) and the rest energy $E_{\mathrm{rest}} = 6.4\,\mathrm{keV}$. The exposure time was set to 20 ksec.

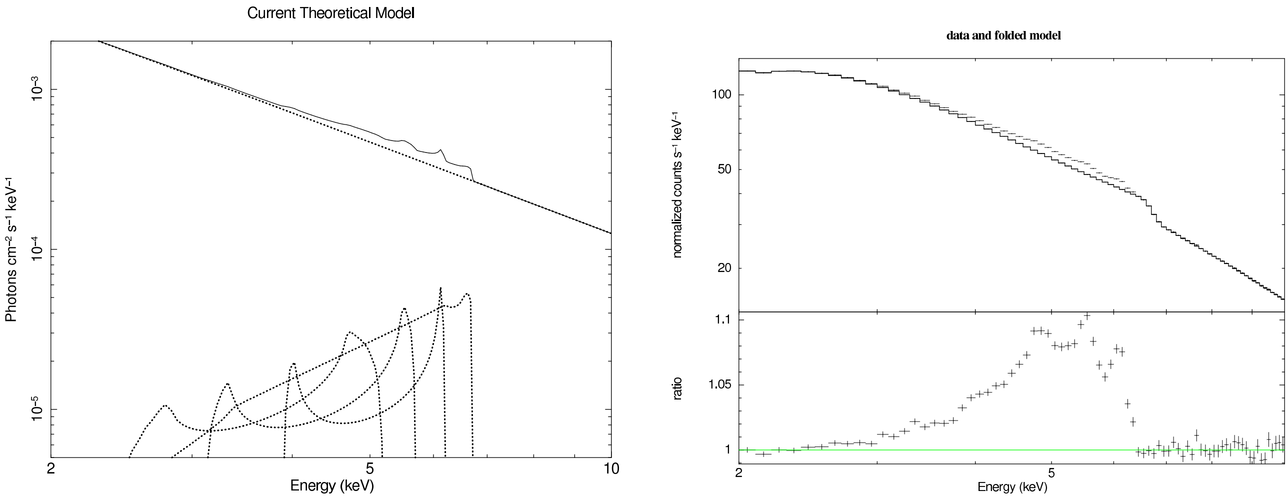

FIGURE 1. Left panel: The complete theoretical model and the model components: a power-law continuum and the individual line profiles from which the energy shifts of the components are derived. Right panel: Simulated data and the ratio to the baseline model consisting of the power-law and the disc-line components. Residuals related to the three additional narrow rings are clearly visible. Taken from [9].

Ring	$g_{\min}$	$g_{\max}$	r_{in}		r_{out}	
			$a = 0.76$	$a = 1.00$	$a = 0.76$	$a = 1.00$
1	0.36	0.81	3.1	2.8	3.7	3.4
2	0.48	0.91	4.1	3.9	4.9	4.7
3	0.59	0.98	5.8	5.6	7.1	6.9

TABLE 1. Parameters of the model inferred from the energy positions of the spectral peaks in the test spectrum from Figure 1. We identified the visible features with the horns of the line components. We imposed the same inclination $i = 30$ deg for all three rings and required the inferred spin values to be consistent with each other. The spin turns out to be constrained only partially, with the values from 0.77 up to 1.00 being consistent with the positions of peaks in the model spectrum when the radius is set appropriately. The fiducial test spectrum was generated for rings positioned at radii $r_{\text{in}} = 3\ r_{\text{g}}$, $4\ r_{\text{g}}$, and $6\ r_{\text{g}}$, respectively. The tabulated values demonstrate the accuracy of the fitting procedure. See the text for details. Taken from [9].

2.2. Determination of shifts from the spectral profile

To determine the relativistic energy shifts of photons, we adopt the method described in our recent paper [12], where we considered the propagation of photons from the source in the limit of geometrical optics in the Kerr metric [13]. There is a partial degeneracy of the parameter values. In our case this exhibits itself by the fact that, in order to obtain the red peaks of the line in the right position, the spin has to be greater than the lower limit of $a = 0.76$. However, the upper bound remains undetermined. For $0.76 \leq a \leq 1$, i.e., up to the maximum spin of the Kerr black hole, we can reproduce the peaks by rearranging the ring radii. This is shown in Table 1 by giving two possible values of r_{in} and r_{out} that are consistent simultaneously with the mentioned minimum and maximum spin values. One can see that the uncertainty in the inferred radii is below 10%, while for spin the relative error represents about 25%.

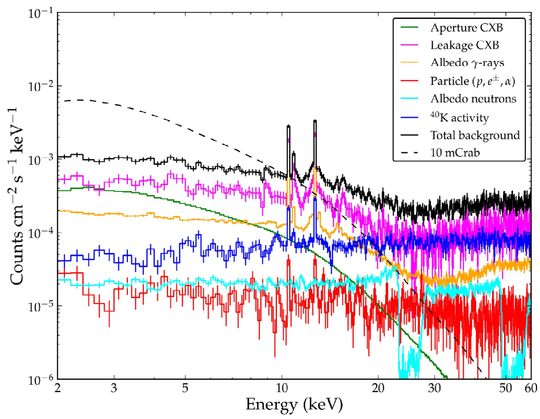

FIGURE 2. The LAD background and its various contributions. The results of a study in which the behavior of each background component was modeled along the satellite orbit. The spectrum of a 10 mCrab source is also shown. [14]

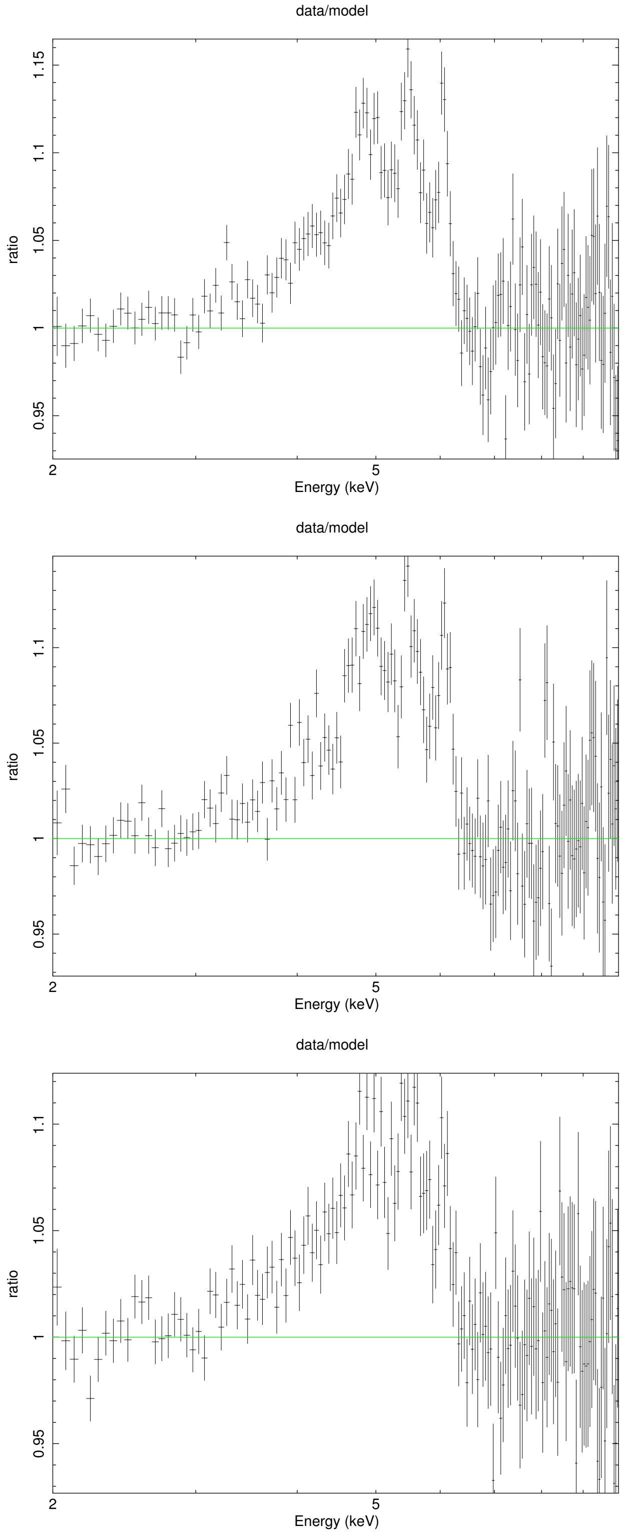

Figure 3. The ratio between the simulated data and the baseline model with a background level of 5% (top), 7% (middle) and 10% (bottom).

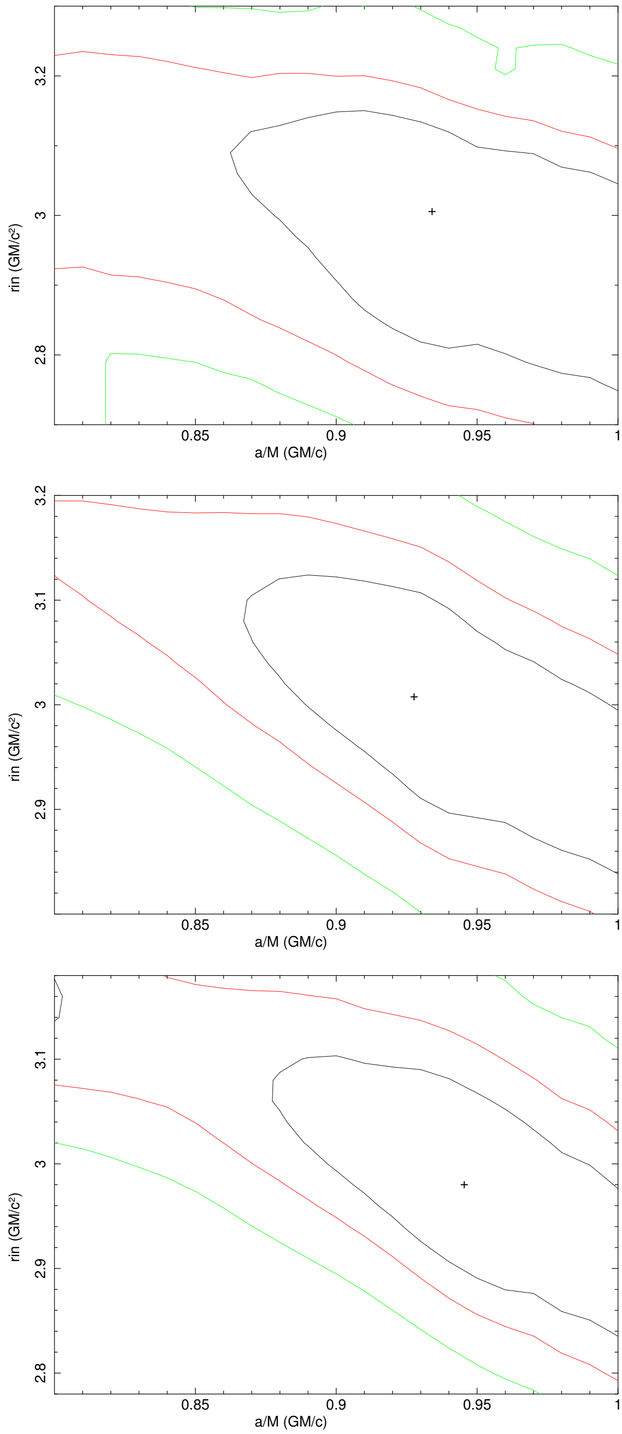

Figure 4. Constraints on the best-fit model with a background level of 5% (top), 7% (middle) and 10% (bottom).

3. Model spectrum considering background

3.1. LAD background

The LAD background has been analyzed and computed by [14] using Monte Carlo simulations of a mass model of the whole LOFT spacecraft and all known radiation sources in the LOFT orbit, see Figure 2. From the simulations, it is obvious that the background is dominated ($> 70\,\%$) by high energy photons of cosmic X-ray background and Earth albedo leaking and scattering through the collimator structure, which becomes less efficient at high energies. These two sources are stable and predictable, although there exist small modulations of these components due to the orbital motion of the satellite around the Earth. One of the varying sources is the particle induced background ($< 6\,\%$ of the overall background). The largest modulation of the total LAD background is estimated as $< 20\,\%$, and can be effectively described by a geometrical model that should predict the background at the level of 1 % or better (1–20 keV).

3.2. Data to model ratio

We considered the model presented in the previous section and tested the expected impact of background contamination by applying `corrnorm` to the background file in XSPEC. Figure 3 shows the data to model ratio with the randomized background at the 5, 7 and 10 % levels. The blue peaks can be recognized in the first two graphs, while the red peaks are lost in the signal-to-noise. The 10 % inaccuracy of the background degrades the visibility of the peaks. Figure 4 demonstrates the expected accuracy with which the model parameters are constrained. The results can seem to be counter-intuitive (the 10 % level is better than 5 %). This is caused by the method of fitting. In our case, we know the parameters of the system and the constraints would look similar. The study of the background deserves more investigation. The constraints on the best-fit model parameters are derived from the simulation data. Confidence contours are shown (1, 2, and 3σ) of the inner ring radius $r_{\rm in}$ vs. dimension-less spin a.

4. Conclusions

In this paper, we have applied the background response file of the proposed satellite LOFT to the test model from [9], and we have studied the variability of the model spectrum. Our result is that 10 % inaccuracy is a limit value of the background, and it should not be exceeded. Accuracy of the background at the 5% level is sufficient to recognize and fit the structures in the model spectrum, and the peaks of the energy shifts, and also to determine the parameters, as described in [12].

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