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Astronomický ústav AV ČR

KYNrefrev – reflection reverberation model

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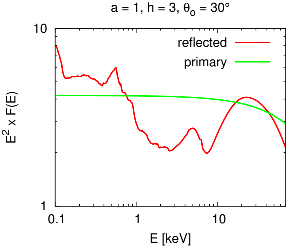
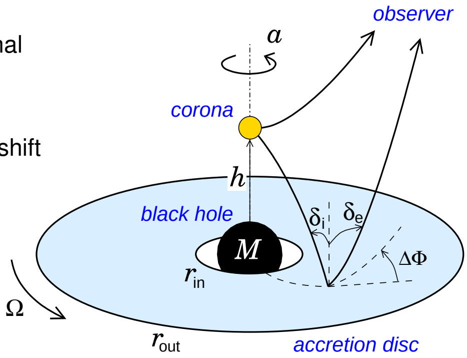
Scheme of the lamp-post geometry

- central black hole – mass, spin
- compact corona with isotropic emission
  → height, photon index
- accretion disc
  → Keplerian, geometrically thin, optically thick
  → ionisation due to illumination
  (L_p, h, M, a, n_H, q_n)
- local re-processing in the disc
  → REFLIONX with different directional emissivity prescriptions
- relativistic effects:
  → Doppler and gravitational energy shift
  → light bending (lensing)
  → aberration (beaming)
  → light travel time
- KYNrefrev





KYNrefrev parameters

1	a/M	GM/c	1.00000
2	theta_o	deg	30.0000
3	rin	GM/c^2	1.00000
4	ms		1
5	rout	GM/c^2	1000.00
6	phi	deg	0.0
7	dphi	deg	360.000
8	M/M8		0.100000
9	height	GM/c^2	3.00000
10	PhoIndex		2.00000
11	L/Ledd		1.00000E-03
12	Np:Nr		1.00000
13	density		1.00000
14	den_prof		0.0
15	abun		1.00000
16	alpha	GM/c^2	-6.00000
17	beta	GM/c^2	0.0
18	rcloud	GM/c^2	0.0
19	zshift		0.0
20	limb		0.0
21	tab		2
22	sw		2
23	duration	GM/c^3	10.0000
24	deltaT	GM/c^3	1.00000
25	nt		256.000
26	ntable		80.0000
27	nrad		500.000
28	division		-1.00000
29	nphi		180.000
30	nt_ratio		1.00000
31	time	sec/Rg	0.0
32	xsw		0
33	smooth		1.00000
34	nthreads		4.00000
35	norm		1.00000

Parameters describing:

- physical properties of the system (blue)
- reflection area and absorption by cloud (green)
- resolution in time, radius and azimuth (red),
  $\rightarrow$ affect speed of the code,
  $\rightarrow$ defaults should be OK, except for extreme cases of low height and low or high inclination
- output inside xspec (orange)

KYNrefrev output

- spectrum integrated over time
- time evolving spectrum of the reflection
- light curves for different energy bands
- real and imaginary parts, amplitudes and phases
  for both relative reflection and total signal
  both for each energy bin and energy band
- real and imaginary parts, amplitudes and phases and time delay
  integrated in frequency range up to the first zero point

Recent developments and future plans

Recent updates:

- re-write into C and as XSPEC model with sum speed-ups
- further speeding up by optimizing resolution parameters

Future plans:

- near future: extrapolation of tail and break due to outer radius
- more physical prescription of disc density (Novikov-Thorne)
- models for neutral cold disc (Goosmann+NOAR),
  XILLVER and REFHIDEN
- more distant future: off-axis flares and extended corona

Transfer function for reverberation

Response to the on-axis primary emission:

$$F(E,t) = \int dt' \int \mathrm{d}S\, G(r,\varphi) \times$$

$$N_{\mathrm{p}}(t')\, N_{\mathrm{inc}}(r)\, M(r,\varphi,E/g,t'+t_{\mathrm{pd}})\, \delta([t-t_{\mathrm{do}}]-[t'+t_{\mathrm{pd}}])$$

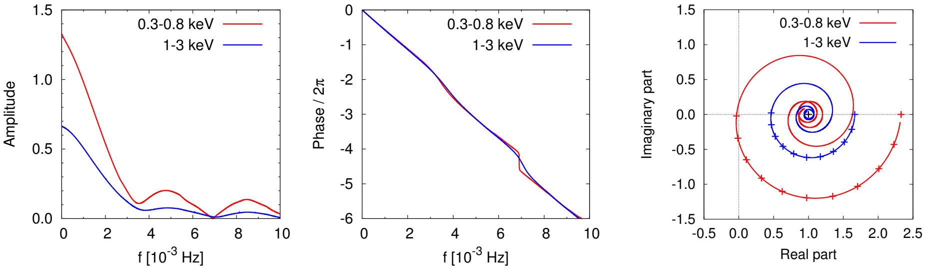
Transfer function $\psi(E,t) \rightarrow$ response to a flare $[N_{\mathrm{p}}(t') = \delta(t')]$:

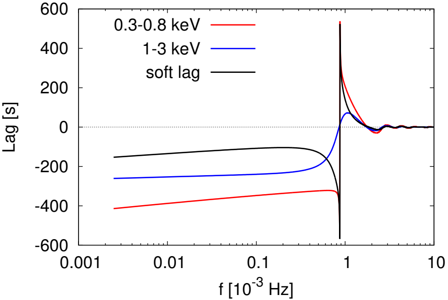
$$F(E,t) = \int dt'\, N_{\mathrm{p}}(t')\, \psi(E,t-t')$$

$$\hat{\psi}_{\mathrm{r}}(E,f) = A_{\mathrm{r}}(E,f) e^{i\phi_{\mathrm{r}}(E,f)} \qquad \psi_{\mathrm{r}}(E,t) = \frac{F_{\mathrm{r}}(E,t)}{F_{\mathrm{p}}(E)}$$

$$\tau(E,f) = \frac{1}{2\pi f}\, \mathrm{atan} \frac{A_{\mathrm{r}}(E,f)\sin\phi_{\mathrm{r}}(E,f)}{1+A_{\mathrm{r}}(E,f)\cos\phi_{\mathrm{r}}(E,f)}$$

Fourier transform



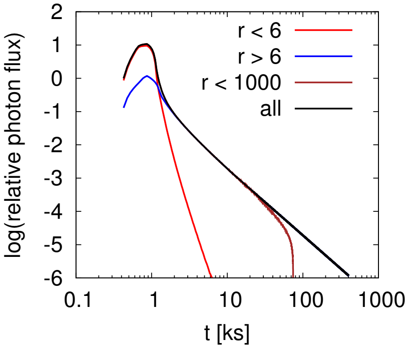


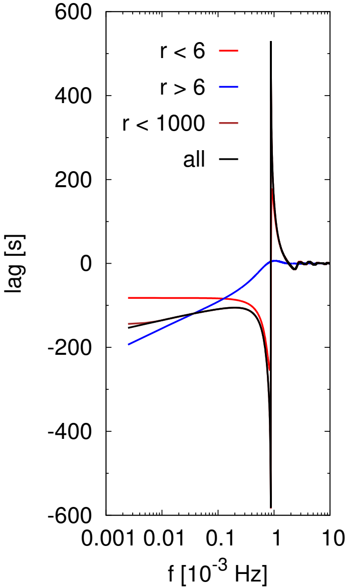
$a = 1,\ \theta_o = 30^\circ,\ h = 3,\ \Gamma = 2,$

$L_{X,obs}(2 - 10\mathrm{keV}) = 0.001\, L_{Edd},$

$M = 10^7 M_\odot,\ n_H = 10^{15}\mathrm{cm}^{-3},\ q_n = 0$

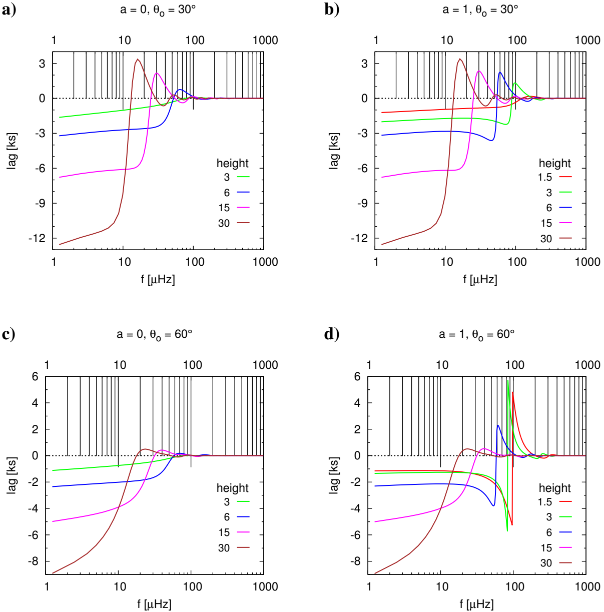
Tail – inner and outer echo





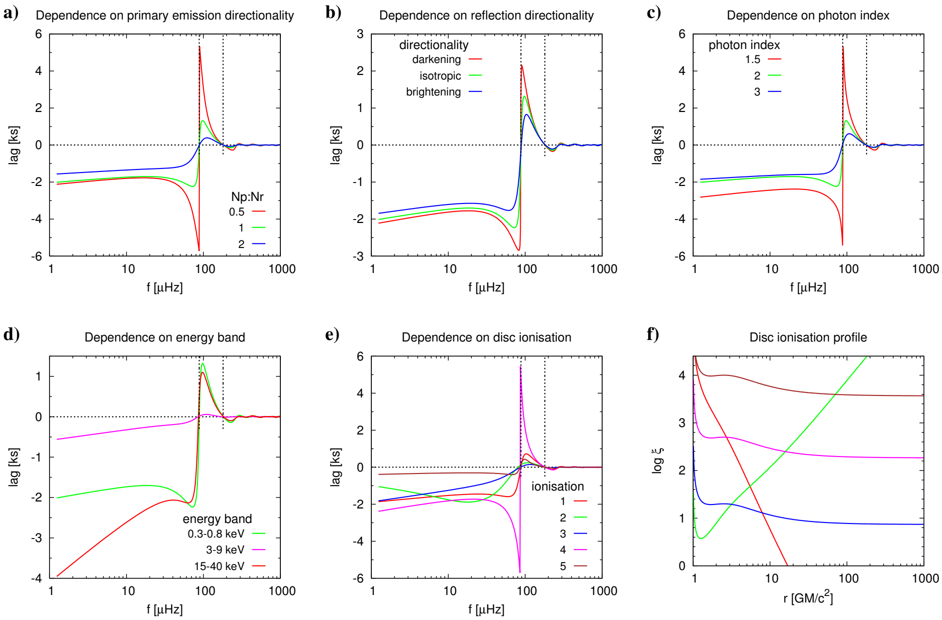
- outer tail in Newton with perfect disc reflection: $\sim t^{-2}$
- radial ionisation dependence may change the tail index: $\sim t^{-q}$
- different contributions of inner and outer parts at low and high frequencies

Lag dependence on geometry

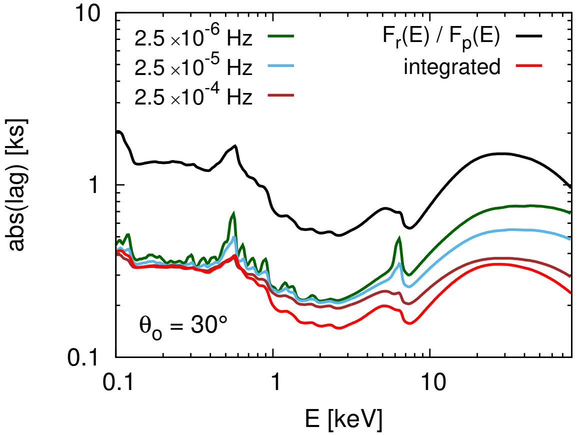


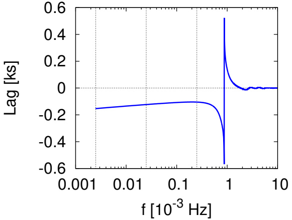
- the lag amplitude:
  - the lag increases with height
  - the lag decreases with inclination (exception: low heights and high spin)
  - the lag decreases with spin (exception: low heights and high inclination)
- the lag null points (due to phase wrapping)
  - shift to lower frequencies for higher heights due to longer timescales of response
  - change slightly with the inclination
  - change negligibly with the spin

Lag dependence on other parameters



Lag energy dependence





- lag–energy dependence follows the relative reflection spectrum
- flattening due to atan and division by $(1 + A_\mathrm{r} \cos \phi_\mathrm{r})$
- low/high frequencies have less/more diluted spectra due to reflection from outer/inner disc regions