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On the Time Lags in Galactic Black Holes

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Abstract. The origin of time lags between hard and soft photons observed in Galactic black holes remains a mystery even 10 years after their discovery (Miyamoto et al. 1988). Since it is generally believed that Comptonization is responsible for spectral formation, these lags are attributed in some models to the delays due to scattering in a Compton cloud. The Fourier frequency dependence ($\sim 1/f$) of the lags and their amplitudes (up to ~ 0.1 s) require then that a hot cloud extends over 10^4 gravitational radii from the central black hole and has an inhomogeneous density distribution, $n(r) \propto 1/r$ (Kazanas, Hua & Titarchuk 1997). The existence of such a cloud is highly improbable due to energetic problems.

In the present paper, we argue that the origin of time lags is *spectral evolution*. We assume that the X/γ-rays in accreting black holes are produced in compact magnetic flares at the surface of cold accretion disks. If the spectrum of the flare evolves from soft to hard, the time delays appear between the arrival of soft and hard photons. A possible reason for the spectral evolution is a decrease with time of the *feedback factor* due to, e.g., inflation of the magnetic loop configuration and/or increase of the bulk velocity of the emitting hot plasma.

1. Introduction

Despite the observed rapid variability, most of the information about the physical conditions in the vicinity of accreting Galactic black holes (GBHs) is still obtained from the time-averaged spectra (e.g., Gierliński et al. 1997; Poutanen 1998). Detailed studies of the X-ray colors, however, have shown rapid spectral changes (Nolan et al. 1981; Negoro et al. 1994) implying rapid changes in the physical conditions of the source. GBHs also show Fourier-frequency-dependent time lags between hard and soft photons (Miyamoto et al. 1988; Miyamoto & Kitamoto 1989; Miyamoto et al. 1991; Cui et al. 1997; Nowak et al. 1999; Cui, these proceedings).

The observed lags are usually attributed to the delays expected from scattering in a hot Compton cloud. Hard photons are the result of more scattering and so emerge after, or lag behind, softer ones. The amplitude of the lags require the existence of a huge cloud of size $R \sim 10^4 - 10^5 R_g$ (here $R_g \equiv 2GM/c^2$) with a density profile $n(r) \sim 1/r$ (Kazanas et al. 1997; Hua, Kazanas, & Titarchuk 1997; Hua, Kazanas, & Cui 1999). In these models it is also assumed that the Compton cloud is static and it is the soft photon input which varies, contrary to what is observed (Miyamoto et al. 1991). The physical mechanism producing such a cloud (where most of the energy is at the outer boundary) is unknown.

In this paper, we present a model, where time-lags are the result of the *spectral variability* (Miyamoto & Kitamoto 1989) associated with the evolution of magnetic flares on the surface of the cold accretion disk. We identify the observed time lags with the timescales of the flare evolution, which are of the order of the Keplerian time scales at radii $\lesssim 50R_g$ from the central black hole.

2. Spectral Evolution of Magnetic Flares

Magnetic flares have long been considered as the source of the rapid variability of Cygnus X-1 and other similar accreting black holes (e.g. Galeev, Rosner & Vaiana 1979; Pudritz & Fahlman 1982). Unfortunately, the physics of magnetic flares is highly uncertain and we have to rely mostly on physical intuition.

It is generally accepted that the main radiative mechanism responsible for the spectral formation is Comptonization of soft photons. The luminosity (or compactness, $l \equiv L\sigma_{\rm T}/(Rm_ec^3)$, where R is the characteristic size of the emission region, ER) of the soft photons that crosses the ER is $l_s(t) = l_{s,0} + D(t)l_h(t)$. The first term in the rhs gives the contribution from intrinsic seed photons produced in the optically thick disk by viscous dissipation, the second term is the soft radiation produced by reprocessing of flare radiation in the disk. The time dependent feedback factor, $D(t)$, determines what fraction of the hard luminosity, l_h, returns to the ER after reprocessing in the disk.

In general, if the Compton amplification factor, $A \equiv l_h(t)/l_s(t)$, continuously increases with time during the course of the flare, then the Comptonized spectrum evolves from soft to hard. This causes the time delays between hard and soft photons of the order of the flare time-scale. There could be a number of reasons of why A increases with time. Here are some alternatives:

- **"Inverse" FRED.** The dissipation rate l_h increases exponentially in the static ER, until it reaches some critical value $l_{h,\rm max}$. Then the plasma contained in the ER is ejected away from the disk thus terminating the flare. In the beginning of the flare, when l_h is smaller than $l_{s,0}$, the soft photons are just the average background of luminosity, $l_{s,0}$, and the spectrum emitted by the flare is very soft. When l_h is large, the seed photon flux is dominated by the reprocessed photons and the spectrum defined by the geometry of the system is hard.

- **Bulk motion.** The dissipation is accompanied by pumping net momentum into the hot plasma of the ER (Beloborodov 1999). The larger the dissipation and, correspondently, the bulk velocity, the weaker the feedback (if the plasma moves away from the disk) and the harder the spectrum. A flare can also be terminated by plasma ejection.

- **Magnetic loop inflation.** The differential rotation of the footpoints of a magnetic loop at different radii on the disk surface causes a twisting of the loop (Romanova et al. 1998). Reconnection occurs in the regions that separate oppositely directed magnetic field lines. Magnetic fields expand and detach from the disk. One expects the overall evolution time-scale of the magnetic field configuration to be of the order of Keplerian time-scale.

In reality any of the aforementioned scenarios (and many more) can be invoked. As an example, we consider here the last model (see Poutanen & Fabian 1999 for details). We assume that $l_h(t) \propto (t/\tau)^2 \exp(-t/\tau)$, and that the ER moves away from the disk with a constant velocity, so that the feedback factor decreases with time (τ is the time-scale of the flare). In the case of a spherical ER, $D(t) \approx D_0/[1+\frac{3}{4}(t/\tau)^2]$, where D_0 is the feedback factor at the beginning of the flare. Fig. 1 shows the spectral evolution.

The flare light curves at different energies, E, are almost self-similar, i.e. can be represented by the same $(t/\tau_E)^2 \exp(-t/\tau_E)$ law with different time-constants. The time-constants τ_E follow a logarithmic dependence, $\tau_E \approx \tau[1 + \frac{1}{8}\ln(E/E_p)]$, where τ is the time-constant of the energy dissipation $l_h(t)$ and E_p is the photon energy where EF_E peaks. The delay between photons of energies E and E_0 is

$$\Delta t \approx \frac{\tau}{4} \ln(E/E_0). \tag{1}$$

This delay of hard photons relative to soft ones causes *time lags* to appear in the composite light curves from an ensemble of flares.

3. Energy Dependent Shot Noise Model

For illustration, we consider a model where flares occur spontaneously as in shot noise models (see Lochner, Swank & Szymkowiak 1991). Let the time constant, τ_s (for soft photons), be distributed according to a power law, $\rho(\tau_s) \propto \tau_s^{-p}$ between $\tau_{\min}$ and $\tau_{\max}$. Shots at different energies are assumed to start at the same time, but have different time-constants, τ_E. For example, in the case of the spectral evolution shown in Fig. 1, the ratios of time-constants at 9, 27, and 81 keV, $\tau_9, \tau_{27}, \tau_{81}$, to the time-constant at 3 keV, $\tau_3 = \tau_s$, are ~ 1.22, 1.49, and 1.82, respectively. For simplicity, we neglect deviations from self-similarity and consider a pure shot noise model with the aforementioned ratios of the time scales. A more elaborate model is considered in Poutanen & Fabian (1999).

We note that flares of duration τ, with the dissipation varying as $(t/\tau)^2 \exp(-t/\tau)$, produce a power density spectrum (PDS) $\propto 1/[(2\pi f)^2 + (1/\tau)^2]^3$ decaying as f^{-6} at high frequencies. Thus they give a contribution to the overall PDS in a very narrow frequency interval around $f \sim 1/(2\pi\tau)$. A power-law distribution of τ assures that the PDS is also a power-law with the slope $\beta = 3-p$ (see Fig. 2a, and Lochner et al. 1991). We take the limits for the time-scale at the lowest energy channel, $\tau_{\min} = 1\,\mathrm{ms}$, $\tau_{\max} = 0.3\,\mathrm{s}$, and $p = 1.5$ (see Pudritz & Fahlman 1982). The time-scales can be related to the Keplerian time-scales at radii between the innermost stable orbit and $\sim 50 R_g$.

Time lags, $\delta t(f)$, decay approximately as $1/f$ above $f_{\min} = 1/(2\pi\tau_{\max})$:

$$\delta t(f) \approx \delta t_{\max} \cdot \begin{cases} 1, & f < f_{\min}, \\ (f/f_{\min})^{-1}, & f > f_{\min}, \end{cases} \tag{2}$$

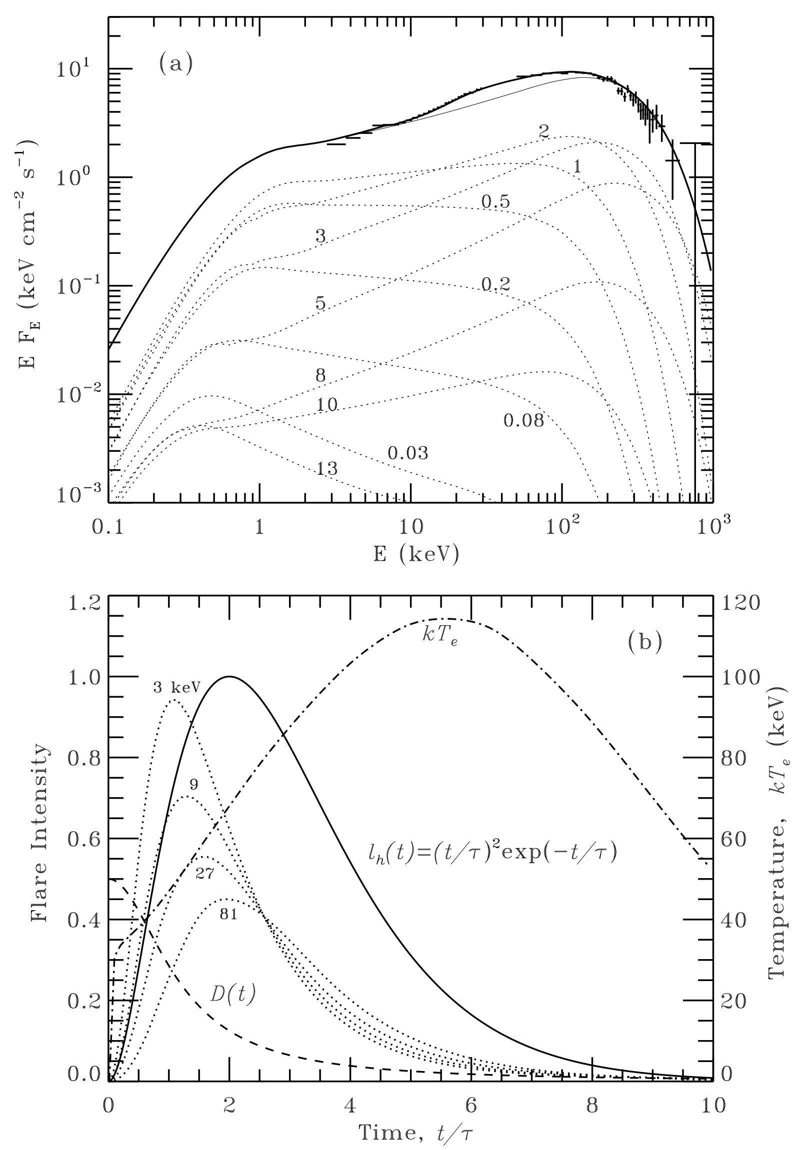

Figure 1. (a) Spectral evolution of a magnetic flare. Time resolved spectra (without Compton reflection) are presented by *dotted* curves; marks are times, t/τ, from the beginning of the flare. Time-averaged Comptonized spectrum is shown by a *thin solid* curve. Time-averaged spectrum of Cygnus X-1 (simultaneous *Ginga* and OSSE data from June 1991, data set # 1 in Gierliński et al. 1997) is plotted with crosses and the best fit with the flare model with a *solid* curve (χ^2/dof= 50.0/75). Interstellar absorption is removed when plotting the model spectrum. (b) The flare light curves at 3, 9, 27, and 81 keV are presented by *dotted* curves. *Solid* curve - the heating rate, $l_h(t) \propto (t/\tau)^2 \exp(-t/\tau)$; *dashed* curve - the feedback factor $D(t)$; *dot-dashed* curve - the temperature of the ER.

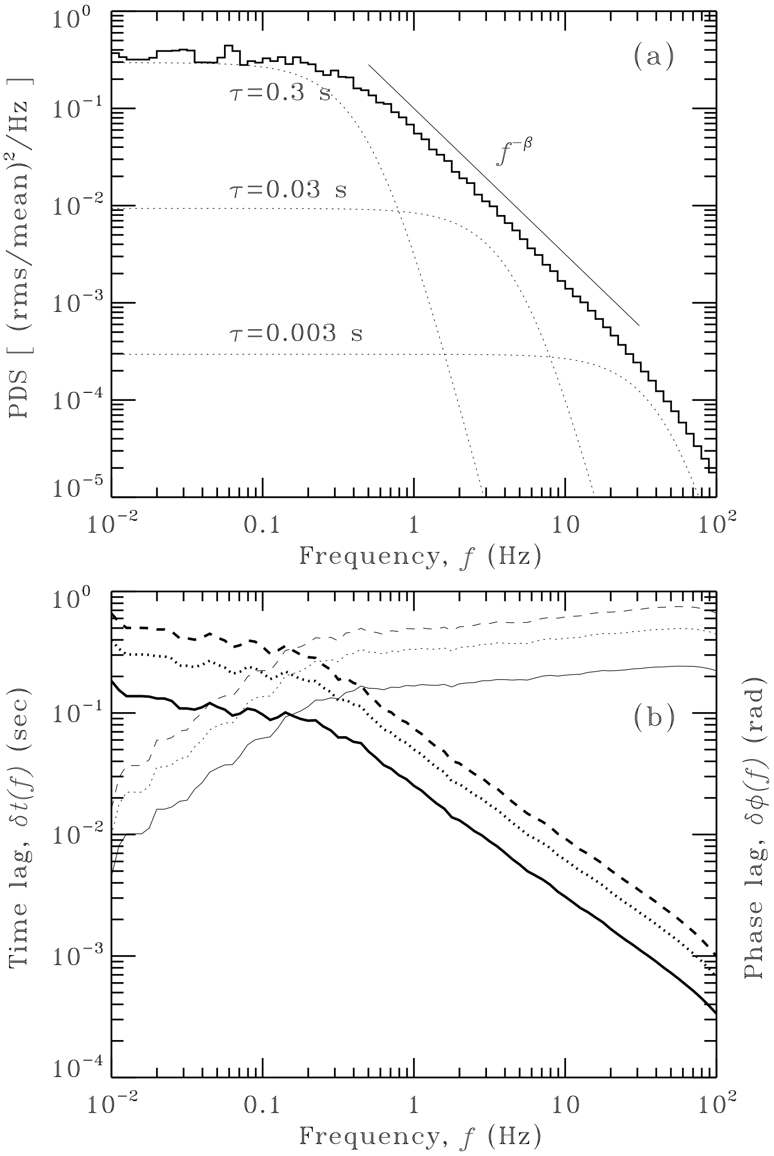

Figure 2. (a) The power-density spectrum (PDS) for the lowest energy channel. Contributions to the PDS from shots of different durations are shown by *dotted* curves. (b) Time lags, $\delta t(f) = \delta\phi(f)/(2\pi f)$ (*thick* curves), and phase lags, $\delta\phi(f)$ (*thin* curves), for various ratios of the time-constants τ_h/τ_s: 1.22 (*solid* curve), 1.49 (*dotted*), and 1.82 (*dashed*). Since time delays are proportional to the time-scale of the flare (see Fig. 1), lags are inversely proportional to the frequency, $\delta t(f) \propto \tau \approx 1/(2\pi f)$ (i.e. phase lags are almost constant) at frequencies $f > 1/(2\pi\tau_{\max}) \sim 0.5\,\mathrm{Hz}$.

where $\delta t_{\max} \approx 2(\tau_h - \tau_s)$ is the maximum achievable time lag. Since time lags are proportional to the time scale of the pulse, $\tau \approx 1/(2\pi f)$, which gives contribution to the PDS at frequency f, they are smaller at higher frequencies. Note that in this model the coherence function (Vaughan & Nowak 1997) is close to unity, since the light curves at different energies are almost perfectly synchronized.

4. Summary

We presented a model for the variability of accreting black holes. We showed that spectral evolution during the course of an energy dissipation event (magnetic flare) can cause the time lags between hard and soft photons. We identified the lags with the Keplerian time-scales at radii of $\lesssim 50R_g$ from the central black hole. A broad distribution of the flare time-scales explains the $\sim 1/f$ dependence of the lags. Time-lags observed in other sources such as weakly magnetized neutron stars (Ford et al. 1999) can naturally be explained by our model. We note that large time lags do *not* mean that the source itself is extended.

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