Modelling the variability of the Fe Kα line from accreting black hole systems

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Motivation

The Fe Kα line from accreting black holes shows complex variability behaviour: it seems to be less variable than the continuum driving its origin (E>7 keV). This is seen directly in Seyfert galaxies (e.g. MCG-6-30-15, Reynolds 1999; IC 4329a, Done et al. 2000). This effect is also seen in Black Hole Binaries: the Fourier-frequency resolved spectra show weaker reprocessed component and smaller EW of the line for higher Fourier frequency (Revnivtsev et al. 1999, 2001).

General trends in the $f$-resolved spectra can be reproduced in the propagation model of variability, in the truncated accretion disk geometry (Kotov et al. 2001; Życki 2003). Here we study in detail the variability of the Fe line.
The geometry

The general scenario we envision here is of compact active regions/perturbations travelling from outside towards the center. They emit X-ray radiation by the inverse-Compton process, with soft photons for cooling coming from the outer optically thick disk, truncated at a certain radius. The X-ray emission is assumed to increase as the emitter approaches the center (a flare of radiation is thus produced), while the spectrum evolves from softer to harder, because of diminishing supply of soft photons. This reproduces the hard X-ray time lags (Kotov et al. 2001). The relative amplitude the reprocessed component decreases during a flare, which means that the response of the line to the continuum flux is not linear (see Życki 2003 for details of the model).

Description of the flares and possible correlations between them is not unique. One can postulate avalanches of flares, as in the model of Poutanen & Fabian (1999). Another possibility are damped (or forced) oscillator-like flares, in accord with the recent description of power spectra as a sum of Lorentzian components. Yet another possibility is suggested by Maccarone & Coppi (2002) who computed the skewness of X-ray light curves: they postulate asymmetric exponential shots filling in an (almost symmetric) exponential envelope. This might also go some way towards fulfilling the rms-flux relation found by Uttley & McHardy (2001).

In the computations presented here the time lags due to finite light travel time from the X-ray emitter to the reprocessor is not taken into account (negligible for $M<10^8 M_{\odot}$).
Simple stationary models

In a simplest situation the parameters of the variability model do not depend on time. This corresponds to a stationary model, where time averaged energy spectra, power spectra, etc. are constant in time. Here we consider the propagation model with avalanches of flares, and compute model event files \((E, t_{\text{arrive}})\), from which a variety of observables can be computed.

![Graphs showing reduced variability of the Kα line](image)

Reduced variability of the Kα line is seen in the power spectra (left). This is noticeable on short time scales, \(dt<0.1\) sec, corresponding to \(dt=\) a few hours-days for an AGN. In the time sequence of spectra (middle), the line flux response is reduced with respect to the continuum, also only for short time bins. ‘a’ is the coefficient of the linear relation between the logs of line and continuum fluxes. Right panel shows similar relation for spectra binned in total flux. All flux units are arbitrary.
Non-stationary models 1.

Energy spectra, power spectra and other observable characteristics are not constant in time (even if averaged over the short time scale variability, $dt \approx 1 \times \dot{M} / (10 \, M_\odot) \, \text{sec}$). In Black Hole Binaries we have indications that they vary on time scales of hundreds and thousands of seconds. For example, on this long time scale the energy spectra show **softening with increasing flux** (this important relation should be tested for e.g. Cyg X-1 on as short time scales as possible as soon as possible!).

One way to reproduce that behaviour is to assume that the parameters of the variability models are modulated by some underlying slowly varying factor e.g. accretion rate. We have thus considered the propagation model in its variant assuming avalanches of flares (see Życki 2003 for details). We assume that there is an underlying modulation representing accretion rate, varying on rather long time scales (power spectrum breaks to slope of -2 at 0.01 Hz). At a given time step the current value of accretion rate determines the normalization of flares (thus influencing the total flux), and geometrical parameters, which determine the flare-average energy spectrum.
Non-stationary models 2.

We have also considered a model where the description of the flares follows the paper of Maccarone & Coppi (2002). Using results of computations of the skewness of X-ray lightcurves, they proposed a description of flares in which short flares fill in a longer temporal envelope. We have modified their prescription to reproduce the observed power spectra (their original prescription does not reproduce the short time scale ($f>1$ Hz) variability. Also, to account to the Flux-Gamma relation, we assume that the geometrical parameters are related to the number of short flares at a given time, softening the spectrum when the number of flares (thus the luminosity) increases.
Flare avalanches model with underlying accretion rate modulation

The model reproduces, by construction, a qualitative Flux - Gamma relation.

Results of simulations of the line variability are similar to the case of a stationary model. Reduced Fe Kα line variability is seen. The increased power at $f<0.05$ Hz (below, left) is due to the assumed underlying variability of accretion rate.
Flare avalanches model with underlying accretion rate modulation

One of the characteristic results of timing simulations is a loss of coherence between the line and continuum ($E=9$ keV here) lightcurves on short time scales. The Fe line lightcurve here is indeed the lightcurve of the line, i.e. the (primary + reprocessed) continuum was subtracted.

![Coherence plot](image.jpg)
"Envelope of pulses" model

The Flux-Gamma relation and skewness of the lightcurves are reproduced by construction.
“Envelope of pulses” model

In this model we too observe reduced variability of the Fe line compared to the variability of the continuum, on short time scales. The continuum and line lightcurves are not coherent above 1 Hz, but there is also an overall loss of coherence at $f<0.1$ Hz.
The r.m.s. - flux relation

The models roughly reproduce the r.m.s.-flux relation (Uttley & McHardy 2001), although with a large scatter.

The modulated flare avalanches model

The envelope model
Summary

- Simulations suggest that it is **not possible** to obtain an absolutely constant flux of the Fe K line, as a purely geometrical effect in the propagation model of variability in the truncated disk geometry. However, the line variability is somewhat reduced compared to the variability of its driving continuum.
- Simulations reproduce the observed r.m.s. - flux relation, although with a rather large scatter.
- We note that the observed behaviour of energy spectra as a function of X-ray flux, i.e. spectral softening with increasing flux, on short time scales ($\approx 10^5$ sec) in Seyfert galaxies present a serious challenge to our models. This is a much too short a timescale for a modulation of e.g. the accretion rate.