Modelling the variability of the Fe Kα line in accreting black holes

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18 March 2004

ABSTRACT
The variability of the Fe Kα line near 6.5 keV seems to be reduced compared to the variability of the hard X-rays which presumably drive the line emission. This is observed both in active galactic nuclei and galactic black hole binaries. We point out that such reduced variability, as well as lack of coherence between the variations of the line and the continuum, are a natural prediction of a propagation model of variability in the geometry of inner hot accretion flow. We compute detail model predictions of the variability characteristics which could be compared with current and future data. We also point out that the model requires a gradual disappearance of the cold disc, rather than a sharp transition from the cold disc to a hot flow.

Key words: accretion, accretion disc – binaries: general – X-rays: binaries – X-rays: galaxies – galaxies: active

1 INTRODUCTION
The Fe Kα fluorescent/recombination line near 6.5 keV is an important diagnostic of accretion flows around compact objects (see Reynolds & Nowak 2003 for a recent review). It is the strongest hard X-ray (E > 1 keV) line which can originate in the innermost regions of accretion flows (≤ 100 Rg). It is indeed observed in energy spectra from all kinds of accreting sources: black hole and neutron star X-ray binaries, cataclysmic variables, active galactic nuclei (AGN).

The line is produced when plasma is irradiated by hard X-ray (E > 7 keV) radiation. If the plasma is Thomson thick the continuum spectral component formed as a result of the irradiation ("Compton reflection") has a characteristic shape, peaking at 20–30 keV (Lightman & White 1988). The line and the Fe K-shell absorption edge are superposed on this continuum (George & Fabian 1991; Matt, Perola & Piro 1991). The properties of the line and edge depend on the ionization of the reflecting medium: with increasing ionization the line and edge shift towards higher energies, while their strength increase (e.g. Życki & Czerny 1994 and references therein). The profile of the line may be modified by relativistic and kinematic effects, if the line originates in e.g. a rotating accretion disc (Fabian et al. 1989). The line and absorption edge are then broadened and smeared. Such broad features are commonly seen in Seyfert galaxies (e.g. MCG-6-30-15, Tanaka et al. 1995, Fabian et al. 2002) and black hole binaries (BHB; e.g. Cyg X-1, Done & Życki 1999; GRS 1915+105, Martocchia et al. 2002), providing a clear evidence for a relativistic accretion disk extending deep into the gravitational potential of the central black hole.

X-ray emission from accreting sources is highly variable in a broad range of time-scales. Most of the variability power is located in the range of Fourier frequency f ≈ (0.1–1)M/(10 M⊙) Hz, corresponding to a time-scale (T = 1/f) of a few seconds for a 10 M⊙ stellar black hole and a few weeks for a 10^7 M⊙ AGN (BHB review in McClintock & Remillard 2003; Markowitz et al. 2003b for AGN). Typical power density spectrum is roughly a power law with slope α ≈ 0 (P(f) ∝ f^α) at low f, steepening to α ≈ −1 at f ≈ 0.1 Hz and to α ≈ −2 at f = 1–3 Hz, for the BHB in low/hard state. Typical root-mean-square (r.m.s.) variability is 20–30%. The variability is stochastic rather than caused by deterministic chaos type of process (Czerny & Lehto 1997).

The observed variability of the Fe Kα line and the entire reprocessed component is somewhat surprising; they generally show rather less variability than the high energy continuum which is presumably driving the line emission and Compton reflection. This is seen both in AGN and BHB. In AGN the Kα line seems either not to respond to continuum variations on time-scales of minutes to days (e.g. Reynolds 2000; Done, Madejski & Życki 2000; Chiang et al. 2000), or the line variability appears to be uncorrelated with that of the continuum (Vaughan & Edelson 2001). In particular, studies of r.m.s. variability amplitude as a function of energy demonstrate the reduced variability in a relatively model independent way (Inoue & Matsumoto 2001; Markowitz, Edelson & Vaughan 2003a). The short term variability of the reprocessed component is more difficult to measure because of
wards the black hole. The structures originate at a certain regions/emitting structures traveling from outside inwards, to-

X–rays are assumed to be produced by compact active re-

The model was also described in˙Zycki (2003).

pulsar SAX J1808.4-3658 (see also Uttley & M

for this model based on the r.m.s.–flux relation in accreting

1999), in particular the correlation between spectral slope

(see Di Salvo et al. 2001; see Done 2002 for review). It is

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model of X-ray emission in the geometry of a hot inner ac-

plasma evaporation/condensation (R´o˙zanska & Czerny 2000

of formation the two-phase plasma flow may be related to

binaries (Zdziarski et al. 2003). The physical mechanism

1999) and long time scale spectral evolution of black hole

and amplitude of reflection (Zdziarski, Lubi´nski & Smith

Churazov & Gilfanov (2001). Recently,˙Zycki (2003) showed

based on early variability studies of Cyg X-1. This was fur-

the contribution to the reprocessing by a distant matter, e.g.

the obscuring dusty torus. Indeed, a narrow Fe Kα line is

observed in many Seyfert galaxies. However, it is the vari-

ability properties of the broad component (hence produced

very close to the central black hole) that are so puzzling.

One suggested explanation invoked complex ionization

effects in the illuminated surface of the disc (e.g. Nayak-

shin, Kazanas & Kallman 2000). Formation of a hot ionized

skin (where the Fe Kα line is not produced) with thickness

proportional to the X–ray flux may lead to anti-correlation

between the line flux and the continuum flux. This model

was quantitatively tested by ˙Zycki & Ró˙zanska (2001), who

concluded that it does indeed predict certain decrease of am-

plitude of variability of the line, although it is not possible

to obtain an absolutely constant line flux.

In this paper we demonstrate that the reduced variabil-

ity of the Fe Kα line is a natural result from a propagation

model of X-ray emission in the geometry of a hot inner ac-

cretion flow. This geometry is one of the possibilities for

accretion flow in low/hard states of accreting black holes

(e.g. Di Salvo et al. 2001; see Done 2002 for review). It is

supported by X–ray spectral studies (review in Poutanen

1999), in particular the correlation between spectral slope

and amplitude of reflection (Zdziarski, Lubiński & Smith

1999) and long time scale spectral evolution of hot black hole

binaries (Zdziarski et al. 2003). The physical mechanism

of formation the two-phase plasma flow may be related to

plasma evaporation/condensation (Ró˙zanska & Czerny 2000

and references therein). The idea of propagating X-ray emitting

structures was put forward by Miyamoto et al. (1988),

based on early variability studies of Cyg X-1. This was fur-

ther developed and tested by e.g. Nowak et al. (1999), Misra

(2000), and formulated in a more general form by Kotov,

Churazov & Gilfanov (2001). Recently, ˙Zycki (2003) showed

that the Fourier-frequency resolved spectra can be repro-

duced in the propagation model, while Uttley (2004) argued

for this model based on the r.m.s.–flux relation in accreting

pulsar SAX J1808.4-3658 (see also Uttley & M’Hardy 2001).

2 THE MODEL

The model was also described in detail in ˙Zycki (2003).

X–rays are assumed to be produced by compact active re-

gions/emitting structures traveling from outside inwards, to-

wards the black hole. The structures originate at a certain

radius, $R_{\text{out}}$, and they move towards the centre at a fraction

of the free-fall speed,

$$v = \beta v_{\text{ff}} = \beta \sqrt{\frac{2GM}{R}},$$

where $\beta < 1$. The plasma heating rate is assumed to depend

on radius

$$l_h(t) \propto R(t)^{-2} b[R(t)],$$

where the exponent $-2$ corresponds to gravitational energy

dissipation per ring of matter. Here $l$ is the compactness

parameter, $l \equiv (L/D_{\text{Thick}})\sigma_T/(m_e c^2)$ (where $D_{\text{Thick}}$

is the characteristic radius of the structure, assumed constant in time),

and $b(R)$ is the boundary term which is assumed to have its

standard form $b(R) = 1 - \sqrt{6R/R_s}/R$ (Shakura & Sunyaev

1973).

The heating rate is normalized to have an assumed maximum

value, $l_{h,\text{max}}$, the same for all flares. The equation of motion

(Eq. 1) can be solved to give

$$r(t) = (r_{\text{out}}^3 - At)^{2/3}, \quad A \equiv \frac{3\sqrt{2}}{2} \frac{\beta c}{R_{\text{thick}}}$$

where the radial positions $r(t)$ and $r_{\text{out}}$ are expressed in units

of $R_{\text{thick}} \equiv GM/c^2$ (lowercase $r$ will denote radial position

in units of $R_{\text{thick}}$). The duration of a flare is

$$t_{\text{rav}} = (r_{\text{out}}^3 - r_{\text{in}}^3)/A,$$

where the final radial position is assumed $R_{\text{in}} = 6 R_{\text{thick}}$. In ac-

tual computations we treat $t_{\text{rav}}$ as a parameter, and solve

for $\beta$. Following Poutanen & Fabian (1999) we generate $t_{\text{rav}}$

according to a probability distribution $P(t) \propto t^\beta$ for $t$ be-

tween $t_{\text{min}}$ and $t_{\text{max}}$.

Soft photons for Comptonization are assumed to come

from reprocessing and thermalization of the hard X–rays, so

that the feedback loop is realized as needed to explain the

correlation between the amplitude of reflection and spectral

index (Zdziarski et al. 1999; Gilfanov, Churazov & Revnivt-

sev 2000). The geometrical scenario considered here is that of

an inner hot flow partially overlapping a cold, optically

thick disc disrupted at a certain radius, $R_{\text{tr}}$, (see e.g. Pouta-

nen, Krolik & Ryde, 1997, for arguments for the overlap).

The luminosity of soft photons crossing a active region is

parametrized as

$$l_s(t) = N_s l_h(t) \times C[r(t)] = N_s l_h(t) \times \begin{cases} 1 & \text{for } r \geq r_{\text{tr}} \\ \left( \frac{r}{r_{\text{tr}}} \right)^\gamma & \text{for } r < r_{\text{tr}}, \end{cases}$$

where $C(r)$ represents a covering factor of the cold repro-

cessing matter. The covering factor is assumed to increase

with $R$ (i.e. $\gamma > 0$), up to $C(r_{\text{tr}}) = 1$. The normalization

constant $N_s \approx 0.5$, as appropriate for a continuous corona

at $r > r_{\text{tr}}$. Thus, during a flare the Comptonized spectrum

has a constant slope of $\Gamma \approx 2$ up to the moment of crossing

the truncation radius, and then the spectrum get harder ($\Gamma$

decreases). The truncation radius and exponent $\gamma$ determine

the average slope of the Comptonized spectrum.

The emitting structures are assumed to originate at a medium

rate of $\lambda$ per second. Time intervals between their

launch are generated from the $\lambda \exp(-\lambda t)$ distribution, as

appropriate for a Poissonian process. We adopt here the flare

avalanches description (Poutanen & Fabian 1999), where

each spontaneous (“parent”) flare has certain probability to

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stimulate a number of “baby” flares. The stimulated flares are delayed after their parent flare (Poutanen & Fabian 1999).

Each emitting structure is followed until it reaches the marginally stable orbit at $R_{\text{mas}} = 6 R_g$. At each step the primary Comptonized component and its reprocessed component are computed.

The Comptonized spectrum is computed using the code THCOMP (Zdziarski, Johnson & Magdziarz 1996), solving the Kompaneets equation. Computations are parametrized by the photon spectral index, which we compute from $\Gamma = 2.33(l_0/L)^{-1/10}$ (Beloborodov 1999a,b), and electron temperature $k T_e/(m_e c^2)$ computed using formulae from Beloborodov (1999b). Plasma optical depth is assumed $\tau_e = 1$.

The spectrum of the Compton reflected continuum is computed from the simple formula of Lightman & White (1988),

$$S_{\text{refl}}(E) = \frac{1 - \epsilon}{1 + \epsilon} S_{\text{prim}}(E), \quad \epsilon = \sqrt{\frac{\kappa_{\text{abs}}}{\kappa_{\text{abs}} + \kappa_e}}, \quad (6)$$

where $\kappa_{\text{abs}}(E)$ and $\kappa_{\text{abs}}(E)$ are the photo-absorption and electron scattering opacities, respectively, the former for a “cold” matter. The above formula is multiplied by a simple exponential cutoff to mimic the Klein-Nishina cutoff. The Fe Kα line is added to the reflected continuum, with equivalent width (EW) as a function of $\Gamma$, following computations of Zycki & Czerny (1994). Specifically, we find that the formula

$$EW(\Gamma) = 1.78 (\Gamma/1.1)^{-0.5-0.15\Gamma} \text{ keV} \quad (7)$$

reproduces the dependence of EW (relative to the reflected continuum) on the spectral slope, $\Gamma$, for cold matter with solar iron abundance, and disk inclination of 30°.

The instantaneous amplitude of the reprocessed component, $\Omega/2\pi$, should be related to the covering factor of the cold plasma, $C(r)$ (Eq. 4). In practice we assume

$$\Omega/2\pi(r) = C(r) = \left\{ \begin{array}{ll} 1 & \text{for } r \geq r_{\text{tr}} \\ \left( \frac{r}{r_{\text{tr}}} \right)^\gamma & \text{for } r < r_{\text{tr}}, \end{array} \right. \quad (8)$$

i.e. $\Omega/2\pi$ decreases from 1 at $r \geq r_{\text{tr}}$ to $\Omega/2\pi \ll 1$ at $r = R_{\text{mas}}$.

The sequence of spectra created by the above procedure is subject to standard analysis in the time and Fourier domains (see e.g. van der Klis 1995; Nowak et al. 1999; Poutanen 2001).

All computations are performed assuming the central black hole mass $M = 10^7 M_\odot$. The time-scales of variability are assumed to follow a simple scaling with the black hole mass. Consequently, the values of parameters of the variability model are adjusted so that the power spectrum density (PDS) has the same shape as PDS of Cyg X-1 in low/hard state, and is shifted in frequency by the mass ratio. This is achieved for $t_{\text{min}} = 5 \times 10^{-3} M_1 \text{ sec}$, $t_{\text{max}} = 2 M_1 \text{ sec}$, $p = -1$, where $M_1 = M/(10 M_\odot)$. The emitting regions are launched at $R_{\text{cont}} = 100 R_g$ at a rate $\lambda = 40 M_1^{-1} \text{ sec}^{-1}$. The truncation radius is assumed $r_{\text{tr}} = 30 R_g$, while $\gamma = 2$. We consider a stationary model, i.e. the above values are constant in time.

3 RESULTS

The flux in the Kα line (the line light curve) is found simply by subtracting the continuum contribution from the total flux in the line bin. The Fe Kα line predicted by our model is narrow because of relatively low velocities of the active regions. This is required to reproduce the relatively long time-scales of maximum power, but it also is a consequence of the assumption that the active regions move purely radially. If they possessed a significant azimuthal velocity component, their trajectories would be longer spirals and the total velocity would have to be accordingly higher, in order to produce the same flare durations. The azimuthal velocity component would in that case give rise to Doppler broadening of spectral features, but the variability properties of the model would remain unchanged.

Temporal profile of a typical flare is plotted in Fig. 1. The profile of the heating rate, $l_0(t)$, and total Comptonized emission are similar to the plotted profile of the 7–30 keV flux. The amplitude of reflection, $\Omega/2\pi$, remains constant at 1 until the emission region has reached the truncation radius, $r_{\text{tr}}$, and then $\Omega/2\pi$ begins to decrease. This has an important consequence for the flux of the Kα line: the line flux peaks earlier than the continuum flux. This is simply because the line flux can be expressed as the product of $\Omega/2\pi$ and $F_{\text{cont}}$, $F_{\text{line}} \propto \Omega/2\pi \times F_{\text{cont}}$. The magnitude of the difference in peaks position depends on the exponent $\gamma$ describing the $\Omega/2\pi(r)$ dependence (Eq. 8), and it is $\approx 0.2$ of the total flare duration for the assumed $\gamma = 2$. The second important consequence of the obtained $\Omega/2\pi(t)$ relation is that the amplitude of the flare in the Kα line is smaller than in the continuum (this is not shown in Fig. 1).

Both the above effects have important consequences for line and continuum light curves, examples of which are plotted in Fig. 2. Variations of the line are clearly smoother that those of the continuum: there is less high-frequency variability and the peak-to-peak amplitude is clearly smaller in the line light curve, although major events in the continuum are reflected in the line light curve. The decoupling of variabil-

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{fig1.png}
\caption{During a flare the Kα line flux peaks earlier than the 7–30 keV continuum flux. Since the line flux can be written $F_{\text{line}}(t) \propto \Omega/2\pi(t) \times F(t)$, it decreases when the amplitude of reflection, $\Omega/2\pi$, decreases for $r < r_{\text{tr}}$. Note that the line and continuum fluxes were rescaled to 1 at the maximum, so the flare amplitudes in these two energy bands are not represented accurately.}
\end{figure}
The variability of the line is more clearly visible on the short term light curve ($10^5$ sec), the differences between the line and continuum curves decreasing for longer time-scales. The curves are very similar when viewed on time scales of order $\sim 10^7$ sec. Another way of demonstrating the reduction of variability is to compute the power spectrum. This is plotted in Fig. 3 together with a number of other characteristics. The PDS of the line cuts off above $f_l \approx 10^{-6}$ Hz much more rapidly than PDS of the continuum. The r.m.s. computed for $f > f_l$ is 0.28 for the continuum, while it is only 0.16 for the line. The frequency $f_l$ is related to the time-scale of longest individual flares ($t_{\text{max}} = 2 \times 10^6$ sec in our computations).

There is a clear lack of coherence between the line and continuum light curves, as shown in panel (b) of Fig. 3. The coherence plotted there is defined as in Vaughan & Nowak (1997), and it is a measure of linear relation between two light curves. Generally, observed light curves show coherence very close to 1 in a broad range of Fourier frequency (Nowak et al. 1999 for Cyg X-1; Vaughan, Fabian & Nandra, 2003, for MCG-6-30-15). This indicates that each active region produces radiation in the entire X-ray band, and so photons of different energies track each other’s variations very closely. Here, however, the line photons do not follow the continuum photons in a simple way, because of the varying geometrical factor $C(r)$. Hence the transformation between the continuum and line photons is complicated and the coherence is reduced below unity.

The time delay between the line and continuum photons is much longer than between the two continuum bands of similar energy separation (the line is leading the variability of the continuum at $E > 7$ keV). Figure 3 demonstrates this effect. Time lags between the 6 keV and 9 keV continuum bands would be shorter than the plotted time lag between 3 keV and 9 keV bands. However, the time lag between the 6.4 keV Kα line and the 9 keV band is actually longer (by a factor of $\approx 5$) than the latter. This is a direct consequence of the line flux peaking earlier than the continuum during a flare, as already discussed (Fig. 1). For example, in a ~day-long observation (Fourier $f = 10^{-5} - 10^{-4}$), the line may lead the 9 keV continuum by as much as 1–3 hours. The cross-correlation function between the Kα and 9 keV light curves is asymmetric, peaking at $\Delta t \approx -10^3$ sec, consistent with the time lags. The cross-correlation functions plotted, $CCF(\tau)$, were normalized by dividing them by the square root of the product of variances, which means that for a perfectly correlated signals $CCF(0) = 1$. We can then observe that while two continuum bands are indeed well correlated, the correlation between line and continuum light curves is weaker, resulting in $CCF(0) \approx 0.82$.

The model r.m.s. spectra show a minimum at the energy of the Kα line, as indeed observed in spectra of Seyfert galaxies (Markowitz et al. 2003a). The minimum is of course a direct consequence of the weakly variable line flux, which contributes to the count rate in that bin, but only weakly so to the r.m.s. variability. Since in our model the Kα line is narrow, the reduction of r.m.s. appears only at the line energy bin. Observed lines are broad, therefore the observed r.m.s.($E$) dependence have broad minima around 6–7 keV.

Fig. 4 shows the zero-lag correlation between the 7–30 keV flux and the Kα line flux. Each point represents a spectrum averaged over $\approx 5000$ sec, meant to roughly represent one RXTE orbit. When the two fluxes are low they are simply linearly related. This corresponds to emission from the outer regions, $r \geq r_{\text{in}}$, where the amplitude of reflection is $\Omega/2\pi = 1$. Higher fluxes correspond to emission coming at least partially from the inner region, below $r_{\text{in}}$, where $\Omega/2\pi < 1$, and so the linear relation breaks down. Fig. 4 shows the $F(7-30) \text{ vs.} F(K\alpha)$ for flux-binned spectra from the same, $10^7$ sec light curve. In this representations the spatial separation discussed above is averaged over to some extent, resulting in significantly weaker relation, with logarithmic slope of $\approx 0.6$. 

\begin{figure}
\centering
\includegraphics[width=\textwidth]{light_curve.pdf}
\caption{Part of a typical light curve: 9 keV continuum and the Kα line. Panel (a): $10^5$ sec ($\approx 1$ day), panel (b): $10^6$ sec. On time scale the variability of the line is clearly smoother (less high-frequency variations, smaller peak-to-peak amplitude) than of the continuum. This is still visible, although less so on the longer time scale plotted. The black hole mass assumed for scaling the time scales is $10^7 M_\odot$.}
\end{figure}
Variability of the Fe Kα line

4 DISCUSSION

We have computed the variability properties of the Fe Kα line from X-ray reprocessing in a propagation model of X-ray emission in accreting compact objects. The model combines results from various spectral and timing studies of accreting black holes. The former suggest the geometry of the standard optically thick accretion disc truncated at a radius larger than the radius of the last stable orbit (e.g. Esin, McClintock & Narayan 1997; Gierliński et al. 1997; Życki, Done & Smith 1998; Done & Życki 1999; Zdziarski et al. 1999, 2003). The latter postulate correlated flares (avalanches) and spectral evolution during flares, in order to explain power spectra and time lags (Poutanen & Fabian 1999; Kotov et al. 2001). Combined spectral-timing studies suggest a connection between the geometry and timing properties (Revnivtsev et al. 1999, 2001; Życki 2002, 2003). Most of the observational results were obtained for black hole binaries, but, were possible to conduct, analysis of data for Seyfert galaxies confirm the general similarity between the two classes of objects (e.g. spectral studies by Done et al. 2000; Chiang et al. 2000; Lubiński & Zdziarski 2001; timing studies of Czerny et al. 2001; Uttley & McHardy 2001; Vaughan et al. 2003; Markowitz et al. 2003b; Papadakis 2004).

The variability properties of the Fe Kα line seem to be similar in both classes of objects in that the line appear to be less variable than the continuum which drives it, and, where the variability is detected, it does not seem to be clearly correlated with the continuum. This is contrary to simple(st) ideas, whereby the continuum and the line are produced in the same region and thus should be closely related. We note that the observational situation is far from clear, though. Time resolved spectral analysis would be the most direct method to determine the variability of the line, but the results may be model dependent (see detailed discussion in Zdziarski et al. 2003). Decomposition of counts from a medium energy resolution instrument like RXTE/PCA into the line and continuum depends on the model assumed for both the line and the reflected continuum. In particular, the effects of relativistic smearing of the reflected continuum was not taken into account. We note though that according to Markowitz et al. (2003a) the results on line variability in
a sample of Seyfert galaxies were insensitive to assumptions about the amplitude of the reflected component: whether its relative amplitude was fixed, or allowed to vary in accord with the Kα line.

Our model does reproduce the reduced variability of the Fe Kα line, compared to the variability of its driving continuum. Line variations may also appear not exactly correlated with continuum variations, because of the time delay between the peaks of the line and continuum fluxes. Both effects are necessary consequences of the adopted geometry, of a truncated disc with inner hot flow. The same geometry can also explain the hard X-ray time lags (Kotov et al. 2001; Życki 2003) through spectral evolution during flares (Poutanen & Fabian 1999). Quantitatively, our assumed ratio of heating to cooling rates, \( C(r) \propto h_0(r)/\dot{L}(r) \), is a much weaker function of radius than could be expected for a compact (size \( \ll r \)) active region and a sharply truncated disc. As already mentioned in Życki (2003), in that latter geometry the supply of soft photons from the disc would diminish so rapidly that the predicted energy spectrum would be much too hard to be consistent with the data. This implies a gradual disappearance of the cold disc, which may be an interesting clue as to how the physical process of disc evaporation proceeds (Różańska & Czerny 2000).

We emphasize that the reduction of variability of the Kα line discussed in the present paper is the same phenomenon as the decreasing reflection amplitude with Fourier frequency, found in X-ray data of Cyg X-1 and GX 339-4 by Revnivtsev et al. (1999, 2001) and modelled by Życki (2003).

In the present paper this effect was analysed with tools usually applied to AGN data, which are usually analysed in time domain rather than Fourier domain. We note, that it does not seem possible to design the parameters of the model, so that the line flux remains exactly constant. This is because, even though the line may be constant during each flare (assuming \( C(r) \propto 1/h_0(r) \)), the number of flares active at any time varies, and this causes variation of the total flux of the line.

A robust feature of the presented model is a connection of the time scale of the line response to the time scale of continuum variability. This is because the line flux responds on the time scale related to the duration of a flare. This in turn has to be chosen such that the observed power spectra are reproduced. The peaks in \( f \times P(f) \) are at rather long time-scales, much longer than just the light travel time through the region of most efficient energy generation. For example, the longest flares in our computations last \( \sim 10^6 \) sec, which in light travel time corresponds to large distance of \( 2 \approx 10^4 R_g \) (for \( 10^7 M_\odot \)). This is simply a manifestation of the well known observational fact that time-scales of maximum X-ray variability power are much longer than the naively expected short dynamical time-scale. The physical mechanisms of producing the relatively long time scales of variability are rather unclear, but some interesting possibilities were recently considered in literature. 3-D magnetohydrodynamical simulations of Narayan, Igumenshchev & Abramowicz (2003) reveal slow \( (v \ll v_H) \) drift of plasma clumps across lines of magnetic field, which lines are compressed by the accretion flow. King et al. (2004) considered a model involving magnetic dynamos operating locally in the disc. The longer and larger flares are results of correlations between dynamos acting in neighboring locations (radii). While individual dynamos operate of short (dynamical) time scales producing short flares, the correlated behaviour produces longer lasting, large events. Whatever the exact physical processes are, it is clear that the accretion flow is highly inhomogeneous and structured, factors that any realistic modelling should allow for.

In the presented model, the line flux is leading the continuum flux. We ignored the light travel time delay of the line photons after the continuum, but this is unlikely to affect our result, since the line is supposed to originate close to the location of emission of primary radiation. The light travel time delay may be estimated as \( \delta t \sim r \times R_g/c \) (assuming the height of the emission region \( h \sim r \)), which gives \( \delta t \sim 10^3 \) sec, i.e. about the time bin in our simulations. Obviously, there may be additional effects due to, for example, adjustment of properties of the reprocessing medium to the increasing irradiation flux, which might affect the result to some extent.

The dependence of r.m.s. variability amplitude on energy is a relatively model independent demonstration of the reduced variability of the line. Our computations qualitatively reproduce the minimum of r.m.s. \( E \) at the energy of the line. Generally, the r.m.s. spectra are energy dependent variability amplitude, or, equivalently, can be thought of as representing energy spectra of the variable component of the spectrum. This can in principle be computed also in narrow ranges in Fourier frequency (Fourier frequency resolved spectroscopy, Revnivtsev et al. 1999, 2001; Życki 2002, 2003), but the quality of AGN data is not sufficient to make use of this technique as yet.

Concluding, the propagation model of high energy emission in the geometry of a truncated accretion disc provides a framework for understanding many of the observed spectral and temporal characteristics of X-ray radiation from accreting black holes.

**ACKNOWLEDGMENTS**

This work was partly supported by grant no. 2P03D01225 of the Polish State Committee for Scientific Research (KBN).
Figure 5. Line flux vs. the 7–30 keV flux. Left panel: each point shows one time bin of 5000 sec. from a 10^7 sec. observation. The line flux follows linearly the continuum flux for low values of the latter, corresponding to the emission coming from outer regions (active region above the cold disc). The higher the continuum flux, the stronger the deviation from a linear relation, and the bigger the spread of points. Right panel: results from spectra binned in flux. The slope of the best fit line is $\approx 0.56$.

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