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Soft state of Cygnus X-1: stable disk and unstable corona

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ABSTRACT
Two component X–ray spectra (soft multicolor black body plus harder power law) are frequently observed from accreting black holes. These components are presumably associated with the different parts of the accretion flow (optically thick and optically thin respectively) in the vicinity of the compact source. Most of the aperiodic variability of the X–ray flux on the short time scales is associated with the harder component. We suggest that drastically different amplitudes of variability of these two components are simply related to the very different viscous time scales in the geometrically thin and geometrically thick parts of the accretion flow.

In the geometrically thin disks variations of viscosity or mass accretion rate occurring at large radius from the black hole on the local dynamical or thermal time scales do not cause any significant variations of the mass accretion rate at smaller radii due to a very long diffusion time. Any variations on the time scales shorter than the diffusion time scale are effectively dampened. On the contrary such variations can easily survive in the geometrically thick flows and as a result the mass accretion rate in the innermost region of the flow will reflect modulations of the mass accretion rate added to the flow at any distance from the black hole. Therefore if primary instabilities operate on the short time scales then the stability of the soft component (originating from the geometrically thin and optically thick flow) and variability of the hard component (coming from the geometrically thick and optically thin flow) are naturally explained.

For Cygnus X-1 overall shape of the power density spectra (PDS) in the soft and hard spectral states can be qualitatively explained if the geometrically thin disk is sandwiched by the geometrically thick corona extending in a radial direction up to large distance from the compact object. In the hard state the thin disk is truncated at some distance from the black hole followed by the geometrically thick flow. The break in the PDS is then associated with the characteristic frequencies in the accretion flow at the thin disk truncation radius.

Key words: accretion, accretion disks – stars: individual (Cygnus X-1) – X–rays: general

1 INTRODUCTION

A well known characteristic of accreting stellar mass black holes is the presence of two drastically different spectral states, first discovered in Cygnus X-1 by Tananbaum et al. 1972 (see Tanaka and Shibazaki 1996 for review). In the *Soft* spectral state luminosity peaks at around 1 keV, while in the *Hard* state luminosity is dominated by photons with the energy of the order of 100 keV. This bimodality is believed to be related to very different regimes of the accretion flow in the vicinity of the black hole. Soft radiation is interpreted as a multicolor black body emission originating from the optically thick (geometrically thin) disk (Shakura, Sunyaev 1973), while hard emission, having a nearly power law shape at low energies and a cutoff above ~ 100 keV, should come from an optically thin and hot medium where Comptonization of soft seed photons by the hot electrons plays an important role (e.g. Sunyaev and Trümper 1979). One of the popular models assumes that an optically thick disk is truncated at some distance from the black hole and followed by an optically thin and hot flow (see e.g. Thorne and Price 1975, Liang and Price 1977, Esin, McClintock and Narayan 1997, Meyer, Liu and Meyer-Hofmeister 2000). The hard and soft spectral states of the source may then correspond to the situation when an optically thick disk is truncated far from or close to the black hole respectively.

Another important property of the X–ray emission from black hole candidates is a strong aperiodic variability on time scales longer than 10 ms (see e.g. van der Klis 1994). The power density spectra are very different during different spectral states suggesting that the variability and spectral properties are closely linked.

Cygnus X–1 is the best studied accreting black hole in our Galaxy. Due to its brightness and persistent nature it was observed virtually by every X–ray observatory flown to date. The source was observed in different spectral states, also having very different properties of the short time scale variability. We discuss below qualitative model aimed to explain the changes in short time scale variability correlated with changes in the spectral shape.

2 VARIABILITY OF THE DISK AND CORONA

2.1 Constant and variable spectral components

The state of the black hole candidates, when the spectrum contains a strong soft component, are usually called "High/Soft" or "Very High" states (e.g. Tanaka and Shibazaki 1996). This soft spectral component has a shape resembling multicolor black body emission and is believed to be produced by the standard optically thick (geometrically thin) disk of Shakura and Sunyaev (1973) type. Along with this "black body" emission a harder component is often present in the spectrum, with an approximately power law spectrum. Study of the variability properties of these two components led to the conclusion that most of the variability is associated with the power law component and not with the "black body" emission (see e.g. Miyamoto et al. 1994 for the GINGA observations of Nova Musca 1991). The same behavior have been observed for various sources manifested by the increase of the fractional RMS with energy. For the RXTE (Brandt, Rotschild & Swank 1996) observations of Cygnus X–1 in the soft state in June 1996 Gilfanov, Churazov and Revnivtsev (2000) found that on the time scales shorter than 100 seconds the amplitude of the soft component variations is at least an order of magnitude lower than that of the harder component.

For illustration we plot in Fig.1a the PCA/RXTE count rate in the soft band $S(t) = R(t, E < 3.3\ keV)$ as a function of the count rate in the harder band $H(t) = R(t, E > 9.4\ keV)$. Here $R(t, E)$ is the observed (background subtracted) light curve in a given energy band. The data points are the 16 s averaged values of the count rate from the "Standard Mode 2" format of PCA. The observations were performed in 1996 on June 4 and 16. From Fig.1a one can see that (**i**) relative amplitude of variations in the soft band is a factor of ~ 2 smaller than in the hard band and (**ii**) the correlation can be reasonably well approximated by a linear relation $S(t) = A + B * H(t)$, where $A > 0$. This relation is shown in Fig.1a with a straight line. Similarly good linear relation exists between the count rates in any pair of the PCA/RXTE channels. Should the observed spectrum vary in intensity only and not in shape, then one would expect linear relation and $A = 0$. The fact that the relation between the count rates in two energy bands is close to linear, but A is not zero, means that additional stable component contributes to one or both energy bands. For any two energy bands above ~ 5 keV the count rate in one band is approximately proportional to the count rate in another band, i.e. A is close to zero. Very significant deviations of A from zero level appear if one of the selected energy bands is below 5 keV. This suggests that stable component is present mostly at low energies. We then repeat the same procedure of fitting the linear relation between $S(t)$ and $H(t)$ for every energy channel setting $S(t)$ to the count rate in this channel and always choosing $H(t)$ as a count rate above 9 keV. Thus $S(t, E) = A(E) + B(E) * H(t)$, where $S(t, E) = R(t, E)$ and $H(t) = R(t, E > 9)$ are the observed light curves. The $H(t)$ therefore serves as a "reference" light curve while $A(E)$ and $B(E)$ characterize respectively the contribution of the stable component to a given channel and the coefficient of proportionality between the variations of the count rate in this channel and the variations of the count rate above 9 keV. For the energy channels above 9 keV there should be additional intrinsic correlation between $S(t, E)$ and $H(t)$ because $H(t)$ contains contribution from $S(t, E)$, but experiments with various choices of the reference light curve $H(t)$ (e.g. using only narrow energy range instead of all counts above 9 keV) proved that resulting $A(E)$ and $B(E)$ vectors are relatively insensitive to the choice of $H(t)$ as long as $H(t)$ contains only contributions from energy channels above $\sim$ 5 keV. The resulting vectors $A(E)$ and $B(E)$ may be interpreted as the spectra (in units of counts s^{-1}per channel) of stable and variable components. If the stable component is indeed present only at low energies then with our choice of the $H(t) = R(t, E > 9)$ the $A(E)$ will reproduce both the shape and the normalization of the stable component, while $B(E)$ will recover only the shape of the variable component. The normalization of $B(E)$ depends on the particular choice of the "reference" light curve $H(t)$.

These $A(E)$ and $B(E)$ spectra have been approximately unfolded using the XSPEC v10 (Arnaud 1996) command **eeufspec** and assuming a power law model with a photon index of $\sim$2.5. This procedure simply divides the observed count rate in each channel by the effective area in this channel, calculated for the assumed spectral model. The photon index of 2.5 approximately corresponds to the shape of the power law tail in the source spectrum during June 1996 observations (Gierliński et al. 1999, Gilfanov et al. 2000). The spectra of constant and variable components unfolded that way are shown in Fig.1b. The stable component $A(E)$ has a very soft spectrum (open circles in Fig.1b). For comparison the light grey line shows the spectrum of the multicolor black body disk emission with the characteristic temperature $T \sim 0.5$ keV. The "variable" component $B(E)$ has a much harder spectrum (filled circles in Fig.1b) and does not contain a strong soft component (see Gilfanov et al. 2000 for details). Note that although a good linear relation between count rates in any pair of energy channels means that deconvolution in two components is accurate enough, these two spectral components may not necessarily have direct physical meaning. However the fact that stable component closely reproduces the multicolor black body disk emission both in terms of shape and normalization (Gilfanov et al. 2000) strongly suggests that stable component obtained from the above analysis simply coincides with the multicolor black body disk emission.

Finally the two upper spectra shown in Fig.1b with solid squares were obtained averaging the observed spectra over the periods of time when the count rate above 9 keV was high and low respectively. These spectra contain data points scattered over a period of time of more than 10 days when

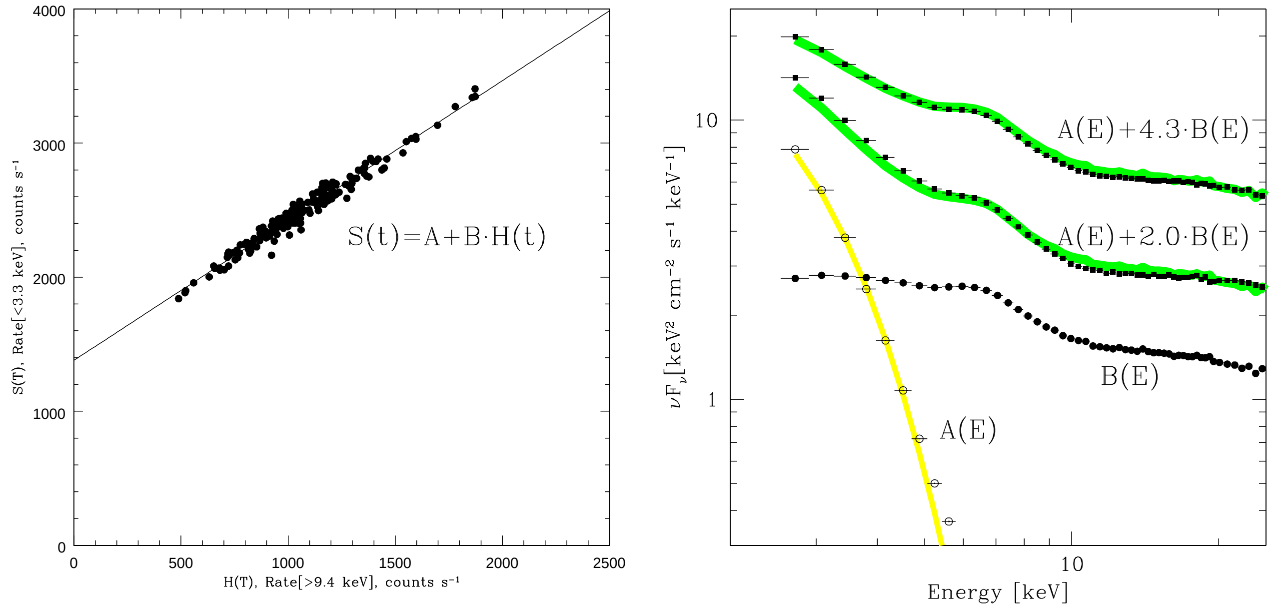

Figure 1. a), Left: The dependence of the count rate in the soft band (< 3.3 keV) on the count rate in the hard band (>9.4 keV). Each data point represent 16 s averaged count rate (RXTE observations on 1996 June 4 and 16). **b), Right:** Spectra of "constant" (open circles – $A(E)$) and "variable" (solid circles – $B(E)$) components, derived from the linear fits of the correlation between count rate in different channels. Normalization of the "variable" component $B(E)$ is arbitrary. For comparison the light grey curve shows the spectrum of a multicolor black body emission with a characteristic temperature of 0.5 keV. The two upper spectra (solid squares) were averaged over the periods of time when the count rate above 9 keV was high and low respectively. The dark grey lines show that these spectra can be reasonably well (within 10–15%) approximated by a model $M(E) = A(E) + I * B(E)$ consisting from the stable and variable spectral components where I (the normalization of the variable component) is the only free parameter.

intensity of the source in the hard band vary by at least a factor of ~4 (see Fig. 1a). The thick grey lines show that these spectra can be reasonably well (within 10–15%) approximated by a model $M(E) = A(E) + I * B(E)$ consisting from the above obtained stable and variable spectral components where I (the normalization of the variable component) is the only free parameter. Thus from this analysis one can conclude that all spectra observed by RXTE on 1996, June 4,16 during individual 16 seconds exposures can be reasonably well approximated by a combination of a constant soft component and a harder component which vary strongly in amplitude, but not much in shape.

2.2 Power density spectrum in the soft state

The typical power density spectrum (PDS) of the X–ray flux from Cygnus X-1 (in the 6–13 keV energy range) is shown in Fig.2. The PDS is calculated in units of squared fractional RMS per Hz, corrected for the Poissonian noise contribution. In softer energy bands the PDS has similar shape, but lower normalization, because of the larger contribution of the stable soft component to the source flux. The energy spectrum of Cygnus X-1 in the soft state is discussed in details in Gierliński et al. 1999 (see also Dotani et al., 1997 and Zhang et al., 1997). The strong soft component was present in the Cygnus X-1 spectrum during these observations (even in the RXTE band above ~3 keV). The characteristic temperature of the black body component is ~0.5 keV (Gierliński et al. 1999) and this component provides more luminosity than the power law tail. Assuming that the black body component is due to an optically thick disk and that no strong advection is present in the optically thin flow one can conclude that the inner radius of the disk is rather close to the black hole. Accurate determination of the disk inner radius from the 1996 June 4,16 RXTE spectral data is difficult because of the poor RXTE spectral response below 3 keV, but the analysis of simultaneous RXTE and ASCA 1996 May 30 data (Dotani et al. 1997, Gierliński et al. 1999) indeed indicates that the inner radius of the disk is close to the black hole. We make a conservative assumption that the inner edge of the accretion disk R_{in} is within $\sim 20GM/c^2$, where most of the gravitational energy of the accreting matter is released.

The PDS of X–ray flux variations in this state (Fig.2) holds the same shape (f^{-1} – flicker noise) from few 10^{-4} Hz up to 10 Hz, suggesting that the same physical mechanism is responsible for the flux variations at all frequencies in this range. Since these variations are associated with the power law spectral component they presumably originate from an optically thin region. Taking into account that f^{-1} slope of the PDS holds down to the frequencies of few 10^{-4} Hz it is difficult to imaging that observed flux variations over this extremely broad dynamic range of time scales (at least 4–5 orders of magnitude) can be provided by instabilities developing in the innermost region within R_{in}. More promising seems the assumption that the observed variability is due to instabilities occurring at different distances (much larger than R_{in}) from the black hole and then propagating into the innermost region, where the energy is released and X–ray photons are produced. In particular Lyubarskii (1997) considered the fluctuations of mass accretion rate in the innermost region associated with the fluctuations of the viscosity parameter α in the accretion flow at much larger radii. If the amplitude of α fluctuations at any radius is the same then variations of the mass accretion rate through the boundary, placed at much smaller radius, will have an f^{-1} power density spectrum. Thus the mass accretion rate is modulated at large distances from the black hole, but the observed (modulated) X–ray flux is coming from the innermost region. The broad dynamic range of the variability time scales in the model of Lyubarskii (1997) can be provided by the broad range of radii at which the viscosity is fluctuating.

Thus on one hand a stable optically thick disk extends down to a very small radii R_{in} (as indicated by the strong and stable soft component) and on the other hand prominent variations of the harder component are present in a broad range of time scales (up to at least 10^3–10^4 s – see Fig.2), which are likely to be associated with instabilities occurring at much larger radii than R_{in}. The simplest explanation required to combine these two facts together is the assumption that along with a stable optically thick accretion disk a variable (optically thin) corona is present, which extends in radial direction up to large distances from the black hole. The large extent of the corona in radial direction is required in order to provide broad dynamic range of the variability time scales. Various models involving optically thin corona have been discussed in the literature (e.g. Bisnovatyi–Kogan and Blinnikov 1976, Liang and Price 1977, Galeev, Rosner and Vaiana 1979, Haardt and Maraschi 1991, Esin, McClintock and Narayan 1997, Esin et al. 1998, Gierliński et al. 1999, see Poutanen 1998 for recent review). The configuration of the accretion flow we adopted is schematically shown in Fig.3a. Here the solid black slab shows the optically thick accretion disk, which is assumed to be stable, sandwiched by an optically thin corona which is shown as a grey shaded region. It is further assumed that instabilities are operating in the corona which modulates the mass accretion rate flowing through given radius. The "sine wave" with varying period schematically shows that the time scales of modulations in the coronal flow increase with the radius. These modulations of the mass accretion rate are propagated down to the inner region of the main energy release (shown by the thin box near the black hole) where the observed X–ray emission is produced. Thus the variations of the observed X–ray flux coming from the inner region of the main energy release reflect the modulations of the mass accretion rate at much larger radii. In this picture one would then expect to observe the spectrum consisting of two components (soft stable component due to the disk emission and harder variable component due to Comptonization in the corona). The relative contribution of these two components to the luminosity of an averaged spectrum would then reflect the ratio of the energy releases in the disk and corona (or mass accretion rates if no strong advection takes place in the corona). The PDS of the harder component may then have the same shape over broad range of frequencies as indeed observed (Fig.2). The relative amplitude of the X–ray flux variations should be lower at low energies where stable multicolor black body component provides dominant contribution the observed flux.

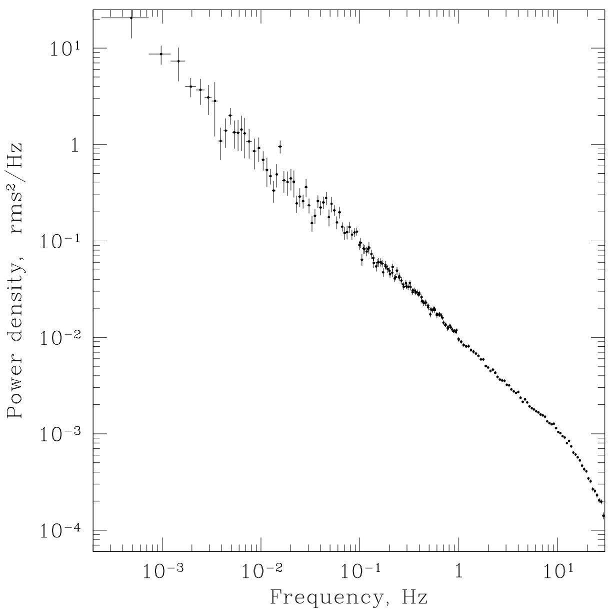

Figure 2. Power density spectrum of Cygnus X-1 during June 1996 soft state (6-13 keV band, RXTE data). At lower energies the shape of the PDS is the same, but the normalization is lower, because of the dominant contribution of the stable soft component to the observed X–ray flux.

2.3 Power density spectrum in the hard state

Let us now consider what kind of PDS we can expect in the hard state. In the hard state the soft (black body) component is weak or absent. We assume below that that the optically thick disk is truncated at a larger distance from the black hole (so that emission from the disk falls below X–ray regime). The adopted configuration of the accretion flow is schematically shown in Fig.3a. Here the optically thick (stable) disk ends at some radius and it is followed by an optically thin flow which joins the coronal flow, which is present above the disk. We assume that properties of this inner optically thin flow in terms of amplitude and characteristic time scales of modulations of the mass accretion rate are similar to those of the corona. We further assume that above the disk truncation radius larger fraction of the mass accretion rate $\dot{M}_d$ is flowing through the thin disk rather then through the corona $\dot{M}_c$. I.e. $\dot{M}_c \ll \dot{M}_d$. The total mass accretion rate in the optically thin flow below the disk truncation radius is $\dot{M}_t = \dot{M}_d + \dot{M}_c$. The PDS (the black solid line in Fig.3b) is then expected to have several distinct regions over frequency. These regions are schematically shown by the vertical lines in the Fig.3b labeled as f_1, f_2, f_3. The corresponding geometrical regions in the accretion flow are marked with the arrows in Fig.3a.

At high frequencies ($f \sim f_3$ in Fig.3b) there is a turnover of the PDS which may be due to the same reason as the turnover in the soft state PDS (Fig.2). The discussion

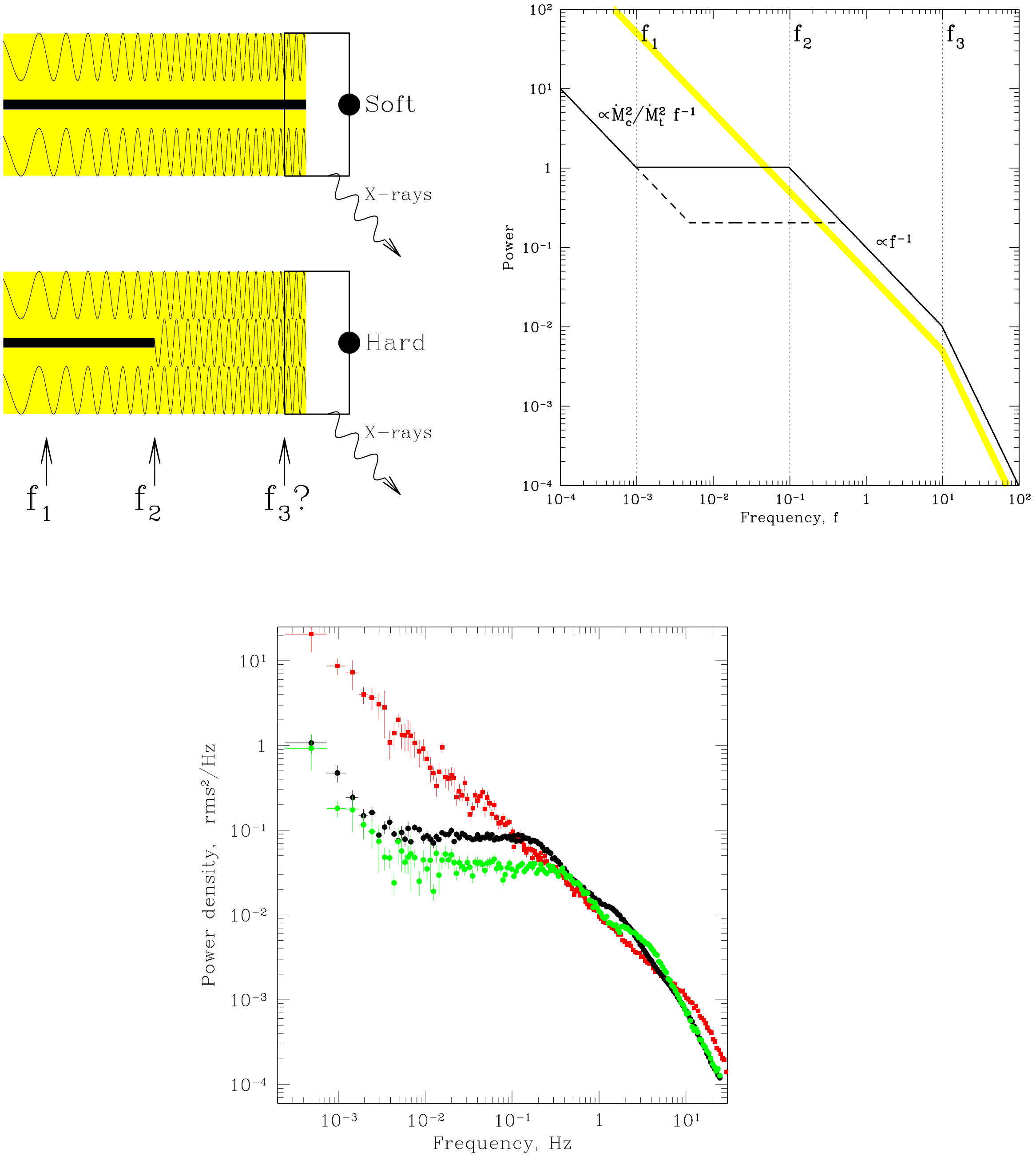

Figure 3. a), Top–Left: Sketch of the adopted geometry for the soft and hard states of Cygnus X-1. The solid circle marks a position of a black hole. The box shown by thin lines shows the area where most of the gravitational energy is released and where most of the X–ray radiation is emitted. The black "slab" shows the optically thick (geometrically thin) accretion disk. In the soft state the inner edge of the disk is close to the black hole, while in the hard state it is truncated far from the energy release region. Sandwiching the disk is an optically thin, geometrically thick corona (grey shaded regions), extending in the radial direction up to a large distance from the black hole. Oscillating curves show schematically that at different radii the mass accretion rate in the corona is modulated on different time scales. This modulated accretion flow reaches the innermost region and causes the fluctuations of the observed X–ray flux over the broad range of the time scales. **b), Top–Right:** The overall shape of the PDS expected in the simple geometry adopted here. In the hard state (thick solid line) there are three breaks (f_1,f_2,f_3 shown by thin vertical lines) in the power spectrum. f_2 is the characteristic frequency in the optically thin flow at the disk truncation radius. Anticipated changes in the power density spectrum associated with the inward motion of the disk truncation radius are shown by the dashed line. In the soft state the power spectrum (thick grey line) is a power law up to f_3. **c), Bottom:** Typical power density spectra of Cygnus X-1 in the hard (black and grey circles) and soft (squares) states. The PDS are constructed from the RXTE data in the 6–13 keV energy range.

of this turnover is beyond the scope of this paper and we only briefly speculate on it in Section 3. Detailed analysis of the high frequency part of the Cygnus X–1 PDS is given in Revnivtsev et al., 2000.

The range of frequencies from f_2 through f_3 is associated with the variability scales corresponding to the optically thin region of the flow below the disk truncation radius (Fig.3a). In this region we might expect the flow to be similar to the corona flow in the soft state and as a result the PDS should roughly reproduce the PDS in the soft state (i.e. $Power \propto f^{-1}$ for $f_2 < f < f_3$). The only difference is that in the soft state additional soft component is contribution to the observed flux. This soft component does not contribute much at the energies higher than 5 keV and we therefore can directly compare the shape and the normalization of the PDS in the hard and soft state for the higher energy bands (Fig.3c). Here f_2 is a characteristic frequency of the modulations introduced by instabilities operating in the optically thin flow at the truncation radius of the disk. Below this frequency only a small fraction of accreting matter contributes to variability – the fraction of matter which goes through the corona. As a result normalization of the power density spectrum, associated with the viscosity fluctuations in this region should drop by a factor of $\sim \left(\dot{M}_c/\dot{M}_t\right)^2$. This component should appear in the power density spectra as a f^{-1} component at very low frequencies as shown in Fig.3b. The frequency below which this component is dominating the PDS is marked as f_1. There is also a transition region between frequencies f_1 and f_2. One can expect the PDS to be flat in this frequency range. Indeed, the variability of the X–ray flux in this range of time scales is not associated with the "locally" induced fluctuations of the accretion flow, which are suppressed by the factor $\sim \left(\dot{M}_c/\dot{M}_t\right)^2 \ll 1$, but rather with the stochastic superposition of the modulations of the accretion rate occurring at smaller radii. The frequency f_1, below which the PDS switches from flat to f^{-1} dependence can then be expresses as $f_1 = f_2 \times \left(\dot{M}_c/\dot{M}_t\right)^2$.

Thus the assumption of the variable corona sandwiching the stable disk (as inspired by the soft state data – Fig.2) leads to a prediction of a specific shape of the PDS in the hard state. For comparison observed PDS in the hard state (for two RXTE observation in March 1996) are shown in Fig.3c. Using the above arguments on the relative normalization of the two f^{-1} regions of the PDS one can estimate that in Cygnus X-1 the fraction of mass accretion rate going through the corona above the disk is $\sim 20\%$. Variations in the PDS shape (in particular the shift of the break frequency) is then interpreted as the change of the disk truncation radius and the related change of the characteristic frequency. The expected change of the PDS caused by inward shift of the disk radius is shown by the dashed line in Fig.3b. Similar behavior of the PDS (correlated change of the break frequency and normalization of the band limited noise) was first reported for Cyg X-1 by Belloni & Hasinger (1990). When the disk truncation radius extends well down to the innermost region the PDS switches from the "3-breaks" shape to the "1-break" shape as observed in the soft state.

3 DISCUSSION

Described above is a qualitative picture inspired by the variability of the source during soft state. The suggested model is a phenomenological one and we speculate below on the possible underlying physics.

The first important question is why the mass accretion rate in the thin disk would be stable, while in the corona it is variable. Note that we do not address here the question of the accretion flow stability (e.g. against thermal and viscous instabilities in the radiation-pressure-dominated part of the disc)*. Instead one can think of the effect on the mass accretion rate of the magneto-hydrodynamic turbulence, which presumably serves as a source of the viscosity in the accretion flow through the fluctuating magnetic stresses (e.g. Hawley, Gammie and Balbus 1995, Brandenburg, Nordlund, Stein and Torkelsson 1995).

Lyubarskii (1997) considered the power density spectrum arising from fluctuations of viscosity at different radii which causes fluctuations of the mass accretion rate. Fluctuations at one radius are related to the fluctuations at smaller radii through the Green function of the diffusion equation (Lynden–Bell & Pringle 1974, Lyubarskii 1997). In his picture fluctuations of viscosity at a given radius on the viscous time scales $t_{visc} \sim \frac{1}{\Omega_K \alpha (H/R)^2}$ causes fluctuations of the mass accretion rate at all smaller radii. Here Ω_K is a Keplerian angular frequency at a given radius R, α is viscosity parameter of Shakura & Sunyaev 1973, H is the half thickness of the disk. However because of the diffusive nature of the disk accretion any fluctuations of the mass accretion rate on time scales much shorter than the diffusion time scale will not propagate towards much lower radii (see Appendix), but instead will vanish in amplitude very close to the radius at which they originated. E.g. if we assume that actual fluctuations at a given radius are occurring at a time scales t_f, comparable with the dynamical time scales $t_d \sim \frac{1}{\Omega_K}$ or thermal time scales $t_{th} \sim \frac{1}{\Omega_K \alpha}$, then in the standard thin disk, where $H/R \ll 1$, we will always have $t_f \ll t_{visc}$. Therefore such fluctuations will never propagate down to much smaller radii. Even if we consider the fluctuations occurring in the inner zone of the geometrically thin disk, which is emitting in X–rays (i.e. multicolor black body component directly observed by X–ray telescopes) we can easily show that the amplitude of fluctuations on a time scale $\sim t_f$ will be significantly suppressed after propagating a distance ΔR in a radial direction such as: $\frac{\Delta R}{R} \sim \sqrt{\frac{t_f}{t_{visc}}}$. For larger $\frac{\Delta R}{R}$ the amplitude of the mass accretion rate fluctuations will vanish. E.g. for fluctuations on the thermal scales $\frac{\Delta R}{R} \sim \frac{H}{R} \sim 10^{-2}$ ($H/R \sim 10^{-2}$ is a typical value for the standard geometrically thin disk, dominated by a gas pressure). Therefore $N \sim \frac{R}{H} \sim 100$ different ("incoherent") region over radius will contribute to the observed flux, effectively suppressing the fluctuations by a factor of $\sim \frac{1}{\sqrt{N}} \sim 10^{-1}$. Thus for the geometrically thin disk fluctuations of α (or mass accretion rate) on the dynamical of thermal time scales will not cause very prominent variations in the observed flux.

On the other hand geometrically thick disks (e.g. ADAF

* Gierliński et al. 1999 argued that the disk was stable during 1996 soft state of the source flows) are much more transparent for the high frequency oscillations. E.g. the fluctuation of the viscosity (α parameter) at some radius (at the dynamical or thermal time scales) will affect the mass accretion rate at all smaller radii and thus may provide fluctuations of observed flux coming from the innermost region of the accretion disk. Thus qualitatively the apparent stability of the disk compared to the corona could be understood as the result of a much longer diffusion time in the disk, which suppresses propagation of fluctuations.

In the above model the characteristic frequencies are related to the position of the disk truncation radius: the smaller the truncation radius the higher the characteristic frequencies (in particular the break frequency). At least qualitatively this trend is consistent with correlation of the spectral and timing parameters observed in the black hole candidates. E.g. for Cygnus X–1 and GX 339–4 the increase of the characteristic frequencies correlates with the steepening of the spectra and the increase of the reflected component (Gilfanov et al., 1999, Revnivtsev et al., 2000), which may be related to the increase of the cooling of the Comptonization region by the soft photons from the disk and the increase of the fraction of the hard flux intercepted by the thin disk as it approaches black hole. In GRS1915+105 and XTE J1550–564 the QPO frequency, which in turn correlates with the break frequency, is well correlated with the soft component flux (e.g. Trudolyubov et al. 1999, Muno et al. 1999).

Of course the above representation of the PDS as a 3-break function is a gross oversimplification. In reality the shape of the PDS will be much more complex. E.g. broad humps may appear near the break frequency because the geometrically thin disk at the truncation radius supplies mass at a steady rate to the "unstable" inner geometrically thick region. In such conditions any increase of the accretion rate in the optically thin region must be followed by the decrease of the accretion rate at later moments of times (since total mass supply rate by the thin disk is constant). As a result a broad QPO–like hump may appear in the power density spectrum (Vikhlinin, Churazov, Gilfanov, 1994).

The truncation radius of the disk may fluctuate with time and affect the observed X–ray flux. Therefore even if the thin disk does not propagate the fluctuations of the mass accretion rate (at the frequencies higher than diffusion time) we may see fluctuations of the soft flux due to fluctuations of the disk truncation radius. The only case when we should expect the soft component to be very stable is when the disk extends all the way down to the marginally stable orbit at $\sim 3R_g$ (i.e. in the genuine soft state). In the "transition" state (i.e. when the disk is close enough to the black hole) fluctuations of the soft component due to disk truncation radius can be observed directly. In the hard state (when the disk is presumably truncated at a large distance from the compact source) emission of the thin disk is almost outside the X–ray band and variations of the soft disk flux can be observed indirectly through the influence of the soft flux on the Comptonization region. E.g. variations of the soft flux entering the Comptonization region with a given optical depth and energy release to the electrons will result in variations of both the flux and slope of the Comptonized spectrum.

The high frequency turnover of the PDS (at about 10 Hz) may be related to the instabilities operating in the region of the main energy release. Part of the gravitational energy has already been released (and emitted) at larger radii. Therefore the amplitude of X–ray flux variations associated with the mass accretion rate fluctuations added to the flow in the inner region may be suppressed. Note that in the case of accretion onto a neutron star a large fraction of energy is released at the neutron star surface. Therefore this turnover may be absent in the power density spectra of the accreting neutron stars.

4 CONCLUSIONS

In the soft spectral state of Cygnus X-1, observed by RXTE in June 1996, the black body component was remarkably stable while the harder (power law like) component varied strongly on the frequency scales from 10 Hz down to few 10^{-4} Hz. We suggest that such behavior is due to presence of an optically thin corona above the optically thick disk, which extends up to a large distance from the black hole. The variations of the mass accretion rate (or viscosity) occurring at a large distance from the compact object are propagated down to the region of the main energy release. The reason for different variability properties of the disk and corona (namely stable disk and unstable corona) may be due to the fact that in the optically thick (geometrically thin) disk any fluctuations at time scales shorter than the diffusion time scales $t_{visc} \sim \frac{1}{\Omega_K \alpha (H/R)^2}$ are effectively dampened and are not propagated down to small radii. The assumption that in the hard state the disk is truncated at some distance from the black hole (larger than the last marginally stable orbit) then naturally lead to an explanation of the overall shape of the power density spectra of black hole candidates in this spectral state.

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APPENDIX A: DAMPENING THE VARIATIONS IN THE GEOMETRICALLY THIN DISK

In this appendix we formally demonstrate the natural fact that in a geometrically thin disk variations of the viscosity at some radius on a time scale shorter than the diffusion time scale causes negligible variations of the mass accretion rate at smaller radii.

Consider for simplicity a geometrically thin (gas pressure dominated) disk with the constant ratio $\frac{H}{R}$, where H is a half thickness of the disk and R is the distance from the compact object. Let us assume that viscosity (α parameter) suddenly increases in a narrow ring at some distance R_1 from the center. Following Lyubarskii (1997) the deviation of the mass accretion rate from the steady state value at the radius $R = r \cdot R_1$ is:

$$\dot{m}(r,t) \propto \frac{C^2}{t^2}\sqrt{r}e^{-\frac{C}{4t}(r^{3/2}+1)} \times \left[I_{-2/3}\left(\frac{Cr^{3/4}}{2t}\right) - rI_{1/3}\left(\frac{Cr^{3/4}}{2t}\right)\right] \quad (A1)$$

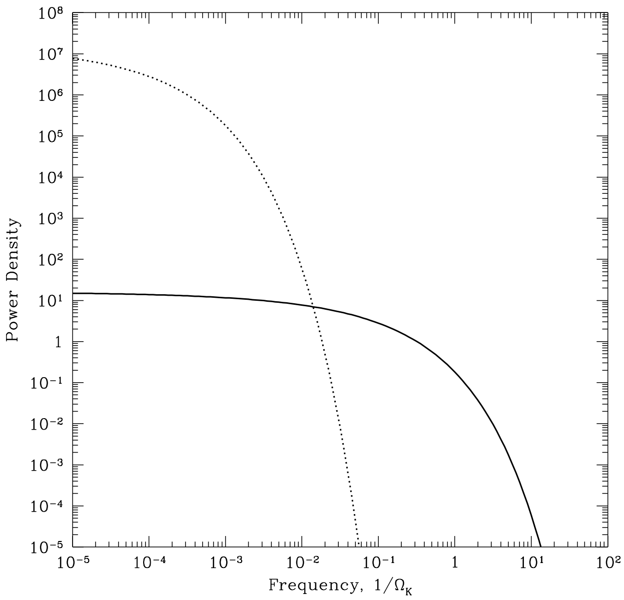

Figure A1. The power density spectrum of the mass accretion rate variations at some radius R caused by a sudden increase of viscosity (α parameter) in a narrow ring at the distance $R_1 \gg R$. Here $\Omega_K = \sqrt{\frac{GM}{R_1^3}}$ is a Keplerian frequency at the radius R_1. The dotted line correspond to the case of a geometrically thin disk ($C \sim \frac{1}{\alpha(\frac{H}{R})^2} = 10^4$) and the solid line was obtained by formally setting C to unity.

where time t is expressed in units of $\frac{1}{\Omega_K}$ (here $\Omega_K = \sqrt{\frac{GM}{R_1^3}}$ is a Keplerian frequency at the radius R_1), $C \sim \frac{1}{\alpha(\frac{H}{R})^2}$, $I_\nu(x)$ is the Bessel function of imaginary argument. The factor C is of the order of 10^4–10^6 for the standard geometrically thin (optically thick) gas pressure dominated disk and C decreases when the thickness of the disk increases. In the limit of $r \ll 1$ (i.e. at the radii much smaller than the radius R_1 where α is changing) the variations of the mass accretion rate is obviously:

$$\dot{m}(t) \propto \frac{C^{4/3}}{t^{4/3}}e^{-\frac{C}{4t}} \quad (A2)$$

The power density spectra associated with the variability in the form (A2) are shown in Fig.A1. Here the dotted curve corresponds to the case of $C = 10^4$ (i.e. the typical value in the standard geometrically thin disk). One can see that (as expected) virtually no variability is present at high frequencies comparable to Ω_K. For comparison the solid line shows the power density spectrum formally calculated for $C = 1^\dagger$. Here significant variability is present up to high frequencies.

† Note that $C \sim 1$ necessarily means that disk is geometrically thick and the above equations, derived in the limit of a geometrically thin disk, are not applicable