Role of the emission angular directionality in the spin determination of accreting black holes with broad iron lines

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We discuss the method to determine the spin of black holes by employing the broad relativistic iron line profiles in the X-ray domain. The precision of the spectral fitting procedure could be compromised by an inappropriate account for the angular distribution of the disc emission. An isotropic distribution or a particular limb-darkening law have been frequently assumed, although some radiation transfer computations exhibit an emission excess towards grazing angles (limb-brightening). We perform radiation transfer computations of an X-ray irradiated disc atmosphere to constrain the directionality of the outgoing X-rays in the 2–10 keV energy band. We study how sensitive the spin determination is to the assumptions about the intrinsic angular distribution of the emission.

Approximations to the angular emission profile

We set the intrinsic line emissivity of the planar disc to be described by one of the following angular profiles:

$$\mathcal{M}(\mu_{\rm e}) = \begin{cases} \ln(1+\mu_{\rm e}^{-1}) & \text{Case 1: (Haardt, 1993)} \\ 1 & \text{Case 2: (locally isotropic emission)} \\ 1+2.06\mu_{\rm e} & \text{Case 3: (Laor, 1991)} \end{cases} \qquad (1)$$

with the dependence on the disc radius being a power law $\mathcal{R}(r_{\rm e}) = r_{\rm e}^{-q}$. The three cases correspond, respectively, to the limb-brightened, isotropic, and limb-darkened angular profiles of the line emission. We define the limb-brightening profile as an emission excess at high-inclination (disc-grazing) angles in comparison with the isotropic case.

The angular emission profile of a detailed reprocessing model

The directional distribution of the intrinsic emissivity of the reprocessing model is shown in the right panel of Figure 1. The Monte-Carlo radiation transfer code NOAR (Dumont et al., 2000) was used for the case of "cold" reflection, i.e. for neutral or weakly-ionised matter, at constant density. Free-free absorption and recombination continua are taken into account, as well as direct and inverse Compton scattering. A continuum photon index of $\Gamma = 1.9$ is set and the flux is integrated over the 2–100 keV range. The NOAR code enables us to obtain the angle-dependent intensity of the reprocessed emission. Although the results of the radiation transfer computations do show a limb-brightening effect, it is a rather mild one, and not as strong as for the Case 1.

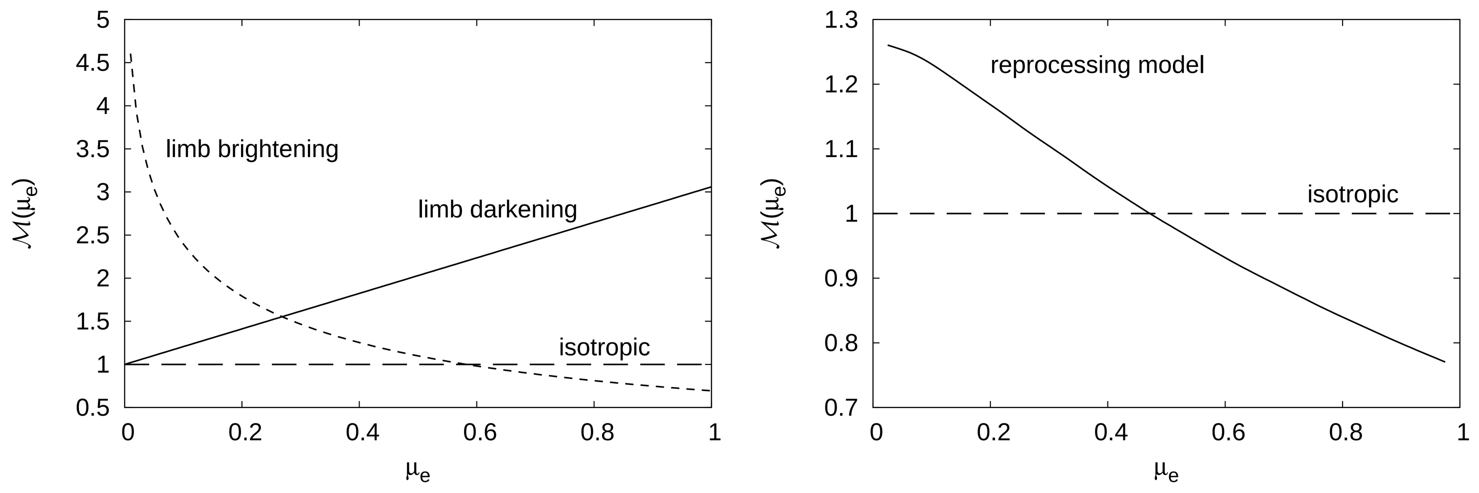

Figure 1. Left: directional distribution of the intrinsic emissivity (Cases 1-3). Right: an example of the directional distribution from the numerical computations (Svoboda et al., 2009).

	Case 1	Case 2	Case 3
	$a_{\rm f} = 0.7$, $\theta_{\rm f} = 30°$		
a	$0.60^{+0.02}_{-0.01}$	$0.69^{+0.01}_{-0.01}$	$0.76^{+0.01}_{-0.02}$
$\theta_{\rm o}$ [deg]	$29.8^{+0.2}_{-0.3}$	$29.7^{+0.3}_{-0.3}$	$29.6^{+0.3}_{-0.3}$
χ^2/ν	1.33	1.27	1.39
	$a_{\rm f} = 0.7$, $\theta_{\rm f} = 60°$		
a	$0.65^{+0.03}_{-0.05}$	$0.73^{+0.03}_{-0.04}$	$0.82^{+0.02}_{-0.02}$
$\theta_{\rm o}$ [deg]	$60.0^{+0.1}_{-0.2}$	$60.0^{+0.2}_{-0.1}$	$60.3^{+0.1}_{-0.1}$
χ^2/ν	1.87	1.00	1.48

	Case 1	Case 2	Case 3
	$a_{\rm f} = 0.998$, $\theta_{\rm f} = 30°$		
a	$0.956^{+0.005}_{-0.005}$	1^{+0}_{-1E-3}	1^{+0}_{-8E-5}
$\theta_{\rm o}$ [deg]	$29.9^{+0.3}_{-0.3}$	$29.5^{+0.3}_{-0.3}$	$28.7^{+0.4}_{-0.2}$
χ^2/ν	1.30	1.58	5.08
	$a_{\rm f} = 0.998$, $\theta_{\rm f} = 60°$		
a	$0.982^{+0.002}_{-0.002}$	1^{+0}_{-3E-4}	1^{+0}_{-6E-5}
$\theta_{\rm o}$ [deg]	$59.9^{+0.1}_{-0.2}$	$60.1^{+0.1}_{-0.2}$	$60.2^{+0.1}_{-0.2}$
χ^2/ν	1.24	1.02	2.51

Table 1. The best-fit spin and inclination angle values inferred for the three cases of the directionality in the KYL3CR model. The data were generated using the KYL2CR model. The quoted errors correspond to a 90% confidence level.

Procedure and results

We implemented the numerical results of the NOAR modelling as the new KYL2CR model in the KY collection of XSPEC models (Dovčiak, 2004). Furthermore, we produced an averaged model, KYL3CR, by integrating the KYL2CR tables over all angles. *A posteriori*, KYL3CR can be equipped with an analytical prescription for the angular dependence (Cases 1–3 in eq. 1). This approach allows us to switch among the three prescriptions for comparison and fast evaluation.

In order to compare the performance of the aforementioned approaches, we generated artificial data using a POWERLAW + KYL2CR model in XSPEC. The parameters are: photon index of the power law $\Gamma = 1.9$ and its normalisation $K_\Gamma = 0.01$, spin of the black hole a, inclination angle $\theta_{\rm o}$, inner and outer radii of the disc $r_{\rm in} = r_{\rm ms}$ and $r_{\rm out} = 400$, index of the radial dependence of the emissivity $q = 3$, and normalisation of the reflection component $K_{\rm kyl2cr} = 0.1$. We simulated the data for two different values of the spin, $a = 0.7$ and $a = 0.998$, and for the inclination angles $\theta_{\rm o} = 30°$ and $\theta_{\rm o} = 60°$. We used a preliminary response matrix for the future IXO (International X-ray Observatory) mission. We chose the flux at a level that corresponds to bright Seyfert 1 galaxies observed by current X-ray satellites. The total flux depends on the extension of the disc and its inclination. Its value is $4.9 - 5.6 \times 10^{-11}$ erg cm^{-2} s^{-1} for our choice of the parameters.

We then fitted the simulated data by a POWERLAW + KYL3CR model searching back for the best-fit results. In this way, we obtained the values of the spin and the inclination angle for different directionality. The fitting results are summarised in Table 1, and contour graphs of a versus $\theta_{\rm o}$ are shown in Figure 2. Besides the spin and the inclination angle, only the normalisation of the reflection component was allowed to vary during the fitting procedure. The remaining parameters of the model were kept frozen at their default values.

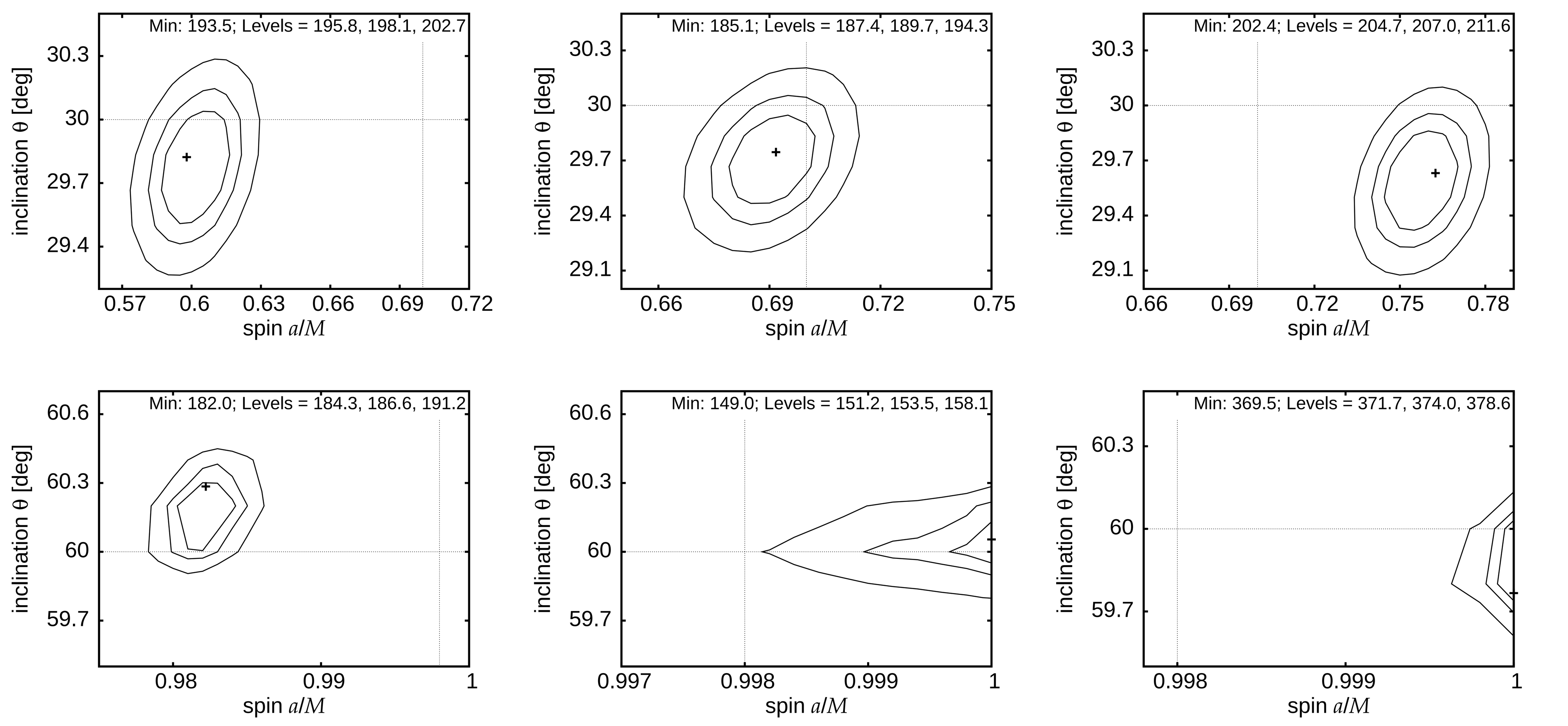

Figure 2. Fitting a POWERLAW + KYL3CR model to simulated IXO data that were generated with POWERLAW + KYL2CR. Results for three different profiles of the emission directionality are shown – left: limb-brightening, middle: isotropic, right: limb-darkening. The contour lines refer to the 1, 2, and 3 sigma levels. The position of the minimal value of χ^2 is marked with a small cross. The values of χ^2 corresponding to the minimum and to the contour levels are shown in a legend at the top of each contour graph. The large crosses indicate the position of the fiducial values of the angular momentum and the emission angle.

Conclusions

The black hole spin measurements using the X-ray spectroscopy of the relativistically broadened line depend on the employed definition of the angular distribution of the disc emission. The suitability of the particular directionality prescription depends on the fiducial values of the spin and the inclination angle; but, on the whole, the isotropic directionality suits to the best precision to our simulated "cold disc" data. Our simulations with the tentative IXO response show a significant improvement that can qualitatively enhance the accuracy of spin determination.

References

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