# Broad emission lines for a negatively spinning black hole


Thomas Dauser[1],
thomas.dauser@sternwarte.uni-erlangen.de
Jörn Wilms[1], Christopher S. Reynolds[2], and Laura W. Brenneman[3]
[1] Remeis-Observatory / ECAP, University of Erlangen-Nuremberg, Germany
[2] Department of Astronomy, University of Maryland, College Park (MD), USA
[3] Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge (MA), USA



## Abstract

We present an extended scheme for the calculation of the profiles of emission lines from accretion disks around rotating black holes. The scheme includes disks with angular momenta which are parallel and antiparallel with respect to the black hole's angular momentum, as both configurations are assumed to be stable (King et al., 2005). Based on a Green's function approach, an arbitrary radius dependence of the disk emissivity and arbitrary limb darkening laws can be easily taken into account, while the amount of precomputed data is significantly reduced with respect to other available models. We discuss line shapes for such discs and present a code for modelling observational data with this scheme in X-ray data analysis programs. Moreover the observability of these lines in current and future X-ray missions is discussed. A detailed discussion will soon be presented in a forthcoming paper (Dauser et al., 2010).




## How do black holes get negative spin and why do we care?

Skew-symmetric, broadened Fe K$\alpha$ emission lines are seen in many Active Galactic Nuclei (MCG−6-30-15), Galactic black hole binaries (Cygnus X-1) and neutron star systems. Since the **line shape depends on the spin of the black hole**, $a$, and the emissivity and inclination of the surrounding accretion disk, the **diagnostic power of relativistic lines is very high**, as they provide one of the most direct ways to probe the physics of the region of strong gravity close to the black hole.

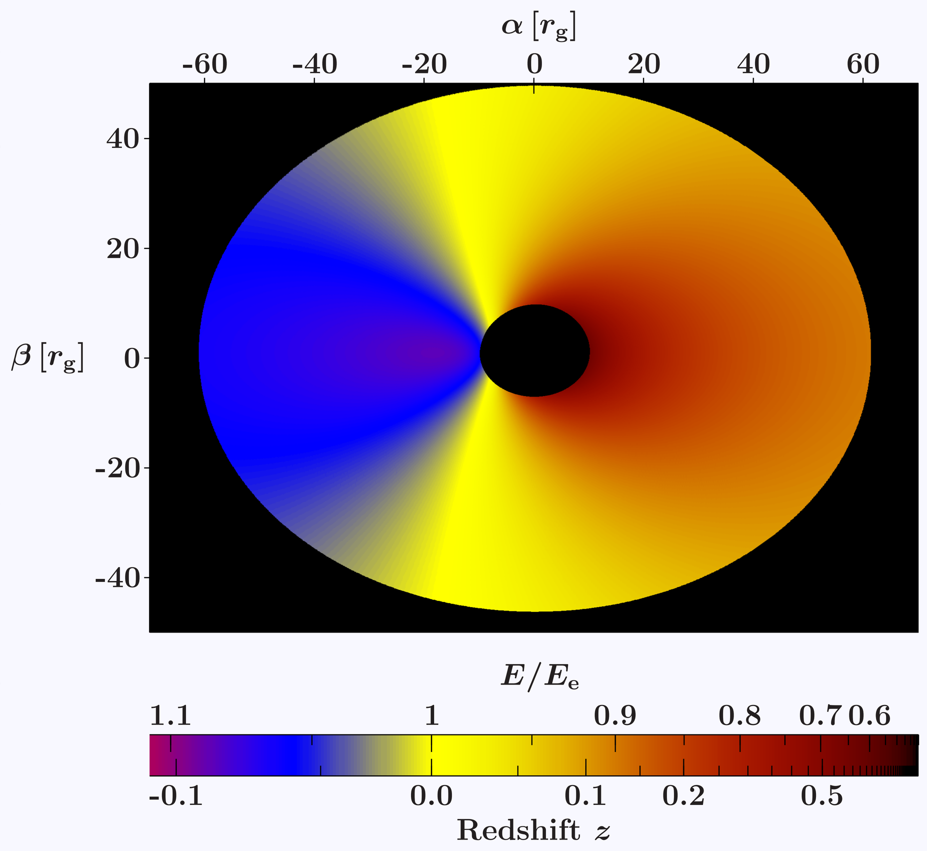
As suggested by stochastic evolution models in the case of AGN (Volonteri et al., 2005) or a supernova kick in a galactic binary system (Brandt & Podsiadlowski, 1995), a **strong misalignment** between the angular momenta of the black hole and the accretion disk can arise and possibly become greater than $90^\circ$, i.e., **the black hole has "negative spin"**. As shown by King et al. (2005), both **parallel** and **antiparallel** alignments of the disk and black hole angular momenta are **stable configurations**; misaligned discs will evolve to one of them.

In fact, accretion onto **rapidly-spinning retrograde black holes** may be of some importance for understanding the properties of powerful radio-loud AGN, as Garofalo (2009) argues that an accretion disk around a retrograde black hole is a particularly potent configuration for **generating powerful jets**, which might also **explain the lack of radio-loud AGN** (Garofalo et al., 2010).

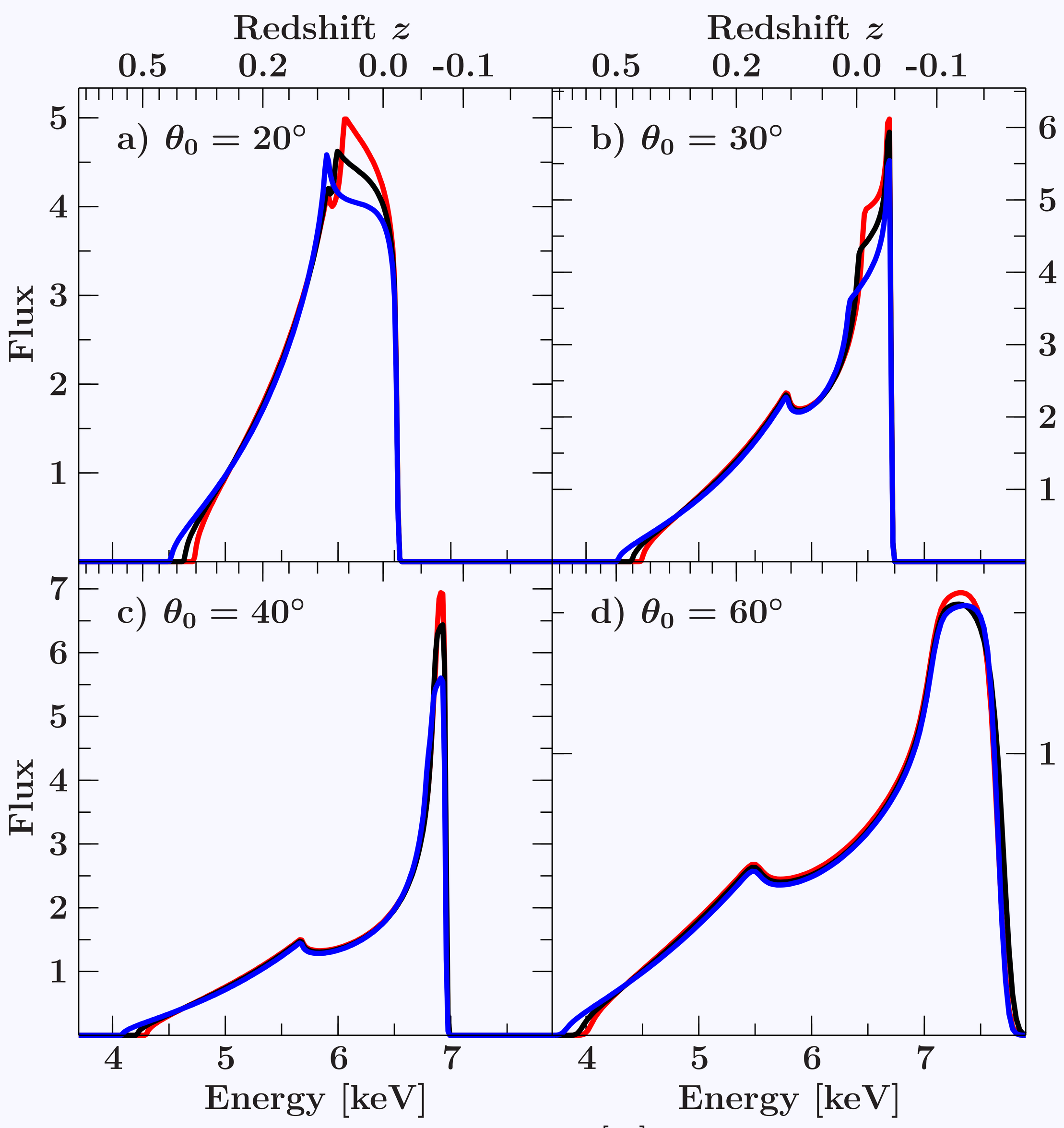
## The accretion disk for a negatively spinning black hole.

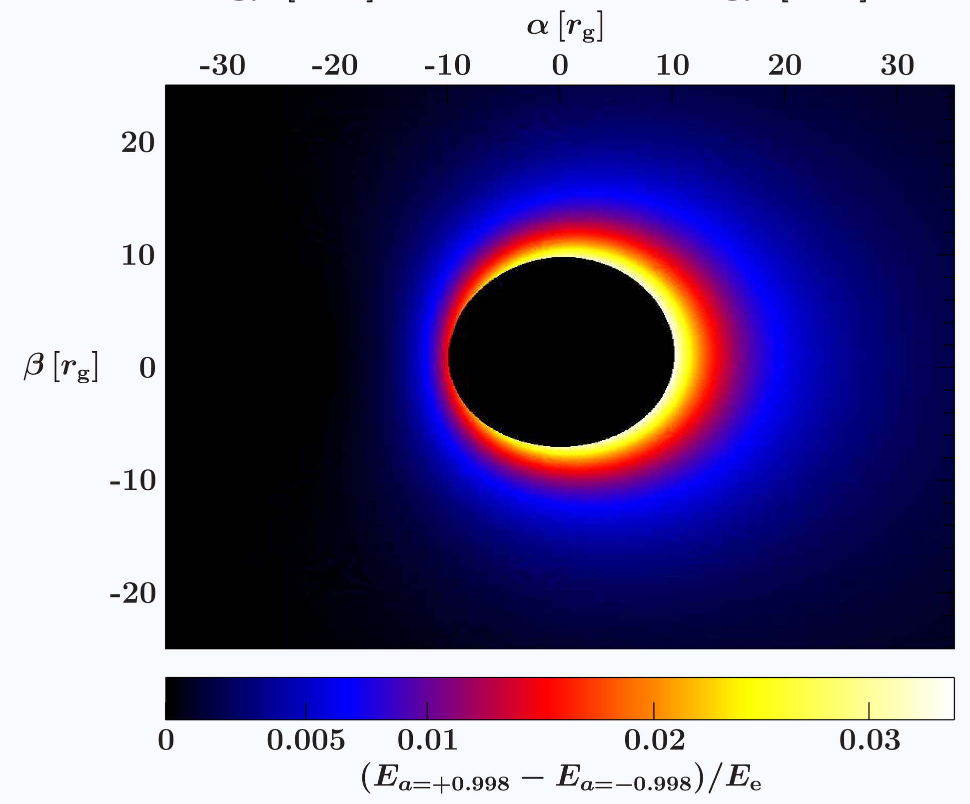
Circular particle orbits around a black hole become unstable beyond a certain radius $r_{ms}$, which sets the innermost possible edge of the accretion disk. This radius depends on the spin $a$ of the black hole and ranges from $r_{\mathrm{ms}}(a = +0.998) = 1.23\,r_{\mathrm{g}}$ for a maximal positively spinning black hole to $r_{\mathrm{ms}}(a = -0.998) \sim 9\,r_{\mathrm{g}}$ for the maximal negative case.

The figure shows the **energy shift emerging photons experience** around a maximally spinning **retrograde black hole** ($a = -0.998$). The inclination is $\theta_o = 40^\circ$ and the disk truncates at $60\,r_g$. $\alpha$ and $\beta$ are the coordinates defined on the plane of the sky (i.e., perpendicular to the line of sight). The blue-shifted left part of the disk moves towards the observer, whereas the right part recedes from the observer and the asymmetries are due to relativistic light bending.




## Line profiles for retrograde accretion disk




The line profiles of a relativistic iron line at 6.4 keV with an emissivity (i.e., the intensity dependence on the radius) of $r^{-3}$ are displayed on the left. The maximal spinning black hole ($a = +0.998$) is drawn in **red**, the non-rotating ($a = 0$) in **black**, and the **blue** line shows the broad emission line for maximal negative spin ($a = -0.998$). In order to allow for a comparison of the pure frame-dragging effects, the inner edge of the accretion disk was set to $r = 9\,r_g$ for all profiles.

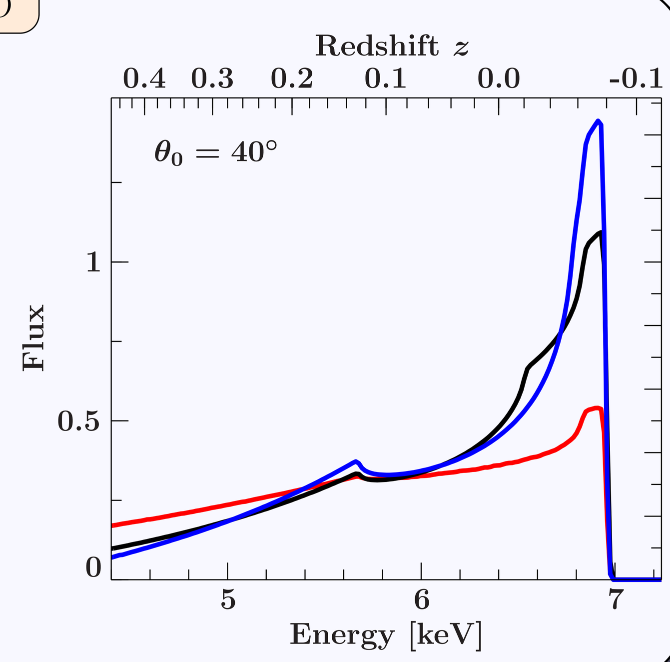
The comparison the profiles shows that in this case the major difference between the different spins is the relative strength of the core of the line to the red wing, which decreases with decreasing $a$. For this case of a large inner radius, the most significant differences in line shape are seen for low values of $\theta_o$ while the red tails are virtually indistinguishable. The slight increase in line flux at the lowest energies is due to the increased Doppler boosting in the case of $a < 0$ (for a given radius, $u^t$ increases with decreasing $a$).

The lower image is the **difference in energy shift** between the image of an accretion disk producing the **red line** (positive spin) and the **blue line** (negative spin) in the profiles for an inclination angle of $\theta_o = 40^\circ$. In order to highlight the differences, the extreme case, meaning the difference between maximally positive and negative rotating black hole, was chosen. As the differences are highest close to inner edge of the disc, a higher emissivity pronounces the deviations in the line profiles. Moreover this figure shows that for an accretion disk with an inner radius larger than $30\,r_g$ no significant differences are be expected.

## Profiles for $r_{\mathrm{in}} = r_{\mathrm{ISCO}}$

Here, the more realistic case where the disk extends down to the marginally stable orbit is shown. Colors are the same as above. Since the **inner edge of the disk is closer to the black hole** for **positively** spinning black holes, more strongly redshifted photons emerge and therefore **broader lines** (especially for emissivities strongly peaked inwards). Maximally **negatively** spinning black holes have the **smallest width**, although the line will still be detectable as being broad even at CCD resolution.

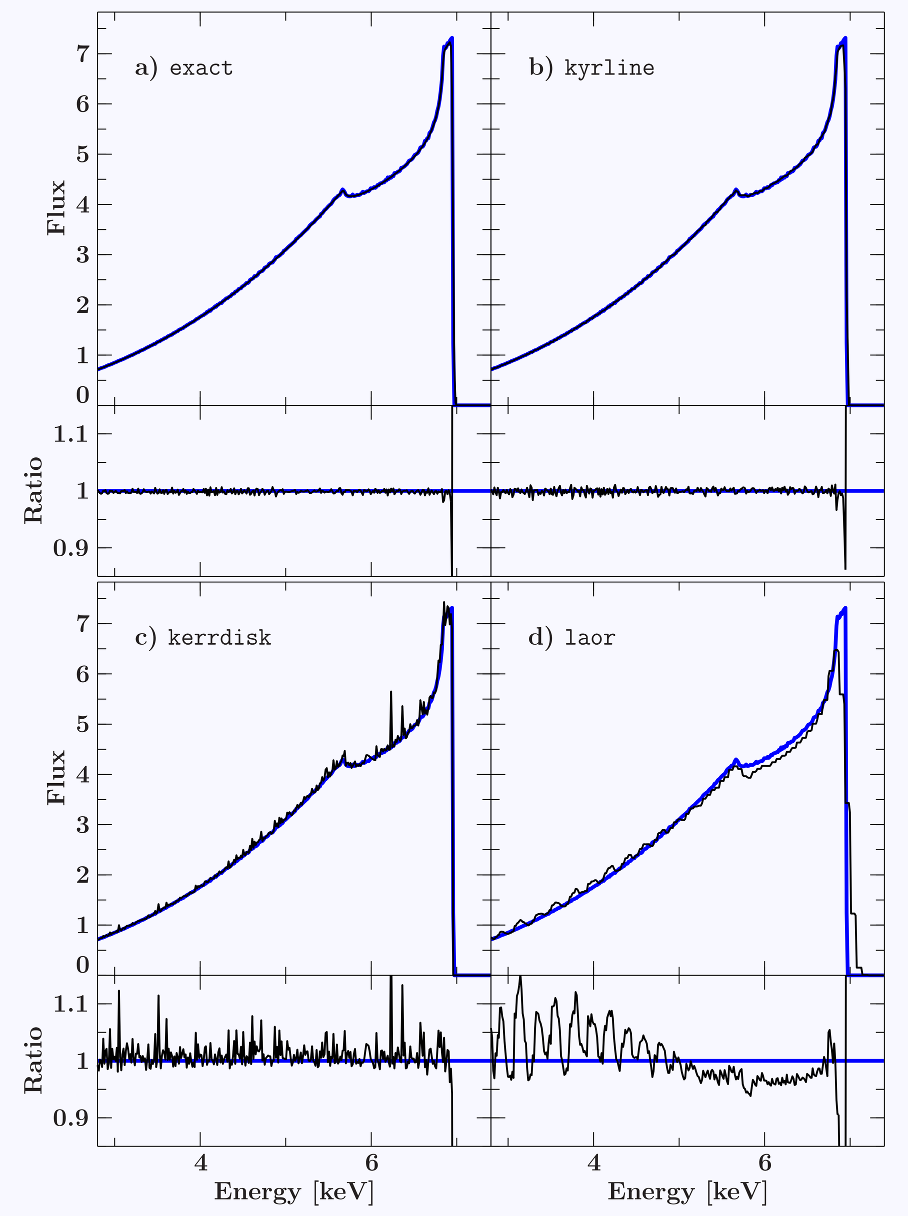
As fluorescent emission only takes place in irradiated parts of the disk which are not fully ionized, a highly ionized inner part would not contribute to the emission line. This results in a effectively larger inner radius of the disk and thus a weaker red tail of the line profile and therefore more similar line shapes.




## Data Analysis: the relline model

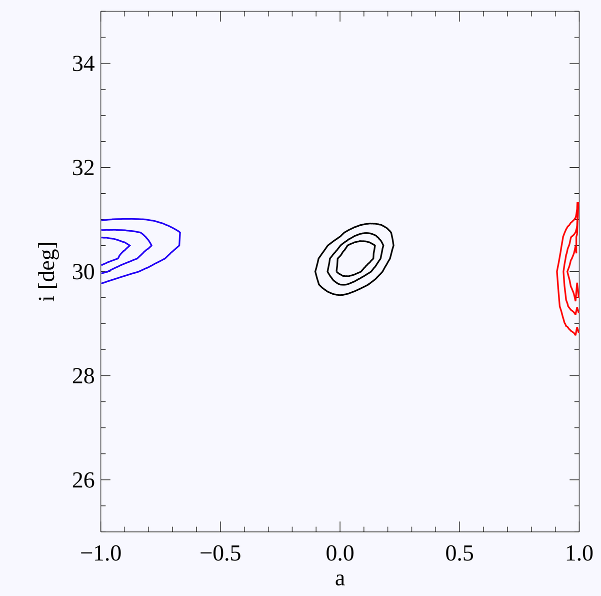
We implemented a model function, called `relline`, that can be added to data analysis software such as ISIS or XSPEC for spin $-0.998 \leq a \leq 0.998$ and inclination $0^\circ \leq \theta \leq 89^\circ$. Both an additive and a convolution model, which can be used for calculating relativistic smearing, are provided.

The figure shows a comparison of the `relline` model **(blue)** to models commonly used in X-ray astronomy **(black)** (Laor, 1991; Brenneman & Reynolds, 2006; Dovčiak et al., 2004). The comparison of the model with an exact numerical calculation in a) that does not make use of precalculated quantities and interpolation shows that there is no significant deviation between both approaches.




The complete model and more information can be found at:
www.sternwarte.uni-erlangen.de/research/relline/

## Observability of negative spin




In order to study the question of observability in greater detail, we have performed simulations of observations of a relativistic line for with the planned International X-ray Observatory (*IXO*). We base the simulations on power-law fits to *XMM-Newton* data from MCG−6-30-15 in a typical state and set the equivalence width of the line to the observed 350 eV. The confidence contours in the figure are for a 50 ksec observation and show that the next generation X-ray instrumentation will allow to separate even the difficult case of negatively spinning black holes.

## References


Brandt N., Podsiadlowski P., 1995, MNRAS 274, 461

Brenneman L.W., Reynolds C.S., 2006, ApJ 652, 1028

Dauser T., Wilms J., Reynolds C.S., Brenneman L.W., 2010, MNRAS in press, arxive:1007.4937

Dovčiak M., Karas V., Yaqoob T., 2004, ApJ Suppl. 153, 205

Garofalo D., 2009, ApJ 699, 400

Garofalo D., Evans D.A., Sambruna R.M., 2010, MNRAS 406, 975

King A.R., Lubow S.H., Ogilvie G.I., Pringle J.E., 2005, MNRAS 363, 49

Laor A., 1991, ApJ 376, 90

Volonteri M., Madau P., Quataert E., Rees M.J., 2005, ApJ 620, 69



Friedrich-Alexander-Universität Erlangen-Nürnberg

ERLANGEN CENTRE FOR ASTROPARTICLE PHYSICS