X-ray spectra from accreting black holes

A new XSPEC model to fit spectra of accretion disks

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We are carrying out a project to develop a new routine that substantially enhances the computational capability of presently available XSPEC models, which is suitable for the analysis of relativistic spectral features. Our approach is flexible enough to allow for easy modification of local emissivity profiles and it can also be used as a rapid stand-alone code capable to deal with time variable and non-axially symmetric structures. We describe basic features of our routine and illustrate some of its applications. Accurate fits can be performed for black-hole parameters (namely, the angular momentum) and the inclination angle.

Introduction

Accretion plays a crucial role in processes of energy liberation and mass accumulation that take place in cores of various astronomical objects. Disc-type configurations represent an important accretion channel and their properties reflect the global geometrical arrangement of a source as well as local microphysics in the fluid medium. A central compact body, undetectable via its own radiation, resides in stellar binary systems and in galactic nuclei where it is surrounded by a rather dense population of stars and gaseous environment. Photons emerging from the accretion disc and its corona are influenced by gravity of the dark object, so they bear imprints of the source field structure upon arrival to a distant observer. For this reason, X-ray spectral analysis is particularly relevant for astronomical study of strong gravitational fields around black holes. Several routines have been developed and linked with the XSPEC package [1] in order to fit the model of a black hole and accretion disk to the satellite data [4, 5]. In this contribution we report on a new variant of the computational approach that we have developed recently. We describe details of the numerical code and show various tests and examples of its applications.

Computational tool

The central compact body governs gravitational field in which the medium of an accretion flow evolves. The accretion process gradually transfers mass and angular momentum onto the body and it contributes in this way to the source evolution. We consider general relativistic description of the gravitational field with the Kerr metric, in which rotation of the central body is not ignored (but the gravitation of the accretion disk is). The fluid in an accretion disk moves along circular orbits above marginally stable orbit and it is freely falling below this orbit (with the specific angular momentum and specific energy of the fluid moving along the marginally stable orbit). We adopt the approximation of geometrical optics in which light rays are null geodesics [2]. A useful form of ray-tracing equations can be found in various papers [3, 7, 8]. In order for our routine to be computationally efficient and completely transparent to the user, all necessary functions – time delay, g-factor, emission angle, and lensing – have been computed beforehand and stored as a single FITS format table. Careful choice of the grids (with non-equidistant step size) and ray-tracing in well-behaved coordinates (ingoing with light) allowed us to optimize the coverage of the whole parameter space and to map the disk plane from the horizon up to $1000\,GM_\bullet/c^2$. The table can be recomputed to accomodate different spacetime metric (including a gravitating disk or a neutron star), further reprocessing of photons in a corona, or even to compute relativistic effects on polarized light. A graphical representation of the table for g-factor and lensing is in Fig. 1, 2. The new model is called ky hereafter. It is supposed to be more accurate and versatile than laor [4], and substantially faster than kerrspec [5]. Among other features, ky allows to fit various parameters such as black-hole angular momentum, observer inclination, accretion disc size, etc. It also allows to change the grid resolution and thus control accuracy and computational speed. Moreover, new user-defined local emissivities can be easily included, either in tabular or in analytical form. There is also an option to explore time variable sources.

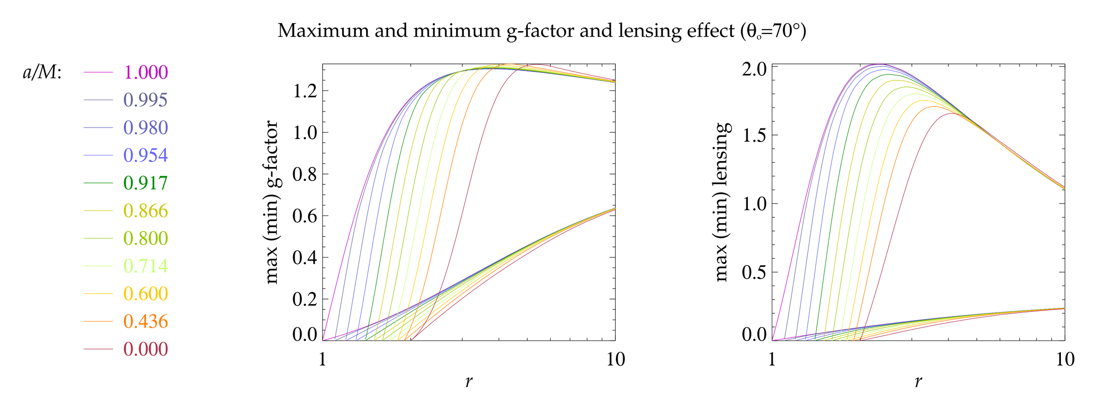

Fig. 2: Maximum and minimum values of g-factor and lensing as a function of distance from the black hole. The width and boundaries of an emission line are dependent on maximum and minimum values of g-factor in the region where the line is emitted.

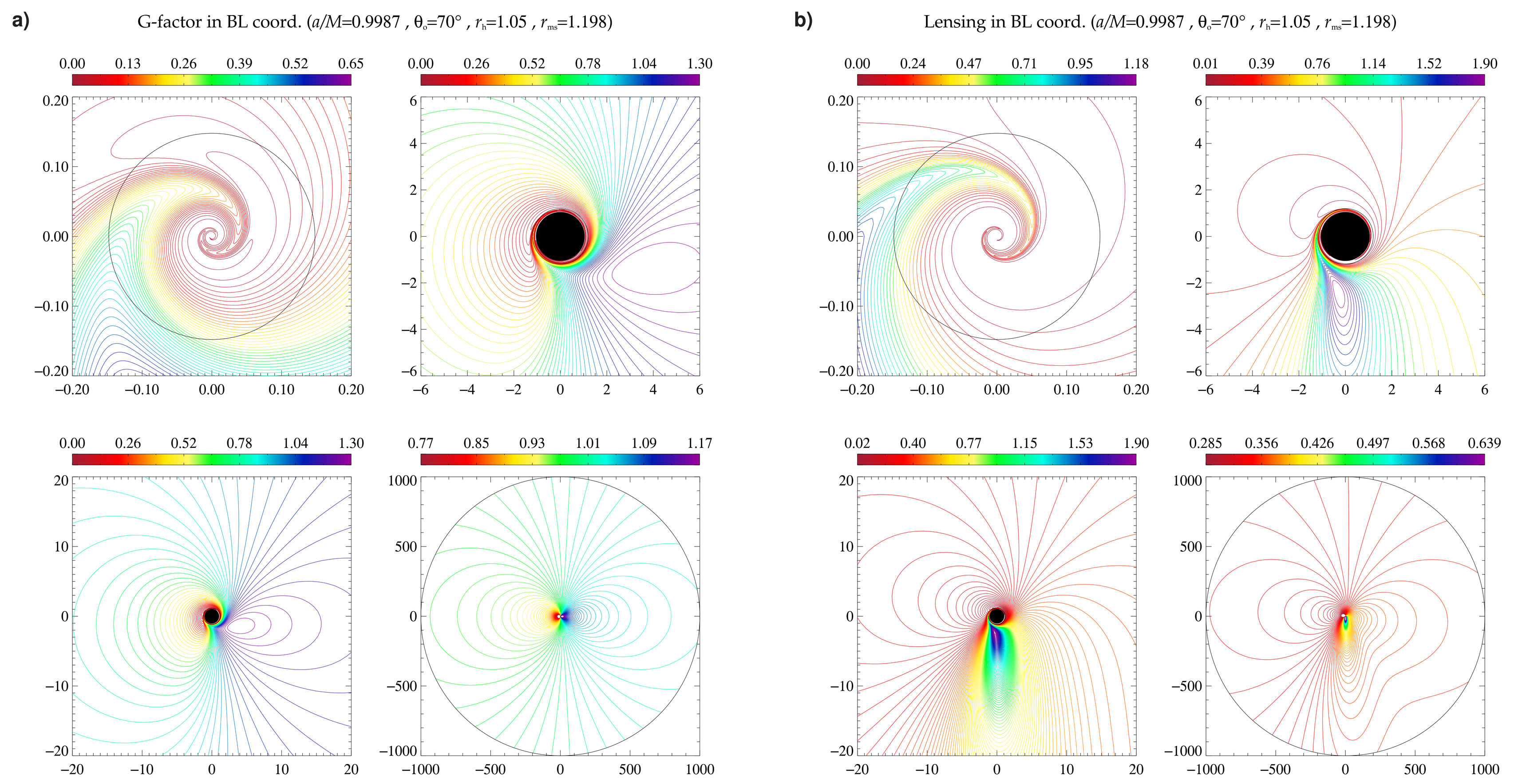

Fig. 1: Contour plot representation of data tables for the equatorial plane of a rotating black hole:
a) g-factor (ratio of the energy of a photon received by the observer at infinity to the energy of the same photon when emitted from the accretion disk),
b) lensing (ratio of the area at infinity perpendicular to the light rays through which photons come to the area on the disk from which these photons are emitted).
These pictures show top view of the equatorial plane in different scales. The x and y axes are in units of $GM_\bullet/c^2$. The black hole (in counter-clockwise rotation with dimensionless angular momentum parameter $a = 0.9987$) is drawn as a black circle in the center of the pictures (except for the upper left pictures where $\sqrt{x^2+y^2} = r - r_{\rm horizon}$ and thus the horizon is located in the point $[0,0]$ here). Rotational axis is perpendicular to the picture. The observer receiving the light rays is located to the top of the pictures with the inclination angle $\theta_0 = 70°$ from the rotational axis. The marginally stable orbit is also drawn in the upper panels.
Note that contours close to the black hole are clockwise twisted because the light rays are dragged counter-clockwise by the black hole on their way to the observer. Photons emitted from the vicinity of the black hole and receding part of the disk are redshifted and those emitted from the approaching part of the disk are blueshifted (the accretion disk is rotating counter-clockwise). Note that lensing is largest behind the black hole (from the point of view of the observer).
Figures for all four functions – time delay, g-factor, cosine of emission angle and lensing – and for various values of rotational parameter of the Kerr black hole and inclination angle of the observer can be found at 'http://astro.troja.mff.cuni.cz/ky/tables.htm'.

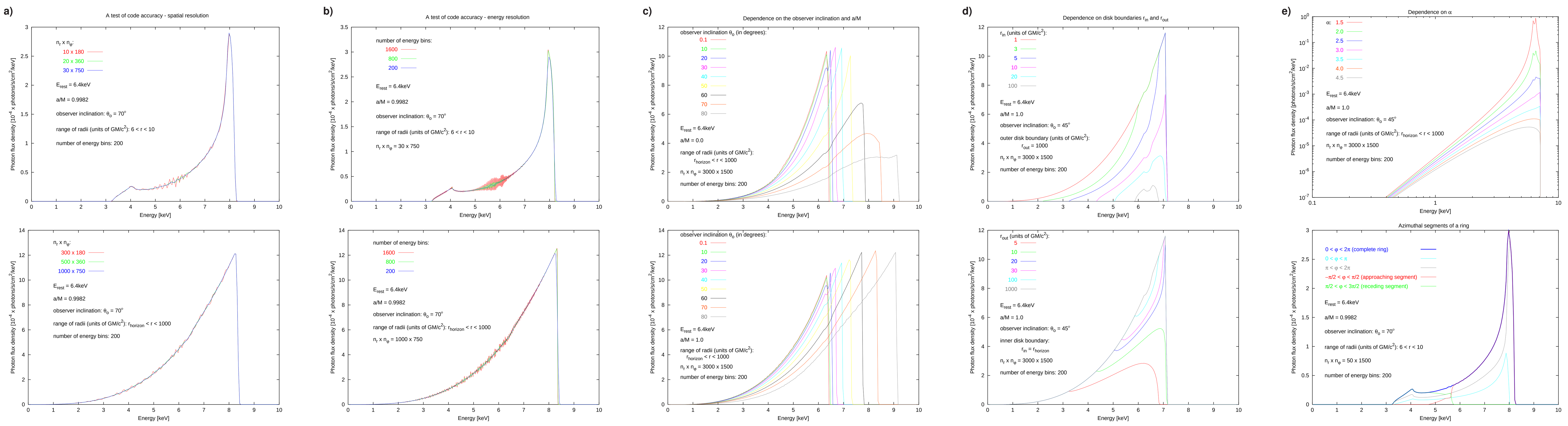

Fig. 3: Code tests and comparisons for simple line profiles (local emissivity is narrow gaussian line with its maximum decreasing as $\sim r^{-\alpha}$):
a) An example of the line computed at increasing spatial resolution (n_r, n_φ are numbers of points on the disk in r- and φ-directions used in the integration over the disk). Apparent wiggles occur when the grid is too coarse.
b) An example of the line computed at decreasing energy resolution. The energy interval $0-10$keV is divided into equal bins when integrating over the disk. The line is smoother for fewer energy bins thus compensating for the lower spatial resolution. The energy bins needn't to be equidistant and are dependent on the data within the XSPEC.
c) Line profiles for various values of observer inclination for Schwarzschild and extreme Kerr black holes. Note the differences for higher inclinations.
d) Line profiles for various accretion disk sizes (various values of $r_{\rm in}$ and $r_{\rm out}$).
e) Line profiles for different values of parameter α of local emissivity (upper graph) and for emissivity originating from different azimuthal segments of the disc (lower graph).
The values of various important parameters of the model are drawn directly into the graphs. Unless otherwise stated, the parameter $\alpha = 3$.

Examples and code tests

Given the local emissivity in the disc plane, we use the data tables to compute a predicted observed spectrum. A narrow line is a good example of local emissivity to start with. The intrinsic width of the line (typically $\lesssim 10$ eV) is much less than its subsequent relativistic broadening, and the local profile (assumed to be Gaussian with the maximum decreasing with the distance from the black hole as $\sim r^{-\alpha}$) is thus smeared in the final spectrum. Typical application is the iron Kα line with rest energy of 6.4 keV. We assume that the line is produced in an equatorial ring ($r_{\rm in} < r < r_{\rm out}$) with isotropic angular distribution. Local emissivity is a function of polar coordinates in the disc plane. It can also depend on local emission angle with respect to the disc normal direction, and it can be time dependent. An example of a computed (observed) line is in Fig. 3 (local emission was a narrow gaussian line). The local emissivity in the routine can be easily changed so that it describes the continuum as well.

The routine ky can be used as a model in the x-ray spectral fitting package xspec – see Fig. 4 for an example fit of the Kα iron line.

When using routine ky as a stand-alone program it is possible to investigate dynamical processes, e.g. to model time dependent spectrum of an orbiting or freely falling spot (see Fig. 5).

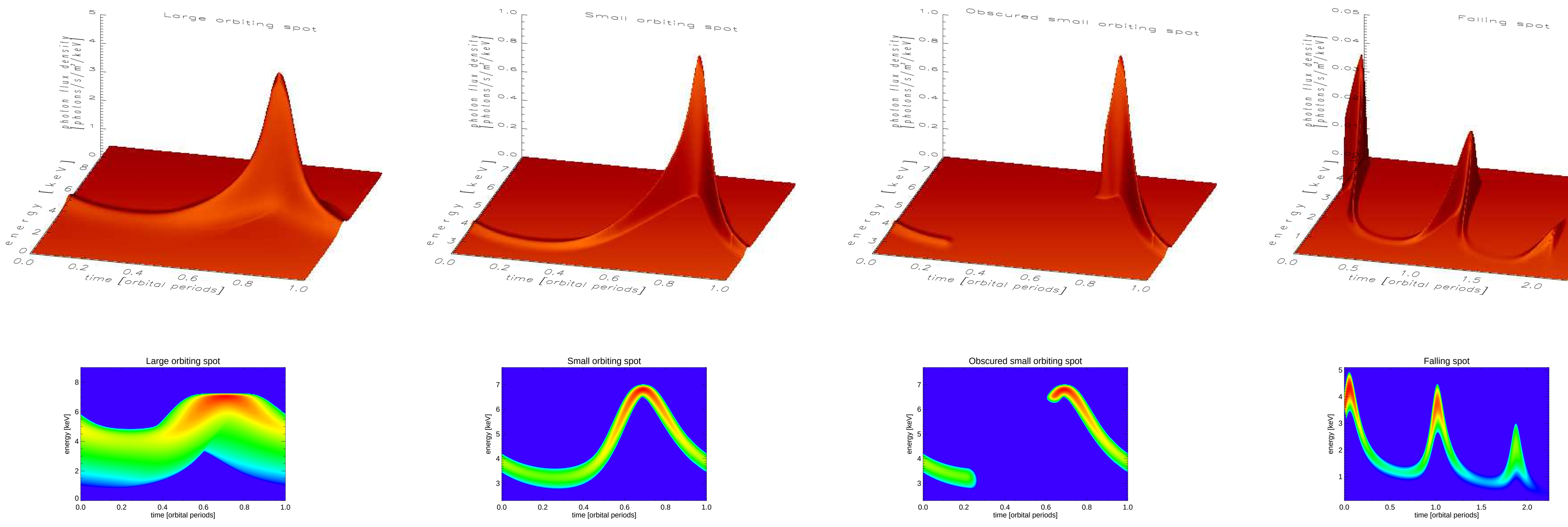

Fig. 5: Dynamical spectrum of an orbiting spot:
a) Demonstration spectrum of a very large spot with diameter $\sim 8GM_\bullet/c^2$ with its center co-rotating with the disk around an extreme Kerr black hole along a circular orbit at $8GM_\bullet/c^2$.
b) Spectrum of a spot with diameter $\sim 1.25GM_\bullet/c^2$ with its center co-rotating with the disk around an extreme Kerr black hole along a circular orbit at $5GM_\bullet/c^2$.
c) Spectrum of the same spot as in b) but on its way around the black hole the spot moves through the region where it is obscured by some material along the line of sight.
d) Spectrum of a small spot with diameter $\sim 0.25GM_\bullet/c^2$ falling freely into a Kerr black hole with $a = 0.9$. The spot begins its fall at $0.93r_{\rm ms}$ ($r_{\rm ms}$ is the marginally stable orbit). Specific energy and angular momentum of the spot is the same as those of the spot moving on a circular orbit at $r_{\rm ms}$.
Spots in a)-c) begin their orbit in front of the black hole (from the point of view of the observer). The spot in d) begins its orbit behind the black hole. The emissivity of the spots is that of the narrow gaussian Kα line decreasing towards the edge of the spot (like Gauss as well). The observer inclination is $\theta_0 = 45°$.

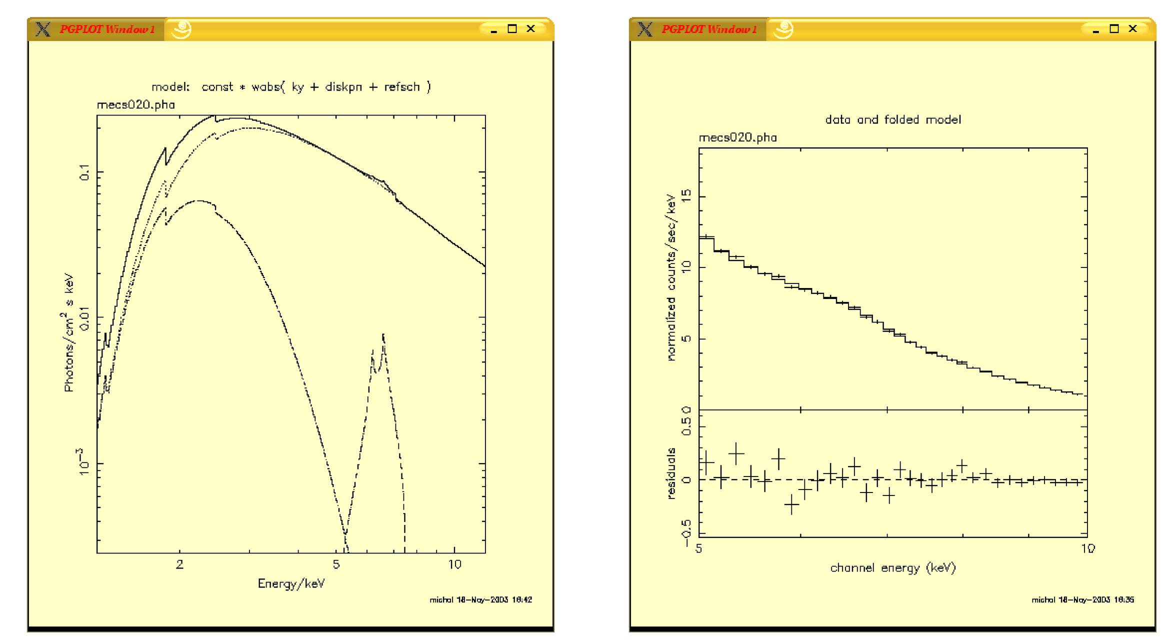

Fig. 4: The xspec model components const*wabs(ky+diskpn+refsch) and an example fit to the data from the BeppoSAX observations of GRS 1915+105 (see [6]). The new model ky is used to fit the iron line Kα.

Conclusions

We have developed a new XSPEC model which is suitable for analysis of relativistic spectral features originating in black-hole accretion disks. We have performed various tests of the routine. The current version of the code can be requested from the authors.

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