The very first results from the use of the X-ray reverberation model KYNREFREV in XSPEC

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

Artistic representation of the effects of Strong Gravity around an accreting black-hole
Reverberation in X-rays

Observational discovery

➢ The analysis of continuous monitoring of the 1H0707-495 during 4 orbits of the XMM-Newton satellite in January 2008.

➢ The discovery of a relativistically smeared Fe L (~1 keV) line led to the discovery of X-ray reverberation in X-rays.

➢ Discovery paper:

“Broad line emission from iron K- and L-shell transitions in the active galaxy 1H0707-495”

Fabian, Zoghbi, Ross, Uttley, Gallo, Brandt, Blustin, Boller, Caballero-Garcia, et al.


(250 citations so far)
X-ray Soft/negative=reverberation lags

Powerlaw leads reflection: Reverberation
X-ray Soft/negative = reverberation lags

Akn564
Kara+13

Low frequency lag featureless so NOT reverberation

High frequency lag shows iron
So is reverberation
Reverberation in X-rays

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 (Chainakun+16, Dovčiak+17).

➢ Goal: understanding the lags versus frequency/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)
Reverberation in X-rays

Cackett+14  

after Campana+Stella95, Reynolds+99
Reverberation in X-rays

In our work we refer as “transfer function” the relative response of the disc to the illumination:

$$\phi_{\Gamma}(E, t) = \frac{F_{\Gamma}}{F_{p}}$$

where $F_{\Gamma}(E, t)$ is the time dependent observed reflected flux from the disc as a response to a flare that would be observed as $F_{p}\delta(t)$. The Fourier transform of the transfer function is calculated as:

$$\hat{\phi}_{\Gamma}(E, f) = A_{\Gamma}(E, f)e^{i\phi_{\Gamma}(E, f)}$$

with amplitude $A_{\Gamma}(E, f)$ and phase $\phi_{\Gamma}(E, f)$ (which is sometimes referred to as transfer function in other works).
Reverberation in X-rays

One can calculate the lag of the signal, computed from the total phase at energy bin $E$ with respect to the total phase at some reference energy bin:

$$\tau(E, f) = \frac{\Delta \phi_{\text{tot}}(E, f)}{2\pi f}$$

To determine the response function of the disc, we assume that the primary X-ray source isotropically emits a flare of duration equal to $1 \, t_g$. Upon being illuminated, each area element of the disc “responds” to this flare by isotropically and instantaneously emitting a “reflection spectrum” in its rest-frame. We assume
The model: “*The relativistic reflection model in the lamp-post post geometry*” (paper I)

Theoretical developments

- 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+, 2017) → KYNREFREV

- *Analysis of X-ray reverberation data (i.e. X-ray time lags) in a sample of Seyfert galaxies using this model with XSPEC* (Caballero-Garcia, Dovčiak+, 2017)
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 $r_{\text{out}} = 1000 \frac{GM}{c^2}$.

- **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 $E_c = 300$ 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.
The model: “The relativistic reflection model in the lamp-post geometry”

Light curves (“observed”) reflection

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

Soft lags vs. frequency

Soft (0.3-0.8 keV versus 1-3 keV) lag frequency “spectra”. Notice the “phase wrapping” (left panel).
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 global spectrum with the KYNREFREV model. → Novel in XSPEC (and very efficient) method!

- We obtain a very good fit ($\chi^2_u \sim 1$) 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 parameters $h$ and $\Theta_o$ – since the ionization of the disc is now included!!).
The model: “The relativistic reflection model in the lamp-post geometry”

Fitting the data (using XSPEC)

The soft lag-frequency fitted global 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) $M/M_8$; 9) height; 13) density; 33) and 34) amplitude and photon index low-frequency hard lags.

Results

- $a/M = 0.25 \pm 0.12 \text{ GM/c}$
- $\Theta_o = 54 \pm 9 \text{ deg.}$
- $M/M_8 = 0.026 \pm 0.002 \text{ M}_\odot$
- $h = 5.0 \pm 0.7 \text{ R}_g$

*Parameters: 1) $a/M$; 2) $\Theta_o$; 8) $M/M_8$; 9) height; 13) density; 33) and 34) amplitude and photon index low-frequency hard lags.*
On the need of an extended corona (?!)

Discussion (comparison with recent work)

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)
Our model

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.
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 vertically extended coronae still.

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

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