Modelling the coupling of variability and spectral emission in black hole X-ray binaries

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Abstract

The emission properties of Black Hole X-ray Binaries (BHXRBs) are commonly studied either in terms of their energy spectrum (counts per energy channel) or in terms of their variability properties by means of power spectral density. Each of these can be modelled separately using X-ray analysis packages, however energy spectra and frequency power spectra have not been modelled simultaneously so far to produce a self-consistent picture of the origin and transfer of variability in these systems.

We discuss new techniques that use frequency and energy-dependent cross-spectra in different energy channels to model variability and spectral information simultaneously. The powerful combination of spectral and timing information will allow us to 'reverberation map' the emitting regions close to the black hole and measure the propagation of signals through the accretion flow.

Spectral-timing: emission components are signals

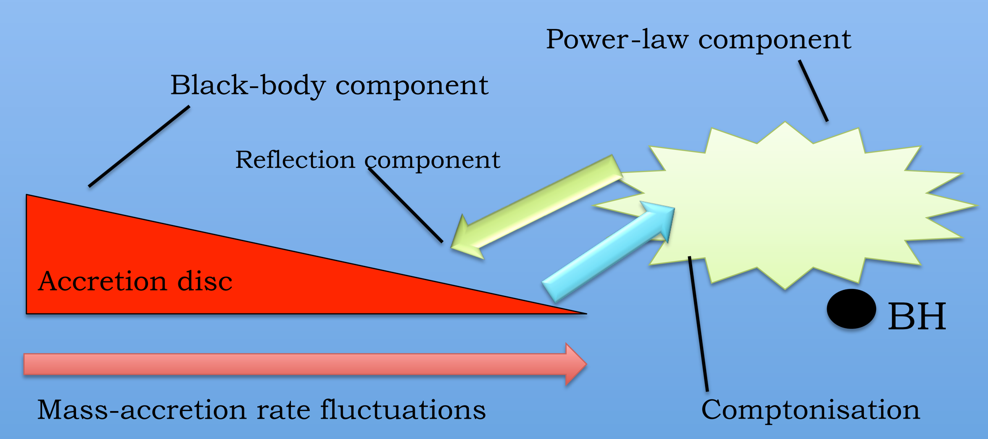
The variability properties of the spectral components in black hole X-ray binaries can be used to constrain the geometry and extent of the accretion flow as well as the location and physical nature of the power-law component (Comptonisation in a central corona, ADAF, base of jet?).

Each emission component shows a spectral shape (dependence of observed flux on energy) and a variability amplitude that can be quantified by means of the power spectral density (PSD) via the Fourier transform. A variable spectral emission component (e.g. the multi-temperature black-body produced in the accretion disc) may modulate the emission in another spectral component (e.g. the power-law), leading to correlated variability, thus linking both processes by a causality connection. The interaction occurs at particular time-scales (viscous, light-crossing...) that can be quantified by means of a time-dependent response function. The resulting output signal then equals the convolution of the input signal with the response function which in the frequency domain simply equals the product of the Fourier transforms:

$$L_{out}(E,t) = h(E,t) \otimes L_{in}(E,t) \qquad \hat{L}_{out}(E,\nu) = \hat{h}(E,\nu) \times \hat{L}_{in}(E,\nu)$$

The function h(E,t) can thus be modelled and used to create cross-spectra in order to **fit** the energy-dependent time-lags or covariance spectra (rms spectra of the linearly correlated components) obtained from the data. The time lags naturally provide a physical distance (e.g. in units of km) between the location of different spectral components, as the distance is proportional to the propagation time-scale. The best-fitting parameters can constrain the location of the emitting components much better than the energy resolution- and calibration-limited averaged spectrum (e.g. to 'reverberation-map' the geometry of the accretion disc via reflection).

A BHXRB in the hard state



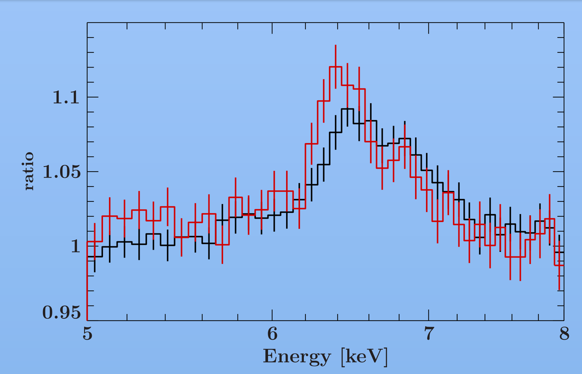
Each spectral component varies with a certain amplitude and its emission leads or lags the emission produced by other components depending on the propagation time-scale. This information can be combined and modelled in terms of a response function and used to constrain the emission properties.

Joint spectral-timing modelling of the hard lags in GX 339-4: constraints on reflection models (Cassatella et al (2012), submitted to MNRAS)

BHXRBs in the hard state show hard-to-soft lags with a dependence on frequency $\tau \propto \nu^{-0.7}$. Recent measurements strongly indicate that the delay is produced by mass-accretion rate fluctuations at a local radius in the accretion disc (Kotov et al (2001), Arévalo & Uttley (2006)) that propagate down to inner radii, thus modulating the emission at different Fourier frequencies corresponding to the local viscous time-scale, at least up to frequencies of the order of 1 Hz.

The hard (4.0 – 10.0 keV) to intermediate (2.0 – 3.5 keV) lags observed in BHXRBs are of unknown origin. In Cassatella et al (2012), we explore the possibility that these delays are produced by reflection of power-law photons produced in a central corona off a flared accretion disc. We create a simple reflection response function following Poutanen (2002) and produce the XSPEC model `reflags`. For a given geometry of the accretion disc, this model is able to reproduce both the expected spectral shape (power-law + reflection spectrum) and the frequency-dependence of the lags. We perform simultaneous fits to the XMM-Newton spectra of GX 339-4 in the 2004 and 2009 hard states as well as the time lags (which can constrain better the large-scale geometry of the disc, as it would only produce an unresolved iron Kα core in the spectrum). While the model reproduces the overall spectral shape, the parameters inferred from the fits produce an extreme geometry, being driven by the large lags. This suggests that another mechanism is also responsible for the lags between these bands.

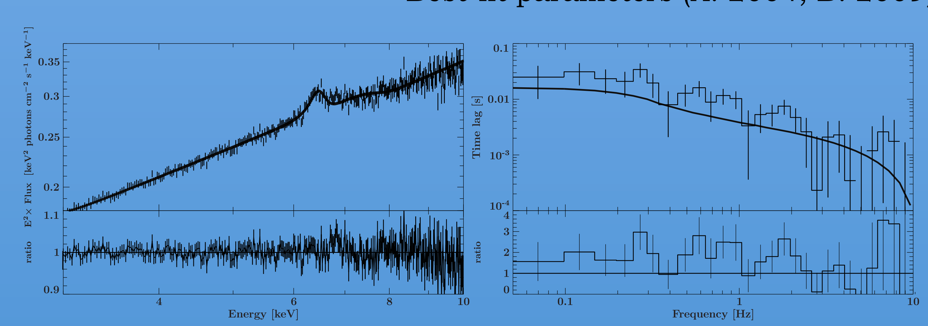
Models created using this approach for different propagation mechanisms can be combined to constrain the properties of the emission in BHXRBs with higher accuracy than in spectral fitting alone.



Ratio to a power-law after fitting the 2.0-5.0 keV and 7.0-10.0 keV continuum (black: 2004, red: 2009)

Parameter	Obs. A	Obs. B
R_{in}/R_g	< 130	< 220
R_{out}/R_g	$(16.8^{+2.4}_{-2.7}) \times 10^3$	$(20^{+50}_{-8}) \times 10^3$
H_{out}/R_{out}	> 0.83	> 0.46
H_{src}/R_g	> 380	> 330
γ	$2.18^{+0.19}_{-0.24}$	> 1.69
i	$39.7^{+0.4}_{-0.5}$	$29.8^{+1.8}_{-4.3}$
Γ	$1.481^{+0.003}_{-0.002}$	$1.468^{+0.004}_{-0.006}$
$\log \xi$	$2.05^{+0.03}_{-0.02}$	$2.03^{+0.02}_{-0.01}$
$\Omega^{eff}/(2\pi)$	1.13	1.28
χ^2/dof	1557 / 1417	1334 / 1416

Best-fit parameters (A: 2004, B: 2009)



Fit to the 2009 spectrum (left) and lags (right)

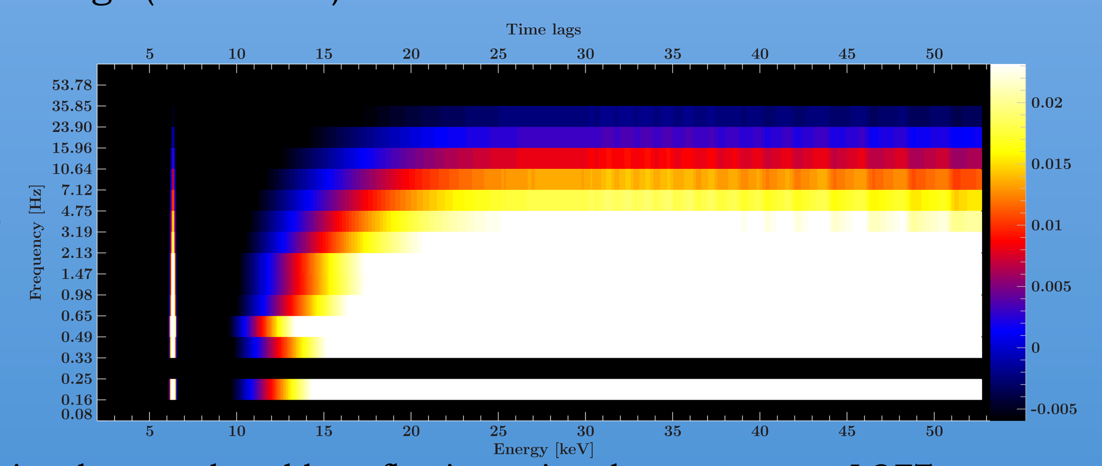
Full spectral-timing characterisation of emission: energy- and frequency-dependent cross-spectral fits with ISIS

(Cassatella et al (2012), in prep.)

We have developed a novel spectral-timing fitting technique to self-consistently characterise both the spectral shape and variability properties of the emission in BHXRBs, using the powerful, publicly available software ISIS (Houck & Denicola 2000). Using this method, users can develop spectral-timing models using response functions (see upper-right panel) in order to simultaneously characterise the properties of the emitting regions using accurate timing measurements together with the spectral information provided by current and future CCD detectors.

This technique works by calculating the Fourier transform of the response function for each energy, that is then convolved through the detector response, producing a quantity C(h, ν) that is then used to compute the cross-spectrum between C(h, ν) for each channel and a reference band. After the fit, the best-fit model can also be used to output quantities such as the frequency and energy-dependent time lags (see below).

This technique offers great potential to 'reverberation-map' the accretion disc with great accuracy, especially with future CCD detectors onboard satellites like LOFT.



Example of a simulation of time lags produced by reflection using the most recent LOFT response

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