Beyond the standard model of the disc-line spectral profiles from black hole accretion discs

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The strong gravitational field of the black hole has indispensable effects on the observed profile of the spectral line from an accretion disc near the black hole. The observed profile of a spectral line is broadened and skewed by fast orbital motion and redshifted by gravitational field. These effects can help us to constrain parameters of the system with a black hole, both in active galactic nuclei and stellar-mass black hole. Here we explore the fact that the 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 the characteristic double-horn profile of several radially confined (relatively narrow) accretion rings or belts could be recognized by the planned instruments onboard future satelites (such as the ESA proposed Large Observatory for X-ray Timing).

Introduction

The observation of the spectral lines from the inner regions of the accretion disc around a black hole gives us information about this 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, the 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 can not be a simple smooth function of radius. Instead, it is expected to have peaks of enhanced emissivity occurring at particular radii, e.g. due to localized irradiation by magnetic flares [1], [2].

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 produced artificial data with appropriate properties and then we analyzed them by using a preliminary response file for the proposed Large Observatory for X-ray Timing (LOFT). The detector should have a large effective area (designed to reach $\simeq 12\ \mathrm{m}^2$) and the energy resolution should be about $200-300$ eV.

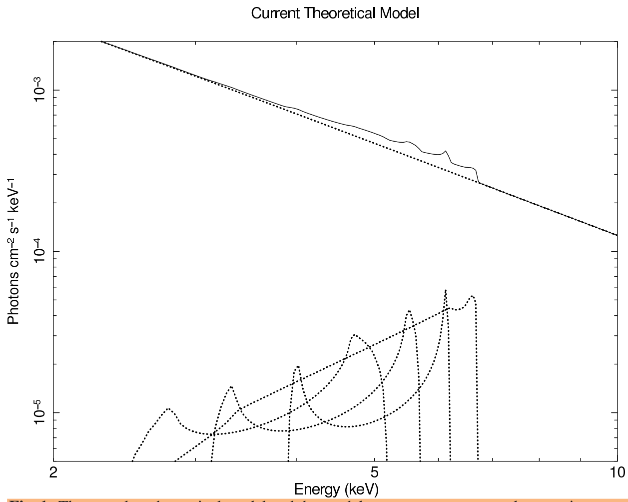

Fig. 1: The complete theoretical model and the model components: a power-law continuum and the individual line profiles from which the energy shifts of the components are derived.

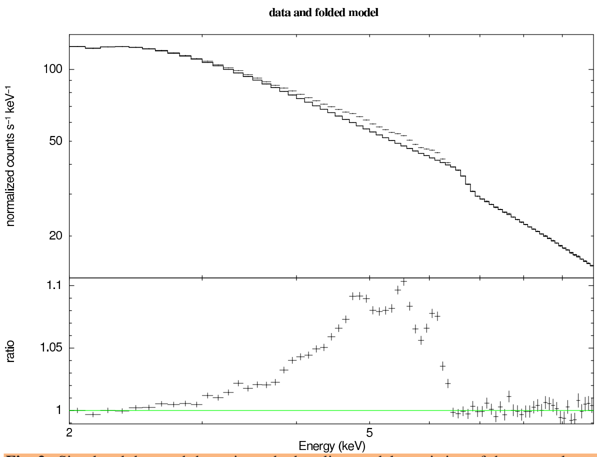

Fig. 2: Simulated data and the ratio to the baseline model consisting of the power-law and the disc-line components (background subtracted). Residuals related to the three additional narrow rings are clearly visible.

The test case

Our fiducial model (Fig. 1) was `phabs*(powerlaw+4*kyrline)`, 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 ($r_{\mathrm{ISCO}} \leq r \leq 400$, 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 Seyfert 1 nucleus) and three rings with the width $0.5r_{\mathrm{g}}$ 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 (Fig. 2) by assuming the 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 $\Gamma = 1.9$, $n_{\mathrm{H}} = 4 \times 10^{21}\ \mathrm{cm^{-2}}$) and the rest energy $E_{\mathrm{rest}} = 6.4$ keV. The exposure time was set to 20 ksec.

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 Fig. 2. We identified the visible features with the horns of the line components.

The determination the energy shifts from the spectral profile

To determine the relativistic energy shifts of photons, we adopt the method described in our recent paper [4], where we considered propagation of photons from the source in the limit of geometrical optics in Kerr metric. 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 right position, the spin 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 the table by giving two possible values of r_{in} and r_{out} that are consistent simultaneously with the mentioned minimum and maximum values of spin. One can see that the uncertainty in the inferred radii is below 10% while for spin the relative error represents about 25%.

Conclusion

The planned LOFT mission with its proposed large effective area and energy resolution will have necessary capability to recognize the possible rings in the spectrum profile. Figure 3 shows the best-fit model from the simulation data. We see the best fit is near our parameters of the model and the error is small.

A typical double-horn profile gives us an opportunity to determine the parameters by measuring the energy shifts of the features within the broad spectral line wings. Even in situations when the contribution of rings is only moderate and the energy shifts cannot be determined immediately from the secondary peaks merely by inspecting the spectrum, the fitting procedure can be employed to reconstruct the model parameters. This requires employing a physically substantiated model of the spectrum and using the entire profile of the broad line and the continuum.

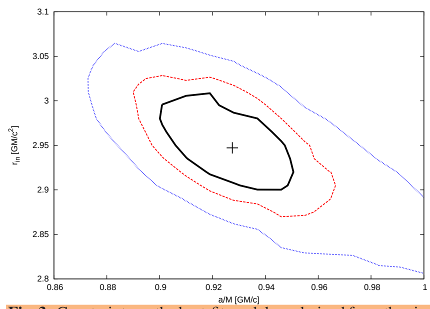

Fig. 3: Constraints on the best-fit model are derived from the simulation data. Confidence contours are shown (1, 2, and 3σ) of the inner ring radius r_{in} vs. dimension-less spin a. The best-fit case found using the LOFT preliminary response matrix and 20 ksec exposure.

References

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