The Spectral States of Black Hole X-ray Binary Sources

Xingming Chen\textsuperscript{1} and Ronald E. Taam\textsuperscript{2}

\textsuperscript{1}Department of Astronomy & Astrophysics, Göteborg University and Chalmers University of Technology, 412 96 Göteborg, Sweden

\textsuperscript{2}Department of Physics & Astronomy, Northwestern University, Evanston, IL 60208

\textbf{ABSTRACT}

A framework for the interpretation of the spectral states of black hole X-ray transients based on the diversity of accretion disk models is introduced. Depending on the mass accretion rate, it is proposed that the accretion disk is described by one or a combination of the following structures: optically thick disk, advection-dominated disk, corona-disk, and non-steady state disk. In particular, it is suggested that the very high, high, low, and off states are characterized by mass accretion rates of decreasing magnitude. The very high state corresponds to mass accretion rates near the Eddington limit in which an optically thin non steady inner region is surrounded by an optically thick structure. In the high state, the inner region is optically thin and advection-dominated or optically thick. The low hard state is interpreted in terms of a disk-corona system and the off state in terms of an optically thin disk dominated by advective energy transport into the black hole. The possible observational consequences of such a paradigm are discussed.

\textit{Subject headings:} accretion, accretion disks — binaries: close — black hole physics — stars: individual (Cyg X-1, A 0620–00, GS 1124-68, GS 2000+25, GS 2023+33, GRO J0422+32) — X-rays: stars

\section{1. INTRODUCTION}

One of the most intriguing properties of black hole candidate X-ray sources (BHCs) is their distinct spectral states. The first known BHC, Cyg X-1, was discovered by Bowyer et al. (1965) and was recognized as probably containing a black hole by Webster & Murdin (1972) and Bolton (1972). Cyg X-1 has an estimated mass in excess of $\sim 7 M_\odot$ and exhibits high and low states as defined by the X-ray flux in 1–10 keV band. The luminosity difference in this energy band between these states is approximately an order of magnitude. In the high state, the spectrum consists of two components, namely, a relatively stable soft blackbody component and a weak, highly variable hard power-law component. On the other hand, in the low state, the intensity shows rapid chaotic temporal fluctuations with fractional rms amplitudes of several times 10\% and which do not
depend strongly on photon energy. The spectrum is exceptionally hard and can be described as a power-law with a photon index $\alpha_N$ less than 2 in the energy band between $\sim 10$ keV and a few 100 keV (Liang & Nolan 1984). Other persistent BHCs include LMC X-3 and LMC X-1. Another type of BHC is the soft X-ray transient among which includes A 0620–00 (V616 Mon), Nova Muscae (GS/GRS 1124–68), and GS 2000+25 (Nova Vul). A recent review of the observational data obtained from these sources has been given, for example, by Tanaka & Lewin (1995).

The spectral and time-dependent behavior of BHCs contain valuable information about the underlying physics of the accretion process. It is generally believed that the soft blackbody spectral component from these sources emanates from an optically thick cool accretion disk (Shakura & Sunyaev 1973). The properties of the low hard state and the power-law component in the high state imply the existence of optically thin, hot matter. However, the structure of the hot optically thin flow is unclear. Specifically, several types of models have been suggested including the optically thin two-temperature disk (Shapiro, Lightman, & Eardley 1976), and various corona-disk models (Liang & Price 1977; Ionson & Kuperus 1984; Haardt & Maraschi 1993; Svensson & Zdziarski 1994). Although the dynamics and stability properties of the corona-disk models have not been well established, it is well-known that the optically thin disk models are catastrophically thermally unstable (Piran 1978).

BHC X-ray transients may provide important clues for a model description of the different spectral states since they exhibit a wide intensity range in which they can be studied. In the case of Nova Muscae 91, it exhibited all the spectral states during its decay after the burst in January 1991 (Kitamoto et al. 1992, Ebisawa et al. 1994). Since the X-ray nova outburst is very probably due to mass flow modulations in the disk due to a thermal limit-cycle instability in the accretion disk and/or a mass transfer induced instability in the companion star (see a recent review by Lasota 1996), it is conceivable that the decay of the light curve reflects the decrease of the mass flow rate in the disk. Near the peak of the burst, the soft X-ray blackbody component and the hard X-ray, power law component, are comparable with the latter component much more variable than the former. This state is called the very-high-state to distinguish it from the high-state which occurs later. In the high state, the soft component remains, but the hard component is very weak or totally disappears. During this state, a “reflare” in the light curve (by a factor about 2) occurred about 70 to 80 days after peak (see Ebisawa et al. 1994). It is important to note that this same kind of reflare is present in the light curve of BHC X-ray transients A 0620–00 and GS 2000+25, which therefore suggests a common origin (Chen, Livio, & Gehrels 1993). At lower luminosity levels (about a factor of 100 from the peak value) Nova Muscae exhibited a low-state in which the spectrum is very similar to that of Cyg X-1.

A unified view for the spectral states of black hole candidate sources has yet to emerge. Recently it has been suggested that the spectral changes are related to the mass flow rate in the accretion disk (van der Klis 1995, Nowak 1995). However, this was adopted as a working hypothesis and no physical explanation was provided. We note that an interpretation of the transition from a low to a high state as due to an increase of mass accretion rate is opposite to
the standard accretion disk theory which predicts thermal instabilities (and a possible transition to an optically thin state) only for high mass accretion rates (e.g., Piran 1978).

Accordingly, in this paper we present a new model for the interpretation of spectral states in black hole candidate systems in terms of accretion disk models characterized by an optically thick component, advection-dominated component, and an optically thin corona. We suggest that the very high, high, low, and off states are a sequence characterized by decreasing mass accretion rates (see also van der Klis 1995). A similar picture, but differing in detail, has recently been suggested by Narayan & Yi (1995) and Narayan (1996). In the next section, the model is presented in terms of current ideas in accretion disk theory. The implications of such a model and its observational consequences are discussed in the last section.

2. MODEL

Recently, Chen et al. (1995) have presented a unified description of accretion disks around black holes. They showed that, at a given radius \( r \), exactly four physically distinct types of accretion disks may exist. Two of them correspond to a low viscosity in the disk, \( \alpha < \alpha_{\text{crit}}(r) \), and the other two correspond to a high viscosity, \( \alpha > \alpha_{\text{crit}}(r) \). These disks are further differentiated by the optical depth in the disk in the former case (i.e., optically thick or thin). For the high viscosity case, the type of disk solution depends upon whether advective energy transport is negligible or dominant, and advection-dominated solutions exist for all values of the mass accretion rate. On the other hand, for a small viscosity, advection-dominated solutions exist except for a gap near the Eddington rate, where no stable solution is possible and instability may occur. More recent developments in disk models, which have included the detailed microphysics of the hot plasma, have shown that \( \alpha_{\text{crit}} \) may, in fact, exceed unity (Björnsson et al. 1996, Kusunose & Mineshige 1996). Therefore, we consider only the case of \( \alpha < 1 < \alpha_{\text{crit}} \).

In Figure 1a the thermal equilibria of an accretion disk is illustrated at a fixed radius for the case in which the viscous stress is proportional to the total pressure. The solution at high column densities is optically thick and exhibits an \( S \)-shaped curve. The solid curve denotes thermal-viscous stability whereas the dotted curve denotes instability. The disk is stable at low mass accretion rates where it is gas pressure dominated and at high mass accretion rates where it is advection-dominated. Instability occurs when the ratio of gas pressure to total pressure is less than 0.4. In contrast, the solution at low column densities is optically thin. Here, the lower branch is local cooling dominated (only bremsstrahlung cooling is included) and is thermally unstable, whereas the upper branch is advection-dominated and is thermally stable (Narayan & Yi 1994, Abramowicz et al. 1995a). We identify the maximum mass accretion rate (due to the radial advection) at the tip of the optically thin branch as \( \dot{M}_1 \) and the mass accretion rate at the lower turning point (due to the radiation pressure effects, \( p_{\text{rad}}/p_{\text{gas}} \geq 3/2 \)) of the optically thick branch as \( \dot{M}_2 \). Note that at the upper turning point (due to the radial advection again), \( \dot{M} \) is usually larger than \( 10^{-50}\dot{M}_{\text{E}} \) (see the \( S \)-curves of Abramowicz et al. 1988 and Chen & Taam...
Hence, we consider only $\dot{M}$ less than that value. We estimate,

$$\frac{\dot{M}_1}{\dot{M}_E} = 2.0 \times 10^3 f (r/r_g)^{-1/2} \alpha^2,$$

$$\frac{\dot{M}_2}{\dot{M}_E} = 4.0 \times 10^{-3} f^{-1} (r/r_g)^{21/16} (\alpha M/M_\odot)^{-1/8}. \quad (1)$$

Here $\dot{M}_E = 4\pi GM/(c \kappa_{es})$ is defined as the Eddington rate, where $\kappa_{es}$ is the electron scattering opacity taken to be equal to 0.34 and $f = 1 - \ell*/\ell$ is considered for the inner boundary effect, where $\ell$ and $\ell*$ are the specific angular momenta at radius $r$ and the inner edge $r*$ respectively.

The specific angular momentum is Keplerian and is calculated under the pseudo-Newtonian potential of Paczyński & Wiita (1980). Formula (1) is calculated as that in Abramowicz et al. (1995a) where only the bremsstrahlung is included for the local cooling.

The variations of $\dot{M}_1$ and $\dot{M}_2$ with respect to the radius of the disk are shown in Figure 1b. It can be seen that $\dot{M}_1$ decreases slowly with increasing radius in the outer part of the disk. This trend reflects the fact that local cooling processes become more efficient relative to the heating rate at larger radii. A similar formula for $\dot{M}_1(r)$ has been calculated by Narayan & Yi (1995) under the self-similar assumption. It has the same scaling with $\alpha$ but the coefficient is smaller by a factor of approximately 10. In their calculation, the detailed radiative cooling processes such as synchrotron and Comptonization are included. Since these processes become more important for smaller radii, $\dot{M}_1$ decreases as $r$ decreases. In their case, $\dot{M}_1/\dot{M}_E \approx 10 - 20\alpha^2$ for $r \lesssim 1000r_g$, while our formula (1) gives $\dot{M}_1/\dot{M}_E \approx 100\alpha^2$ for $r \approx 1000r_g$. More recent calculations have shown that, with similar detailed microphysics, the self-similar solution gives a smaller $\dot{M}_1$ than that calculated under the Keplerian disk assumption. For example, for $M = 10M_\odot$, $\alpha = 0.1$, and $r = 30r_g$, Björnsson et al. (1996) obtained $\dot{M}_1/\dot{M}_E \approx 0.4$ (see also Kusunose & Mineshige 1996) while Narayan & Yi (1995) gave $\dot{M}_1/\dot{M}_E \approx 0.035$ (see their Figure 1 and scale $\dot{M}_1$ to the same $\alpha$ and $\dot{M}_E$). There are probably two factors contributing to this difference. One is the self-similar assumption which underestimates the value of the angular velocity (see global solutions of Chen, Abramowicz, & Lasota 1996 and Narayan, Kato, & Honma 1996a) and thus results in a smaller heating rate. A smaller heating rate shifts the advection dominated thermal equilibrium curve lower and shifts the optically thin local cooling dominated thermal equilibrium curve higher, therefore $\dot{M}_1$ becomes smaller. Note that the Keplerian approximation overestimates the angular velocity and, hence, the heating rate. Therefore, $\dot{M}_1$ lies within the range determined by these approximations. The second factor is related to the inner boundary condition which cannot be included in the self-similar solution. An accurate $\dot{M}_1$ can only be obtained by constructing global solutions of the disk including detailed radiative microphysics. For the purpose here, considering both effects of the radiative microphysics and the angular velocity, we may assume $\dot{M}_1$ as a very weak function of $r$, defined as $\dot{M}_{c1}$ for $r \lesssim 1000r_g$:

$$\dot{M}_{c1}/\dot{M}_E \approx 50\alpha^2. \quad (3)$$

Note that even a smaller $\dot{M}_{c1}$ as that of Narayan & Yi (1995) will not effect our conclusion later, since a slight increase of $\alpha$ will easily compensate for it.
The increase of $\dot{M}_2$ with radius in the outer part of the disk is attributable to the tendency that radiation pressure becomes important at larger radii only at higher mass accretion rates. Figure 1b clearly shows that $\dot{M}_2$ has a minimum of $\dot{M}_{c2}$ at radius of about $r_c \approx 8 - 9 r_g$, where $r_g = 2GM/c^2$:

$$\frac{\dot{M}_{c2}}{\dot{M}_E} = 0.2(\alpha M/M_\odot)^{-1/8}. \quad (4)$$

It is clear from Figure 1b that no steady solutions exist for $\dot{M} \gtrsim \dot{M}_{c1}$. That is, in this mass accretion rate range the region characterized by $r < r_2$ is non steady (see Figure 1b). We note that this region could be extensive, $r_2 \sim 100 r_g$, if $\dot{M}$ is large. It can be calculated that for $\dot{M} \approx \dot{M}_E$ and $\alpha \gtrsim 0.1$, the effective optical depth of the disk in regions $r \lesssim 100 r_g$ is less than unity. We suggest that this region is hot and optically thin and is the seat of the chaotic hard X-ray variability. Outflow is highly likely especially if $\dot{M} > \dot{M}_E$. The region exterior to $r_2$ is optically thick which produces the soft X-rays. The hard and soft X-ray luminosities may be comparable depending on the location of $r_2$. This state is identified with the very high-state.

At lower accretion rates, $\dot{M}_{c1} > \dot{M} > \dot{M}_{c2}$, region $r < r_2$ is described by an advection-dominated flow which is hot, optically thin and stable (see also Narayan & Yi 1995). It is seen that, as $\dot{M}$ decreases to near the bottom of the line $r_2$, the optically thick gas pressure dominated disk solution starts to be available in the region to the left of the line $r_2$ inside a few $r_g$. The global solution in this small region will however remain optically thin because its "outer" boundary condition is optically thin and advection dominated at this stage. In addition, since the flow is transonic and the radial drifting time is almost a free-fall time scale, the once hot advection dominated flow does not have time to settle to a cool state there. Since most of the gravitational binding energy is advected into the black hole, the disk produces very little hard X-rays. On the other hand, the region exterior to $r_2$ is optically thick and the soft X-ray emission dominates the total luminosity. This disk configuration describes the system in its high-state. Note that, as the mass accretion rate decreases, the ratio of the hard X-rays to the soft X-rays decreases since the spatial extent of the advection-dominated region decreases while that of the optically thick region increases.

As the mass accretion rate declines further, $\dot{M}_{c2} > \dot{M} > \dot{M}_{c3}$, the entire disk becomes optically thick and the spectrum is similar to that described above for the high state. This structural change, however, may result in an increase of luminosity, corresponding to a reflare, due to the sudden decrease of the inner radius of the disk, $r_{in}$, from $r_2 = r_c \approx 8 - 9 r_g$ to $r_2 \sim 3 r_g$ (since now, the whole disk can be optically thick). Since the disk luminosity is approximately inversely proportional to the inner disk radius, its shift results in a luminosity increase by a factor of $\sim 2 - 3$.

A transition to a new stage occurs for $\dot{M}_{c3} > \dot{M} > \dot{M}_{c4}$, where the system is in a corona-disk configuration. The formation of corona above the disk may be due to an evaporation mechanism facilitated by the electron conduction process as envisaged by Meyer & Meyer-Hofmeister (1994). The corona is hot and optically thin and is responsible for the production of the hard X-rays. The underlying disk is optically thick. This state corresponds to the low-state. In this corona-disk
model, the soft X-rays (produced by the viscous dissipation in the underlying cold disk as well as by the reprocessing of the hard X-rays from the above corona) are also Comptonized in the corona. Therefore the overall energy spectrum can be described as a power-law (Haardt et al. 1993). The soft blackbody component, however, has a temperature of only \( T_{bb} \lesssim 0.1 \) keV because of the low mass accretion rate. This component, however, is difficult to detect since the spectrum peaks in the wavelength region where interstellar absorption is high.

At the lowest rates of mass accretion, \( \dot{M} < \dot{M}_{c4} \), the electron conduction process may lead to the formation of a totally optically thin disk. In this case, the flow is advection-dominated, thereby producing very little luminosity corresponding to the off-state. In particular, Narayan, McClintock, & Yi (1996b) have applied the advection-dominated accretion flows to the off-state of A 0620–00 (see also Lasota, Narayan, & Yi 1996). We note that Narayan (1996) has applied the advection-dominated accretion flows to the low-state of BHCs, which however require a high viscosity parameter (\( \alpha \sim 1 \)) to produce the observed X-ray luminosity. In addition, the low-state has also been modeled by a small inner advection-dominated flow plus an outer disk-corona structure by Abramowicz, Chen, & Taam (1995b). The model, presented here, may reconcile these differences depending on the values of \( \dot{M}_{c3} \) and \( \dot{M}_{c4} \).

The critical values of \( \dot{M}_{c3} \) and \( \dot{M}_{c4} \) are difficult to estimate, but further work along the directions advocated by Meyer & Meyer-Hofmeister (1994) on CV’s may be fruitful. For example, \( \dot{M}_{c4} \) may be determined by the balance between the evaporation rate into the corona and the mass accretion rate of the disk.

A schematic diagram illustrating the above description for the systematic variation of the disk configuration with declining mass accretion rates is shown in Figure 2.

### 3. DISCUSSION

An interpretive framework for the spectral states of black hole candidate sources has been presented in terms of the mass accretion rate only. The accretion disk models upon which the framework is based require a moderately large \( \alpha \). Since \( \dot{M}_{c1} \propto \alpha^2 \), both very small and very large \( \alpha \) will give an extremely small or large \( \dot{M}_{c1} \) respectively, which is largely excluded by the interpretation of observational data (see below). Considering the uncertainties involved with \( \dot{M}_{c1} \), we estimate \( \alpha \sim 0.1 \) – 0.3, which gives an \( \dot{M}_{c1} \) corresponding to a luminosity near the Eddington limit. This is probably the case for Nova Muscae. This value of \( \alpha \) is consistent with the disk instability model which produces the outburst and fits the exponential decay of the light curve with an e-folding time of about 30-40 days (Cannizzo, Chen, & Livio 1995, and references within).

It is seen that the critical mass accretion rate, \( \dot{M}_{c2} \), below which the disk can be stable and optically thick depends on the disk parameter very weakly. Since it corresponds to the luminosity level where the “reflare” occurs, it provides an estimate of the absolute value for the luminosity for a given accretion efficiency. If the distance to the source and the inclination angle of the binary
system are known, the observed luminosity can be used to provide an estimate of the mass of the black hole. Independent of the distance to the source, $\dot{M}_{c1}/\dot{M}_{c2}$ can be determined from the ratio of the peak flux during the high state to the flux just before the reflare. The observations of Nova Muscae (Ebisawa et al. 1994) and GS 2000+25 (Tsunemi et al. 1989) indicate that this ratio is about $\sim 7 - 10$, which is consistent with $\alpha \approx 0.1 - 0.3$.

In the present model, the “reflare” occurs as a result of the inward shift of the inner edge of the optically thick disk. Thus, the ”reflare” is unique to a black hole source, with significant emission in the soft X-ray band expected. In fact, this model predicts a decline in hard X-rays during the reflare (see, for example, Ebisawa et al. 1994). This phenomenon cannot be explained by other models (see Wheeler et al. 1996 for a review). It also predicts that, if there is also an optical/UV “reflare”, it would result from the reprocessing of X-rays and, thus, it should be delayed in this model. This is in contrast to the irradiation (of the secondary star) model suggested by Chen et al. (1993) and the irradiation of the outer disk as envisioned by Kim et al. (1995) in which, the optical/UV “reflare” is expected to arise prior to the X-ray reflare (see also Mineshige 1994).

Our model does not predict a very high state if the accretion rate is less than $\dot{M}_{c1}$. In this case, the “reflare” should occur earlier provided that the mass accretion rate is greater than $\dot{M}_{c2}$. This may be the case in A 0620–00 in which the ”reflare” occurred after 50–60 days after peak luminosity (see the light curve in Kaluzienski et al. 1977 and Tanaka & Lewin 1995).

Our model also implies that, if a source has no high-state (i.e., stays hard), then there should be no reflare. This appears to be the case in GS2023+33 (V404 Cyg: Kitamoto et al. 1989, Miyamoto et al. 1995) and in GRO J0422+32 (Nova Persei: Sunyaev et al. 1993, Callanan et al. 1995, Vikhlinin et al. 1995). Note that the big-bump of hard X-rays in J0422+32 which occurred more than 100 days after peak (Callanan et al. 1995) may have the same origin as the second larger reflare observed in A 0620-00 and Nova Muscae, which we believe is different from the “reflare” we have studied here (see Chen et al. 1993).

We note here that although the efficiency of producing luminosity is very different, the energy spectra from the optically thin hot medium, of the inner region nonsteady flow in the very high-state, the corona in the low-state, and the advection dominated flow in the off-state, are rather similar since the radiative cooling mechanism is similar (for a spectral calculation, see Narayan et al. 1996b). The contribution of soft X-rays from the outer optically thick disk in the very high-state is easily observed since the mass accretion rate there is high and the typical blackbody temperature is around 1keV. On the other hand, in the low state, the underlying cold disk inside the corona has a very low blackbody temperature, $\lesssim 0.1$ keV, and therefore, its detection is difficult. Interesting, Balucinska-Church et al. (1995) recently observed a soft X-ray ($T_{bb} = 0.13 \pm 0.02$ keV) excess in Cyg X-1 and they identified it as the disk emission. The luminosity of this soft excess is about $4.7 \times 10^{36}$ erg s$^{-1}$ assuming a distance of the source as 2.5 kps.
Narayan (1996) modeled the low-state as an advection-dominated accretion flow. In the black hole X-ray transient case, then, the luminosity should drop significantly from the high state (local cooling dominated) to the low state (advection dominated), independent of the viscosity parameter. This has however not been observed and is unlike the off-state where the X-ray luminosity and the mass accretion rate inferred from other observations indicate a very low luminosity efficiency implying an advection dominated disk (Narayan et al. 1996b). There are other observational tests to distinguish the advection dominated model from the ‘sandwiched’ corona-disk model for the low state. For example, in the latter case, the spectrum should consist of a reprocessed (in the corona above) hard X-ray reflection (off the disk) component. Haardt et al. (1996) have constructed a corona-disk model to explain this type of spectral component from Cyg X-1 (Gierliński et al. 1995). Theoretically, time-dependent simulation of both types of models could determine whether or not the chaotical variability of the low-state can be reproduced within each model.

In conclusion, the unified description of accretion disks around black holes have appealing characteristics which can be applied to the spectral states of black hole candidate systems. In the proposed model the spectral states are governed by the mass accretion rate alone. This picture, however, is incomplete since the evidence from a combination of observational results from a number of BHC sources reveal that the luminosity level at which the transition from a low state to a high state on the ascending portion of the outburst differs from the transition from the high state to the low state during the descending portion by a factor of about 100 (see Miyamoto et al. 1995). A possible explanation for this hysteretic behavior is that the transition from the low to high state is physically distinct from the transition from the high to low state. For example, the spectral state during the rising portion of the outburst may correspond to an optically thin disk in its advection-dominated state (i.e. the solution corresponding to low column densities in Fig. 1a). The disk may remain advection-dominated until a transition occurs to the high soft state at accretion rates near $\dot{M}_1(r)$. On the other hand, the transition from the high state to the low state on the decay phase of the outburst reflects the operation of the evaporation mechanism in the corona. Thus, the transition from optically thin to optically thick and vice versa are not necessarily symmetric and differences in the luminosity level at which such transitions occur may be expected to be different. To confirm the framework outlined in this paper and to quantify the interpretation for such transitions, models for accretion disks based on a global solutions rather than the local solutions must be constructed. The implications of such solutions on the hysteretic behavior inferred in observed sources remain for future investigations.

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Fig. 1.— (a) The thermal equilibria of an accretion disk in the mass accretion rate-column density plane. Two critical mass accretion rates are denoted by $\dot{M}_1$ and $\dot{M}_2$, corresponding to the maximum rate for an optically thin disk and the first turning point of the optically thick disk respectively. (b) The radial variations of $\dot{M}_1$ and $\dot{M}_2$ (solid lines). The dotted line is for $\dot{M}_{c1} = 2$ from equation (3). Note that $\dot{M}_2$ has a minimum of $\dot{M}_{c2} \approx 0.23$ at about $r_c \approx 8 - 9r_g$.

Fig. 2.— A schematic description of the disk configurations and the spectral states of black hole candidates (see text).