KYNREFREV: implementation of an X-ray reverberation model in XSPEC

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Forthcoming publications

1) **M. Dovčiak**, M. D. Caballero-Garcia (ASU CAS, Prague), A. Epitropakis, I. Papadakis (D. of Physics, Heraklion), G. Miniutti (CAB, Spain), et al.

*(to be submitted in ApJS) → On the model*


*(to be submitted in MNRAS) → On the data (using the model)*
The model: “The relativistic reflection model in the lamp-post geometry”

Artistic representation of the effects of Strong Gravity around an accreting black-hole
The model: “The relativistic reflection model in the lamp-post geometry”

History

➢ Model based on the properties of the accretion disc in the *strong gravity regime* (Dovčiak, Karas & Yaqoob, 2004) → KYRLINE, KYCONV

➢ Model adapted for use in XSPEC under the lamp-post geometry (Dovčiak et al., 2014) → X-ray spectral studies

➢ Model adapted for studies of *reverberation mapping* in the lamp-post geometry of the compact corona illuminating the accretion disc in AGN (Dovčiak et al., 2014b) → X-ray spectral and timing studies

➢ Model adapted for use in XSPEC for simultaneous *spectral and reverberation mapping studies* of black holes *in the whole mass range* (Dovčiak, Caballero-Garcia, Epitropakis, Papadakis, Miniutti, +, in prep.) → KYNREFREV

➢ *Analysis of X-ray reverberation data* (i.e. *X-ray time lags*) *in a sample of Seyfert galaxies using this model using XSPEC* (Caballero-Garcia, Epitropakis, Dovčiak, Papadakis, Miniutti, +, in prep.)
The model: “The relativistic reflection model in the lamp-post geometry”

Overview

- X-ray reverberation mapping of the inner parts of the accretion disc → clues to the geometry of the corona.
- Reverberation mapping in the lamp-post geometry of the compact corona → ionisation of the disc.
- The theoretical lag versus frequency and energy → model parameters: height of the corona, inclination of the observer, disc ionization profile and black hole spin.

The sketch of the lamp-post geometry. (Credits: Dovčiak+14)
The model: “The relativistic reflection model in the lamp-post geometry”

The model components

- **Black hole**: Schwarzschild or maximally rotating Kerr, with mass \( M \) and dimensionless spin parameter \( a = 0 \) -1.
- **Accretion disc**: co-rotating, Keplerian, geometrically thin, optically thick, *ionised* disc extending from the ISCO up to \( r_{\text{out}} = 1000 \, GM/c^2 \).
- **Corona**: hot point-like plasma on the rotation axis at height \( h \) and emitting power-law radiation, \( F_p \sim E^{-\Gamma} e^{-E/E_c} \), with a sharp low energy cut-off at 0.1 keV and \( E_c = 300 \, \text{keV} \).
- **Observer**: located at infinity, inclination angle \( \Theta_o \) with respect to the symmetry axis of the disc.
The model: “The relativistic reflection model in the lamp-post geometry”

Approximations

- **Light rays**: Fully relativistic ray-tracing code in vacuum for photon paths from the corona to the disc and to the observer & from the disc to the observer.

- **Reflection**: REFLIONX (Ross & Fabian, 2005), tables for constant density slab illuminated by the power-law incident radiation used to compute the re-processing in the ionised accretion disc.

- The ionisation of the disc, $\xi \rightarrow$ amount of the incident primary flux (dependent on the luminosity of the primary source, height of the corona and mass of the black hole) $\rightarrow$ density of the accretion disc (different density radial profiles are used).

- Several limb brightening/darkening prescriptions for directionality of the re-processed emission.
Parameters

There are 36 variable parameters. Most of them are fixed to their recommended values.

The most important ones (some of them to be modified by the user) are:

Physical

- $a/M$ – BH angular momentum ($-1 \leq a/M \leq 1$)
- $\Theta_0$ – observer inclination (degrees)
- $M/M_8$ – BH mass ($10^8 M_\odot$)
- $h$ – height on the axis of the primary source ($GM/c^2$)
- $t_f$ – duration of the flare ($GM/c^3$) → 10 → NO LONGER USED
The model: “The relativistic reflection model in the lamp-post geometry”

Resolution

- Define the resolution of the code & related with the speed of the code.
- The most important ones (*some of them*) to be modified by the user) are:
  - $\Delta T$ – length of the time bin (GM/c$^3$) → 1
  - $n_{\text{tbin}}$ – number of time bins (defines where the linear extrapolation starts) → NO LONGER USED
  - $n_{\text{rad}}$ – number of grid points in radius → 500 (*)
  - $n_{\text{phi}}$ – number of grid points in azimut → 180 (*)
  - $nt$ – number of time subbins per one time bin (critical in the speed of the code & fixed to 1) → NO LONGER USED
  - $n_{\text{threads}}$ – how many threads should be used for computations (fixed to 4 BUT CAN BE ANY NUMBER). CODE IS PARALLELIZED.
The model: “The relativistic reflection model in the lamp-post geometry”

Output (OUTSIDE XSPEC – for developers only)

➢ The length of the response function to the flash (box-shaped) and/or of the primary flux component.

➢ The time-integrated spectrum of the reflection (i.e. response) component and/or the primary flux component.

➢ The real and imaginary part, the amplitude and the phase of the FFT of the response function and delays at each energy range and time bin.

➢ Nomenclature of the files:

```
kyreflionx_AAA_BB_CCCC_DDD.txt
kyreflionx_AAA_BB_CCCC_DDD....dat
```

where AAA, BB, CCCC and DDD are 100x the horizon value (100 for $a=1$ and 200 for $a=0$), the inclination in degrees, 10x the height and 10x the duration of the flare, respectively.
The model: “The relativistic reflection model in the lamp-post geometry”

Output (outside XSPEC) → Light curves “observed” reflection

Left: Soft (0.3-0.8 keV versus 1-3 keV) light curves.
The model: “The relativistic reflection model in the lamp-post geometry”

The model (outside XSPEC) → Soft lags vs. energy/frequency

Left: Soft (0.3-0.8 keV versus 1-3 keV) lag spectrum.
The model: “The relativistic reflection model in the lamp-post geometry”

How to get these results (for developers only)

- *Time lags* can be easily calculated from the output XSPEC files (*bands*phase*tot*.dat).
- The oscillations of the lag-frequency dependence are due to *wrapping* of the Fourier phase of the disc response.
- No need for the user to worry about details of the *transfer function* (defined inside the code).
The model: “The relativistic reflection model in the lamp-post geometry”

Recent developments

➢ We speeded up the code by pondering resolution parameters (every run now takes a few seconds only).

➢ We fine-tuned the parameters ↔ code to better account for strong relativistic effects at the innermost regions → no intervention/knowledge by the user.

➢ Extrapolation of the tail or break due to outer radius.

➢ The user can set up the frequency and the energy range that corresponds to observations.
The model: “The relativistic reflection model in the lamp-post geometry”

Fits with XSPEC

- We have produced time-lags from 1H0707-495 from 20 ks segments in different energy bands taking the 2-4 keV reference energy band.
- We fitted the 0.3-1 keV time-lags versus frequency spectrum with the KYNREFREV model.
- We obtain a very good fit ($\chi^2_\nu \sim 1$) with a run-time of the order of seconds (i.e. alike normal X-ray energy-spectral fitting).
- The values for the parameters obtained are well-constrained and in agreement with Emmanoulopoulos+14 (with exception of the parameter $h$ – we will explore it further).
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Fit statistic : Chi-Squared = 27.79 using 36 PHA bins.
Test statistic : Chi-Squared = 27.79 using 36 PHA bins.
Reduced chi-squared = 0.9926 for 28 degrees of freedom
Null hypothesis probability = 4.755007e-01
Weighting method: standard
The model: “The relativistic reflection model in the lamp-post geometry”

Fitting the data (using XSPEC)

The soft lag-frequency fitted spectrum of 1H0707-495 (0.3-0.8 keV versus 1-3 keV) as obtained using XSPEC.
The model: “The relativistic reflection model in the lamp-post geometry”

Parameters: 1) a/M; 2) Theta_o; 8) M/M8; 9) height; 13) density; 33) and 34) amplitude and photon index low-frequency hard lags.

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The model: “The relativistic reflection model in the lamp-post geometry”

Installation instructions

➢ For the installation inside XSPEC:
  - Get the source files (contact M. Dovciak).
  - KY tables: KBHlamp_qt.fits, KBHtables80.fits
  - REFLION(x) tables: reflion.mod, reflionx.mod

➢ The code is compiled inside XSPEC, by doing:
  - initpackage kynrefrev lmodel.dat /path_to_kynrefrev

➢ For use inside XSPEC:
  - lmod kynrefrev /path_to_kynrefrev
  - mo kynrefrev
The model: “The relativistic reflection model in the lamp-post geometry”

Plans for the future

➢ More physical prescription of the radial density of the disc (Novikov-Thorne). [ Now we are using a phenomenological power-law ]

➢ Models for neutral disc by Rene Goosmann+NOAR, XILLVER and REFHIDEN.

➢ More distant future: off-axis flares and extended corona.
The average arrival times of photons as a function of energy where the accretion disc is illuminated by a vertically collimated corona extending between 1.5 and 10 $r_g$ above the singularity. The overall arrival time including both continuum and reflected photons is shown for fluctuations propagating at varying speed. (from Wilkins+16)
The model: “The relativistic reflection model in the lamp-post geometry”

Discussion

![Graph showing Lag (in seconds) diluted by primary radiation versus energy (keV) with respect to the (0.1-10 keV) energy band at the frequency of $10^{-4}$ Hz. Different radial power-law density profiles of -2 (black), -1 (red) and 0 (green) have been considered. The mass of the BH is $M=10^7 M_\odot$ and the adimensional spin, inclination of the observer and height of the primary source are $a = 1$, $\theta = 30^\circ$ and $h = 3 R_g$, respectively.]

(Paper in prep.)
The model: “The relativistic reflection model in the lamp-post geometry”

Conclusions

➢ First lamp-post reverberation model taking into account all known physical aspects is ready for use into XSPEC (Dovčiak, Caballero-Garcia, Epitropakis, Papadakis +, to be submitted in ApJS).

➢ Comparison with the recent reverberation model based on extended coronae (Wilkins+16) does not support the emergency for the use of extended coronae still.

➢ Nevertheless, more work is needed in the future in order to address possible extended coronae geometries (taking into account all the possible physical effects).

➢ To address this goal, collaborative efforts (like FP7-Strong Gravity project) are absolutely mandatory.
Acknowledgements

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