Observational Signature of the ‘Boundary Layer’ of Galactic and Extragalactic Black Holes

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Abstract. We present spectral properties of an accretion disk model, in which a Keplerian accretion disk is flanked by a sub-Keplerian halo component terminating at a standing shock. The post-shock region (which may be considered to be the boundary layer of a black hole) reprocesses the soft photons emitted from the Keplerian accretion disk. We show that switching of states (from hard to soft and vice versa) could be accomplished by a change in the accretion rate of the Keplerian disk component. Our consideration, for the first time, resolves a long-standing problem of identifying the illusive ‘Compton cloud’ responsible for the switching of states.

Key words: accretion disks — transonic flows — black hole physics — hydrodynamics — radiation mechanisms: Compton and inverse Compton — radiative transfer — X-rays: general

Typical continuum spectra of accreting galactic and extragalactic black hole candidates exhibit both ‘soft’ and ‘hard’ components. Occasionally, the same object shows variabilities in these components such as hardening of the hard component as the soft luminosity diminishes and vice versa. In the former case, the energy spectral index is typically $0.5 - 0.7$ and the object is considered to be in the hard state, whereas in the latter case, the index is typically $1.2 - 1.5$ and the object is considered to be in the soft state. Whereas the hard component is long understood to be the characteristic of Comptonization of disk soft photons by an external ‘hot coronae’ (as the deficit of soft photons reduces the efficiency of cooling of the hot region; Sunyaev & Titarchuk, 1980, 1985; hereafter referred to as ST80, ST85 respectively; Titarchuk, 1994; hereafter T94), the origin and placement of this hot component have eluded satisfactory explanation. We propose that these varied behaviors could be explained by assuming the supplied matter to be not strictly Keplerian, as is usually assumed, but a mixture of the Keplerian matter with a sub-Keplerian halo. The sub-Keplerian matter could form out of Keplerian disk itself and also be supplemented by winds from the companion. Since angular momentum of matter which could be accreted ‘with ease’ is very small, low viscosity flow takes a longer distance to accomplish small angular momentum at the inner edge, if they start from a Keplerian disk far away. Higher viscosity flow only passes through inner sonic point, lower viscosity flow can pass through both. (Chakrabarti 1990, hereafter C90; Chakrabarti & Molteni 1995, hereafter CM95; Chakrabarti & Titarchuk 1995, hereafter CT95; Chakrabarti 1996, hereafter C96). In AGNs, entire matter supply could be sub-Keplerian and a part of this can become Keplerian if the viscosity is high enough. A generic accretion disk close to a black hole would thus have a quasi-Keplerian optically thick disk in the equatorial plane which is flanked by a sub-Keplerian halo terminating in an angular momentum supported, stable, enhanced density region (shock) close to the black hole horizon. Here the halo ‘feels’ the centrifugal barrier and matter piles up behind it (typically, at $r = 8 - 10r_g$, $r_g$ is the Schwarzschild radius) for marginally bound angular momentum of a Schwarzschild black hole and at a distance roughly half as much for a rapidly rotating Kerr black hole. Distance could be much higher if the angular momentum of the halo component is high (C90). Soft photons radiated by the pre-shock, optically thick, geometrically thin, Keplerian flow are intercepted by the geometrically thick, optically slim ($\tau \sim 1$), almost freely falling, hotter post-shock flow and are re-emitted as the hard X-ray component after inverse Comptonization. In this self-consistent scenario, outflow generated by the evaporated disk matter and from the companion winds may become responsible for producing the so-called ‘reflected’ component and the observed iron lines which clearly show a combination of P-Cygni type and down-scattered type line profile (CT95). As discussed in great detail in C90, CT95, CM95, C96), the
location where the flow deviates from the Keplerian disk ($r_{Kep}$) depends on viscosity parameter and Mach number of the flow, the latter being a function of the cooling processes. If the cooling efficiency is everywhere negligible (which is valid for very low accretion rate), then it may be impossible to form a Keplerian disk in the first place, in which case, the Keplerian component on the equatorial plane will be present only very far away from the black hole. This will then be the quiescence state of a novae before the outburst. The general picture of how the matter accretes on a black hole is schematically shown in Fig. 1.

Fig. 1: Schematic diagram of the most general solution of the accretion process around a black hole. Keplerian disk which produces the soft component is flanked by the sub-Keplerian halo which terminates in a standing shock. Post-shock flow heats up soft photons from the accretion disk through Comptonization and radiates them as the hard component. Outflows from the disk can be responsible for the so-called reflected component and the Fe emission lines at various stages of ionization.

Let $L_I = f_{ds}L_{SS}$ denote the fraction of the Keplerian (i.e., Shakura-Sunyaev [1973] type) disk luminosity $L_{SS}$ of the soft radiation intercepted by the bulge of the shock, $F_e = L_H/L_I$ denote the enhancement factor of this flux due to cooling of the electrons through inverse Comptonization (ST80, ST85, T94) ($L_H$ is the hard component luminosity), and $f_{sd} \sim 0.25$ (for a spherical bulge) denote the fraction of $L_H$ intercepted back by the disk. The soft component observed from a disk around the black hole candidate is therefore contributed by the original disk radiation plus the absorbed intercepted radiation: $L_S = L_{SS} + L_{SS}f_{ds}F_e f_{sd} B$, and $L_H \sim L_{SS} f_{ds} F_e$, where $B = 1 - A$, $A$ being the albedo of the Keplerian disk. The enhancement factor $F_e \sim 3(\nu_c/3\nu_d)^{1-\alpha} \sim 10^{-30}$ because, typically, the electron temperature $T_e \sim 50$ keV and the disk temperature $T_d \sim 5$eV for parameters of active galaxies and $T_c \sim 150$keV and $T_d \sim 100$eV for stellar black hole candidates. Hence, we easily achieve a convergence, $f_{ds}F_e f_{sd} B < 1$ of our algorithm since $f_{sd} \sim 0.25$, $f_{ds} \sim 0.05$, and $B \sim 0.5$. Here, $\alpha$ is the energy index $(F_e \sim \nu^{-\alpha})$ in the the up-scattering dominated region of the hard spectra.

We now present the detailed continuum spectra resulting from the above considerations (Fig. 1). We included hydrodynamics of standing shock waves, most accurate prescription of Comptonization (T94), the Coulomb exchange of energy between the protons and electrons, the bremsstrahlung energy loss of the electrons, and an accurate prescription for the disk albedo. Two temperature hydrodynamic equations are exactly solved by fourth order Runge-Kutta method to derive the temperature distributions from which the spectral index is computed (see CT95 for detail. N.B.: the accretion rate sequence in the caption of Fig. 2 of CT95 is inadvertently reversed.).

Fig. 2: Variation of spectrum with accretion rate: $\dot{m}_d = 1.0$ (dotted), $\dot{m}_d = 0.1$ (short dashed), $\dot{m}_d = 0.01$, (long dashed) and $\dot{m}_d = 0.001$ (solid). The accretion rate in sub-Keplerian halo component is kept fixed at $\dot{m}_h = 1.0$. Hard component softens and soft component brightens with $\dot{m}_d$. $M = 5M_\odot$ is used. Dot-dashed curve is drawn when the effects of bulk-motion Comptonization is also added.

Figure 2 shows a comparison of four runs for the spectra around a black hole of mass $5M_\odot$ (uncorrected for the spectral gardening factor) and the halo accretion rate $\dot{m}_h = \frac{M_\odot}{M_{Edd}} = 1.0$. The disk accretion rates $\dot{m}_d = \frac{M_{\dot{m}}}{M_{Edd}}$ are 1.0 (dotted), 0.1 (short dashed), 0.01 (long-dashed) and 0.001 (solid). With the increase of the disk accretion rate, soft photons intercepted by the post-shock bulge is increased, cooling this region efficiently. Thus the temperature $T_e$ of the electrons is reduced and the energy index $\alpha$ is increased. The luminosity and the peak frequency of the soft component go up monotonically with $\dot{m}_d$. The dash-dotted curve shows the appearance of the weak hard tail due to bulk-motion Comptonization (Blandford & Payne, 1981; Titarchuk, Mastichiadis & Kylafis, 1996; hereafter TMK96) in the soft state. When the accretion rate of the disk is very high, the abundant soft photons cool the post-shock region completely, and the optically thick, quasi-radial flow (made up of the disk and the halo) drags photons along with it, while Comptonizing them due to the rapid bulk motion prevailing close to the black hole. Decent fits of soft states of LMC X-3 (Ebisawa, Titarchuk & Chakrabarti, 1996; hereafter ETC96) and GS2000-25 and Novae Muscae (Chakrabarti, 1997) are obtained already. These show that a significant amount of accretion takes place in the form of sub-Keplerian flow. In contrast, radial
velocity in the neutron star boundary layer is very small, and the bulk motion Comptonization is negligible.

In Fig. 3 we present the energy spectral index $\alpha$ (observed slope in the $2-50\text{keV}$ region) as a function of the mass accretion rate of the Keplerian disk component ($\dot{m}_{\text{d}}$). Different curves are parameterized (marked) by the mass accretion rate of the halo component ($\dot{m}_{\text{h}}$). The lower left corner represents the so-called ‘hard-state’ (HS) with $\alpha \gtrsim 1$, while middle region represents the so-called ‘soft-state’ (SS), $\alpha \gtrsim 1$. Both are due to reprocessing in the post-shock flows (PSF). For even high accretion rate on the right, we show the spectra from the consideration of (Newtonian) convergent inflow in spherical geometry assuming that half the photons are lost at the inner edge $r = 1$ of the flow. For a given halo rate, we note that a transition between states can be achieved by a change in $\dot{m}_{\text{d}}$. The important point to note is that both in the extreme hard state (thermal Comptonization) and the extreme soft state (bulk motion Comptonization), the spectral index remains almost constant even when the accretion rate of the disk changes by orders of magnitude. This is completely consistent with the observations of the black hole candidates. In the intermediate accretion rate ($\dot{m}_{\text{d}} \sim 0.1-1.0$), both types of Comptonization may cause double breaks in the hard component.

![Fig. 3: Variation of energy spectral index $\alpha$ as accretion rate of the disk $\dot{m}_{\text{d}}$ (X-axis) and the halo $\dot{m}_{\text{h}}$ (as marked) are changed. In the left part a hard component is produced purely due to the thermal Comptonization, whereas in the right part bulk motion Comptonization becomes important. In the intermediate region both the effects could be seen (dashed and solid curves).](image)

We summarize these properties of our solution in Table 1 where the correlation (arrow-up) or anti-correlation (arrow-down) of the observable quantities (luminosities $L_X, \gamma$ in X-ray and $\gamma$-ray regions) with the input accretion rates are shown. Smaller arrow represents a weaker correlation. For a massive black hole, results remain very similar as the electron temperature is found to be very weak function of the central mass ($T_e \propto M^{0.04-0.1}$). Shock waves other than those discussed here (e.g., those produced by pre-heating and magnetic braking), if present, should produce exactly the same type of spectra. If the angular momentum of the sub-Keplerian halo is so small that shocks do not form at all, or the viscosity and the accretion rate (cooling) so small that the entire flow is sub-Keplerian near the black hole (C90, C96) then the sub-Keplerian component could intercept the soft photons from the Keplerian disk in the same way, and switching of states is possible by varying $r_{Kep}$ through viscosity. However, in this single component scenario there should always be anti-correlation between the hard and soft states which is not observed. We know of no solution other than ours which is based on actual mathematical properties of transonic accretion flows on a black hole. After our presentation of this work at the symposium, some parametric model (with $r_{Kep}$ as an adhoc parameter) has been proposed (Lasota et al, preprint). Such one component model should generally produce soft states (Chakrabarti, 1997).

| TABLE 1 |
| Trends of Luminosity and Spectral Index |
|---|---|---|---|
| Input & Output | $L_x$ | $L_\gamma$, $\alpha$ | $L_x$, $\alpha$ |
| $\dot{m}_{\text{d}}$ | $\uparrow$ | $\uparrow^a$ | $\downarrow^a$ |
| $\dot{m}_{\text{h}}$ | $\uparrow$ | $\downarrow^{b,c}$ | $\uparrow^b$ |

$^a$ dependence is weaker for $\dot{m}_{\text{d}} \lesssim 0.1$

$^b$ dependence is weaker for $\dot{m}_{\text{h}} \gtrsim 1$

$^c$ $\alpha_X \sim 1 \rightarrow 1.5$, $L_x/L_S \lesssim 10^{-3}$, converging flow with very high accretion rate.

The contribution of the hard component reflected from the accretion disk is found at the best to be only ten percent (CT95). The resulting equivalent width is only around several tens of electron volts. Since the post-shock region behaves like thick accretion disks (Paczyński & Wiita, 1980; Rees et al., 1982; C96), the rotating outflow (Chakrabarti, 1986) can be produced from the funnel of the post-shock region which is cooler (because of rotation) and at the same time, has a large covering factor. Hard photons passing through this wind will be down scattered to produce the typical iron line emission spectra (elongated red wing with some or negligible blue absorption) that is observed. The down scattered X-ray continuum passing through this wind will also produce a ‘transmission bump’ commonly interpreted as the reflection bump (CT95). However one requires ‘blobby’ jets to produce the observed equivalent width. Such blobbiness is indeed observed in disk-jet simulations (Ryu, Molteni, Chakrabarti, in preparation).
Our present solution of the problem explains shapes of the hard states from all the black hole candidates, such as GX339-4, GS2023+338 and GS1124+68 (Tanaka, Y., 1989; Ueda et al. 1994; Ebisawa et al. 1994). The black hole candidate novae, GS2000+25, GS2023+338, and GS1124+68 show very similar decay of luminosity in the post-outburst phase, but the spectral evolutions are very different. These differences could be accounted for by variations of the properties of the halo. For instance, GS2023+338 is always in hard state throughout the outburst, suggesting a high $\dot{m}_h$ but lower $\dot{m}_d$ (because the black hole mass itself could be higher). The suppression of the soft component could also be due to a shock distant from the black hole (very high angular momentum inflow) or very weakly viscous, low accretion rate, sub-Keplerian flow which intercepts soft photons from outer Keplerian disk. GS2000+25, on the other hand, remained in the soft state during the outburst, suggesting a high $\dot{m}_d$, but a low $\dot{m}_h$. In the rising phase of GS1124+68 the increase of $L_H$ below $\sim 10$ keV is accompanied by its decrease above $\sim 10$ keV. This object (along with other black hole candidates, such as A0620-00) is also observed in two distinctly different states, as are other black hole candidates, such as Cyg X-1 and GX339-4. These are signatures of increasing accretion rates. A possible scenario of novae outburst is presented in ETC96.

From Fig. 3 we note that while increase of the spectral slope requires increasing the disk accretion rate, the same is accomplished by decreasing the halo accretion rate. This opposite behavior explains occasional scatter in spectral slope even when the soft luminosity may be increasing (Yaqoob, 1992). Another important point to note that our results have been plotted using the dimensionless net accretion rate in the rotating converging inflow (ETC96). In order that this mechanism be successful, the limit cycle behavior at the Keplerian component must regulate the disk accretion rate and viscosity, quiescence states of black hole candidate novae could be readily explained by a high $r_{Kep}$. This inner edge comes closer to the black hole when the viscosity and the Keplerian disk accretion rate becomes higher (C90). This will produce the novae outbursts (ETC96). In order that this mechanism be successful, the limit cycle behavior at the Keplerian component must regulate the disk accretion rate as in the conventional models (Meyer & Meyer-Hofmeister, 1989; Cannizzo, 1993). What we have shown is that hard state or soft state formation depends on the relative magnitude of the two accretion rates. Thus, for a given total rate at the outer Keplerian disk, the rates can redistribute as viscosity changes, and induce corresponding state change.

Although the spectral index of the convergent inflow plotted in Fig. 3 is for spherical flow with zero angular momentum, it is easy to generalize the result for finite angular momentum (Titarchuk & Chakrabarti, in preparation). Fig. 4 shows the variation of spectral index with accretion rate and angular momentum of the flow in the post-shock region. The solid, dotted, dashed, long dashed and dot-dashed curves are for $l = 0$, $0.5$, $1.0$, $1.5$, $2.0$ respectively (in this unit, marginally stable and marginally bound angular momenta in Schwarzschild geometry are 1.83 and 2.0 respectively). Observation of $\alpha \sim 1.0 - 1.5$ along with optical depths of the so-called Compton cloud (the post-shock region) $\tau \sim 1 - 2$ are consistent.

Fig. 4: Variation of spectral index in the soft state as a function of the net accretion rate in the rotating converging inflow. See text for details.

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