KYNREFREV — the XSPEC model for X-ray reverberation in the lamp-post geometry

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Abstract: In the last decade the X-ray reverberation echos produced by reflection of the coronal emission from the inner parts of the accretion disc was observed in several AGN. To estimate the properties of the system showing these features fast and modular XSPEC model is needed. In this contribution we want to introduce such a model that is ready to be used for both the frequency and energy dependencies of lags in the lamp-post geometry and that is fast enough for fitting the data effectively. The parameters of the model, like the black hole spin, height of the corona, density of the disc affecting the disc ionisation profile, reflecting disc region (inner and outer edge and azimuthal segment), circular obscuring cloud and others are summarised. The black-body reverberation due to the thermalised part of the illuminating radiation, that is important mainly for low mass AGN and for soft X-ray energy band, is included as well. The power-law hard lag for frequency dependence is also available directly in the model.

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The model components

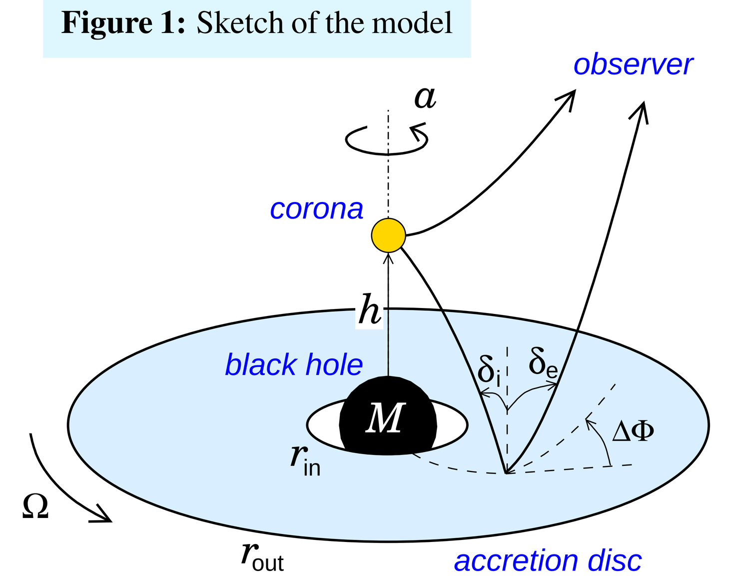
Black hole: Kerr metric for central gravitating body with mass M and spin a in the dimensionless geometrical units $G = c = M = 1$ is used.

Accretion disc: co-rotating, Keplerian, geometrically thin, optically thick ionised disc with different radial density profiles.

Corona: hot point-like patch of plasma located on the rotation axis at the height h above the centre and emitting isotropic power-law radiation $f = E^{-\Gamma}$ with the power-law index $\Gamma = 2$ for the specific photon number density flux.

Observer: located at infinity, viewing the system with an inclination angle θ_o with respect to the symmetry axis of the disc.

Figure 1: Sketch of the model



Methods and approximations

Light rays: Full relativistic ray-tracing code in vacuum is used for photon paths from the corona to the disc and to the observer and from the disc to the observer.

Reflection: The REFLIONX, Ross & Fabian (2005), tables for constant density slab illuminated by the power-law incident radiation is used to compute the re-processing in the ionised accretion disc. The ionisation of the disc, ξ, is set by the amount of the incident primary flux (dependent on the luminosity of the primary source, height of the corona and mass of the black hole) and by the density of the accretion disc. We consider several limb brightening/darkening prescriptions for directionality of the re-processed emission.

The KYNREFREV model parameters

par1	a/M	black hole angular momentum
par2	theta_o	observer inclination in degrees
par3	rin	inner edge of non-zero disc emissivity
par4	ms	switch for inner edge;
		0: we integrate from inner edge = par3;
		1: if the inner edge of the disc is below marginally stable orbit (MSO) then we integrate emission above MSO only;
par6	phi	lower azimuth of non-zero disc emissivity (degrees)
par7	dphi	(phi + dphi) is upper azimuth of non-zero disc emissivity $0° \le$ dphi $\le 360°$
par8	M/M8	black hole mass in units of $10^8\,M_{\odot}$
par9	height	height on the axis (measured from the center) at which the primary source is located
par10	PhoIndex	power-law energy index of the primary flux
par11	L/L_{Edd}	dE/dt, the intrinsic local (if negative) or the observed (if positive) primary isotropic flux in the X-ray energy range 2-10keV in units of L_{Edd}
par12	Np:Nr	ratio of the primary to the reflected normalization
		1: self-consistent model for isotropic primary source
		0: only reflection, primary source is hidden
par13	density	density profile normalization in 10^{15} cm^{-3}
par14	den_prof	radial power-law index of the density profile
par15	abun	Fe abundance (in solar abundance)
par16	therm	fraction of thermalised flux from the overal incident flux illuminating the disc
		0: only the reverberation of reflected radiation is computed
		$<$ 0: only the reverberation of thermal radiation is computed
		$>$ 0: both the thermal and reflection reverberation is included
		abs(par16) $>$ 1: the fraction of thermalisation is computed from difference between the incident and reflected fluxes
par17	arate	accretion rate in units of L_{Edd} if positive or in Solar mass per Julian year if negative
par18	f_col	spectral hardening factor for thermal disc emission
par19	alpha	alpha coordinate of the obscuring cloud centre on the sky of the observer
par20	beta	beta coordinate of the obscuring cloud centre on the sky of the observer
par21	rcloud	radius of the obscuring cloud
par22	zshift	overall Doppler shift
par23	limb	limb darkening or brightening law for the emission directionality
		0: for isotropic emission (flux ~ 1)
		1: for Laor's limb darkening (flux $\sim 1 + 2.06\mu$)
		2: for Haardt's limb brightening (flux $\sim \ln(1 + 1/\mu)$)
par24	tab	which reflion table to use; 1: reflion; 2: reflionx
par25	sw	switch for the way how to compute the refl. spectra
par26	ntable	defines fits file with tables; ntable=80
par27	nrad	number of grid points in radius
par28	division	type of division in radial integration
par29	nphi	number of grid points in azimuth
par30	deltaT	length of the time bin
par31	nt	number of time subbins per one time bin
par32	t1/f1/E1	defines lower end of interval according to the required output:
		t1: integration time to be used in XSPEC for the spectrum (0 means average spectrum, i.e. divided by the flare duration)
		f1: frequency for the energy dependent Fourier transform (0 means average values in the range of 0 to the first wrapping frequency;
		E1: in case of frequency dependent lags it defines the lower value of the energy band of interest in keV
par33	t2/f2/E2	the same as par32 but for higher end of the interval
par34	Eref1	defines the lower value of the reference energy band for lag or amplitude energy or frequency dependence
par35	Eref2	the same as par34 but for higher end of the energy interval
par36	dt/Af	lag shift for lag-energy dependence in case of par38=6
		multiplicative factor in case of adding empirical hard lags Af $\times f^{qf}$ to lag-frequency dependence, used for par38=16
par37	Amp/qf	multiplicative factor for the amplitude-energy dependence in case of par38=5
		powerlaw index in case of adding empirical hard lags Af$\times f^{qf}$ to lag-frequency dependence, used for par38=16
par38	xsw	defines output in the XSPEC (photar array)
		0: spectrum for time interval defined by par32 and par33
		the following values correspond to energy dependent Fourier transform at the frequency band defined by par32 *and* par33:
		1, 2, 3, 4: real and imaginary parts, amplitude and phase of FT
		5 and 7: amplitude divided by amplitude in the reference energy band (integration in freq. is done in real and imaginary parts or directly in amplitudes)
		6 and 8: lag with respect to reference energy band (integration in frequencies is done in real and imaginary parts or directly in lags)
		the following values correspond to frequency dependent Fourier transform for the energy band of interest defined by par32 *and* par33*:*
		11, 12, 13, 14: real and imaginary parts, amplitude and phase of FT
		15, 17: amplitude divided by amplitude in the reference energy band (rebinning is done in real and imaginary parts or directly in amplitudes)
		16, 18: lag with respect to reference energy band (rebinning is done in real and imaginary parts or directly in lags)
par39	nthreads	how many computational threads should be used for calculations
par40	norm	has to be set to unity!

Table 1: Description of model parameters defining the black hole, accretion disc, reflection, numerical resolution, output array and others.

The model is available at: `https://projects.asu.cas.cz/stronggravity/kynrefrev`

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