Jets and spectral states with three-components of accretion flow around a black hole

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ABSTRACT

It is generally believed that high energy radiation (power-law components) can be mostly produced by a hot corona gas in the accreting black holes. There is a very popular hybrid disk radial coupling model that the inner part of cool Keplerian disk (or Shakura-Sunyaev disk) can produce advection-dominated accretion flow or corona-like structure, which can also generate outflows/jets. Here we argue that this simple coupling model cannot explain the whole hardness-intensity diagram of the spectral states and their transitions, and associated jets of a X−ray binary. Based on recent theoretical works on advective disk structures around a black hole, as well as many observational behaviors of a source, we conclude that there should be a third component of hot accretion flow with the radial coupling model, which can successfully explain all the spectral states and transitions. Interestingly, this model also provides a new scenario for the jet generation, launching, and evolution during the states with help of created barrier of the inner flow. We have also find out the jet kinetic power expression with our new jet generation scenario.

Keywords: accretion, accretion disks – black hole physics – hydrodynamics

1. INTRODUCTION

The black hole X−ray binaries (BXBs) are showing many types of spectral states in observations, and their states can be represented on the hardness-intensity diagram (HID) (Fender et al. 2004; Romero et al. 2017; De Marco et al. 2021; de Haas et al. 2021). This diagram is also called as q- diagram, see first plot of middle row in Fig.1. It is believed that a typical BXB can follows the cycle from quiescence state (QS) - low hard state (LHS) - high hard/soft intermediate states (HISs) - high soft state (HSS) - low intermediate states (LISs) - quiescence state (QS). Commonly, the jets are found in LHS to HISs (Mirabel & Rodríguez 1998), and when they launched from the disk, then a source enters HSS (In case of full outburst de Haas et al. 2021). Moreover, the quasi-periodic oscillations (QPOs) are also associated during LHS to HIS (Remillard & McClintock 2006).

We know that the multicolor blackbody spectrum component of the spectral states is well explained by a non-adveclive cool Keplerian disk (KD), which was proposed in 1973 (Shakura & Sunyaev 1973). We used a hot corona for the understanding of high energy power-law components in the study of active black holes (BHs). The origin of this corona is a mystery! Eventually for the modeling of the sources, there are some advective solutions or lamppost model (unknown origin or may be jet base) was proposed by the authors (Chakrabarti & Titarchuk 1995; Esin et al. 1997; Fabian et al. 1989), which can act like the hot corona. Those advective solutions can also generate the outflows/jets. In this regards, there are two hot advective solutions are very popular and named as the shock solution (Chakrabarti 1989), and advection-dominated accretion flow (ADAF) solution (Narayan & Yi 1994). Interestingly, many authors have evidenced in their studies that the ADAF and KD can be coupled due to some instabilities (Esin et al. 1997; Honma 1996; Kumar & Gu 2019). Thus the KD can also work as a gas source for the ADAF. This radial coupling model is also known as two-zone radial hybrid disk model (Esin et al. 1997), and the non-adveclive (Keplerian) to advective (sub-Keplerian) flow coupling region is called as transition region. Eventually, many studies have used this
model to explain the spectral states and their transitions with adjusting the location of the transition region \((R_t)\), and mass accretion rate \((\dot{m})\). In BXBs, it is believed that the accretion rate is increasing during QS - LHS - HISs - HSS path and decreasing during HSS - LISs - QS path, but both paths are different. Now the problem is here and explained in the following section.

2. **HID WITH TWO-COMPONENT FLOWS**

If the ADAF-KD radial coupling is true and the ADAF can act like corona and also generate outflows then the presentation of the observed spectral states can not be similar to \(q\)- diagram. It would be look similar to \(T\)- diagram (flipped \(\Gamma\)), and the source can not follow the left part of the HID. Since when the source reached on HSS and having KD, which can be extended to ISCO radius. Now, the source can move to LISs/QS, so the KD must disappear\(^1\) via same advective coupling flow, and same way but with increasing location of \(R_t\) due to lack of sufficient mass accretion rate at the outer boundary; which means that the inner KD disk is gradually converting to the ADAF, so retracing \(R_t\) (Opposite to \(R_t\) is decreasing during LHS - HISs - HSS). Thus, the spectral state should be retraced on the HID (like HSS - HISs - LHS), and finally, the KD is disappeared, and source reach to QS stage. However, this is not happening in the BXBs, but it is true that the KD should disappear from the HSS - LISs - QS. Thus, there is a two possibilities here:

1. The ADAF-KD coupling is not existed, so when the inner part of KD flow is reached to the ISCO radius, and should be disappeared from the outside through the ISCO due to no stable orbits within the ISCO. Thus this scenario favors the two-component accretion flow (TCAF) model, which is also a hybrid disk model but the KD is sandwiched between the sub-Keplerian hot flow (Chakrabarti & Titarchuk 1995). This hot flow can also be have shocks in the inner region of the disk depending on the outer boundary conditions (OBCs), which are explained in detail (Kumar & Yuan 2021). But the disappearance of the KD from outside is not suitable with the behavior of BXBs path from HSS→LISs→QS because the last emitted photon should be soft photon, which should come from the ISCO and last inner part of the KD. So technically, the QS should be located in left part of the HID, and the HID should be similar to \(p\)- shape not \(q\)- shape. Thus the TCAF model is not suitable to explain the HSS→LISs→QS path. So, we prefer that the KD should disappear from the inside through the ADAF coupling, and it can produce the weak non-thermal photons, thus the QS can be located in the right side of the HID, and follows the \(q\)- shape. Moreover, the failed (or hard-only, restricted-successful de Haas et al. 2021) outbursts can also supports for the ADAF-KD coupling, since in those cases, the source can reach to any low state (LIS or QS) after the outburst without following HSS, means the truncated KD can not reach to the ISCO. Now the truncated KD must disappear through the ADAF/ADAF-like coupling flow with approaching towards the QS or other low states.

2. The ADAF-KD coupling is existed, but inner part of the ADAF disk can not produce enough Comptonized photons maybe due to lack of seed soft photons, and weak intrinsic radiations (Bremsstrahlung and synchrotron), so failed to explain the LHS and HISs. The lack of soft seed photons maybe due to radial coupling geometry, which can not provide the enough interception of the photons of the KD with the inner hot part of ADAF. Moreover, the outer part of the ADAF has higher gas density, and can work as the warm corona or reflector for the KD photons due to moderate/high optical depth with intermediate/low temperature gas, which depends on the location of \(R_t\), and transition accretion rate \((\dot{m}_t)\) at \(R_t\). This behavior is found natural in the theoretical study of ADAF when matter becomes advective from the non-advective cool KD flow (Kumar & Yuan 2021).

Overall, the key points are that individually, both (ADAF-KD coupling or TCAF) models are unable to explain the whole behavior of the BXBs, and it is also clear that the ADAF-KD model is not suitable to act like corona or produce the outflowing gas in the LHS and HISs. However, this coupling is much suitable for the understanding of the HSS→LIS→QS path. Thus, the ADAF-KD coupling disk needs some extra (or third) component of sub-Keplerian hot accretion flow, which can explain the high hard X-rays and generation of bipolar jets. Or in other words, the insertion of the ADAF component in the TCAF model. So, the hybrid disk structure can has total three component of the accretion flow, which are the KD, inner ADAF and third component. This Three-Component of Accretion

\(^1\) The KD can be disappeared two-ways: 1. It can disappear from inside with increasing the location of transition radius, 2. It can disappear from outside or in other words, the KD is not truncated. Both ways can have different time scales of the KD disappearance, and the later case can take much time due to non-advective nature of the KD flow (viscous time-scale is large). We prefer former case and reason explain in main text, and addendum.
Model (abbreviated as TCAM) can has many advantages in explanation of the typical and peculiar properties of the BXBs, like, understanding of the soft-excess radiation, help in formation of the outflow/jet with the gas of the third component through ADAF barrier, heartbeat states (repeatedly moving between HSS and HIS Fender et al. 2004) of GRS 1915+105 through intermittent inflow of the third component, and failed outburst (not following all the HID stages, especially skip the HSS stage de Haas et al. 2021), and so on. We can also assume that the quick changes in the active galactic nuclei (known as ‘Changing-look’ active galactic nuclei, AGN) can also be understood with change in the inflow rate of the third component. The detail properties of the TCAM is explained in the following sections. Importantly, we would like to mention that the gas of KD can produce the ADAF like flows, which are mostly sub-sonic nature (becomes transonic very close to the BH), and the third component can undergo shock transition when becomes super-sonic far away from the BH. So both advective flows (ADAF and third component) are different in nature and the third component is mostly hotter and faster (Kumar & Yuan 2021). Hereafter, we will call the third component as a hot component flow.

3. PROPERTIES OF INNER ADAF

Kumar & Yuan (2021) have shown that the nature of the advective solutions can be changed with changing temperature (T) of the accreting gas at an outer accretion boundary (AB), which changed the viscous time scale of the flow, since $\tau_{\mu\nu} \propto T$, where $\tau_{\mu\nu}$ is the viscous stress tensor. The viscous time scale changes the angular momentum (AM) transportation and viscous heating in the flow, which can change the dynamical time scales and radiative emissivities. It has also been found that the ADAF or ADAF-like flow is least advective and highest AM flow in the all possible general advective (sub-Keplerian) flows. We have noticed some interesting properties of the ADAF with changing size of it as following:

- The local specific energy (or Bernoulli parameter, say $B$) of the ADAF is decreasing with decrease in $R_t$, and when $R_t < 5r_g$ then whole flow has $B < 1$ or 0 (Kumar & Gu 2018, 2019; Kumar & Yuan 2021). So the ADAF may not has outflows due to negative local energy as mentioned in Narayan & Yi (1995).

- The AM distribution, and optical depth of the ADAF raises with deceasing $R_t$, even keep same inflow rate, for instance, when $R_t \lesssim 100r_g$ then the ADAF flow becomes optically slim/thick (optical depth $\tau_T > 1$, for $\dot{n}_t = 0.01\dot{M}_{\text{Edd}}$ see left panel of Fig.3 in appendix B). If $R_t < 10r_g$ then the AM distribution of flow becomes close to the Keplerian AM distribution, which may behave like optically thick slim disk, and may contribute in very high soft-state. Moreover, the temperature and inflow velocity decreases with decrease in $R_t$.

So the small/intermediate size of the ADAF can produce intermediate energy part of the spectrum (maybe soft-excess radiation), specially, the outer part of ADAFs with Compton thick/slim scattering, which is close to the KD. So the HSS -LIS- QS and soft-excess (depends on accretion rate) can be suitably understood by the ADAF-KD model. The key point is that the ADAF is changing their nature with size and accretion rate, so one could be very careful during modeling of the BXBs with adjusting the $R_t$. Moreover, qualitative power-law relation between $R_t$ and flow variables of the ADAF is presented in Kumar & Gu (2019), which can be used in the modeling.

4. THREE-COMPONENT FLOWS

As we discussed above that for understanding of LHS and HISs stages require the hot component along with the ADAF-KD model. This hot component can produce the high energy power law component and outflowing gas, and it can disappear with launching off the jet due to lack of accreting gas at the AB. The strength of the jet should be depend on the strength (mass flux) and nature (magnetized/non-magnetized) of accreting gas of the hot component. It can also be considered that the jet strength can also depends on the ADAF strength (rigidity), which can provide partial/strong barrier to the gas of the hot component, and the gas can turn upward (some details in appendix B). The strength of the ADAF is increased with decreasing size of it (or $R_t$), which raised the gas density and AM of the flow (Kumar & Yuan 2021). In the typical HID, we believed that the KD flow is evolved from LHS - HISs - HSS, and disappeared during HSS - LISs - QS, but origin of the KD flow is very poorly understood. Now, there could be three possibilities of formation of it with the hot component flow, and temperature distribution of the accreting gas at the outer AB:

1. The part of sub-Keplerian gas flow can condensate to form the KD or KD-like flow around the equatorial plane, which has local thermal equilibrium (LTE). Unfortunately, this physical process is not much understood but
recently, we have found some possibility to form the KD flow on the equatorial plane in the two-dimensional inflow-outflow study with two viscous stress tensor namely, $\tau_{\tau\phi}$ and $\tau_{\theta\phi}$ and this work is under preparation (Kumar et al. 2021). When the gas moves upward then the AM of the flow can effectively transfer towards the equatorial plane, so the equatorial gas can obtain the Keplerian distribution with some suitable combinations of both viscous tensors. Thus we believed that this may happen in the real situation with the help of the viscous stress tensors or other kinds of the dissipative processes in the accretion flow.

2. Recently, we have investigated two types of the inflow gases at the outer AB, namely, the hot ($T_{AB} \sim T_{\text{vir}}$) and cold ($T_{AB} \ll T_{\text{vir}}$) gases, and both produced different types of AM distributions in the solutions, where $T_{\text{vir}}$ is a Virial temperature (Kumar & Yuan 2021). So, it indicates that the cold accreting gas at AB can produce the KD or KD-like disk with some dissipative processes, since the cold accreting gas always produced high AM flow (low efficiency of AM transfer) than the hot accreting gas. Other the hot accreting gas can generate sub-Keplerian hot accretion flow (3rd component), which can make corona-like structure and jet gas close to the BH. It is natural that the accreting gas at outer AB can has non-uniform temperature distribution. Recently, formation of two-phase (cold gas surrounded by hot gas) inflow gas due to a thermal instability has been investigated very far away from the BH (Bu et al. 2020).

3. Third possibility is both (points 1 and 2) processes can help in formation of the KD flow$^2$.

The key point is that the both flows (hot sub-Keplerian and cool KD) should evolve together during the LHS to HIS, and the KD flow should evolve close to the equatorial plane due to high AM. Interestingly, there is an interpretation of the two simultaneous flows on the basis of observations (Smith et al. 2002).

5. SUMMARY AND DISCUSSION

Based on the above new views with the latest theoretical understanding of the accretion flows (Kumar & Gu 2018, 2019; Kumar & Yuan 2021; Kumar et al. 2021), there are the typical hybrid disk configurations that can possible to explain the HID stages, which are presented in the Fig.1 with assuming all the above stated possibilities and physical processes in the flow. The dominance/strength of each component of these configurations of the disk is dependent on the quality and quantity of the accreting gas at the outer AB. In starting with QS stage (Fig.1A), it has very weak or no accretion flow. When the accretion flow is evolved enough then BXB enters to LHS stage with filling space around the BH. When LHS is starting to evolve with luminosity means both flows (sub-Keplerian and KD) are building up the disk. The key point is that the condensation/formation of the KD disk should be much faster than the evaporation in the inner part of it. The evaporated gas can make inner ADAF or ADAF-like disk, which also get stronger as the other both flows evolved. Now, the possible roles of the ADAF disk can i) produce weak intrinsic radiations (Bremsstrahlung and Synchrotron emission), and soft-excess (Compton thick/slim scattering) when $R_t \lesssim 100r_g$, ii) make barrier (centrifugal and pressure supported surface) for in-falling gas of the hot component flow, which can help in the jet generation or storage of the gas around the inner region of the disk or when preceding flow is compressed enough then the flow can make strong shock in the disk. Although, the shocks can be generated without the additional ADAF barrier as shown in many theoretical and numerical studies (Kumar & Gu 2018; Kumar & Yuan 2021; Lee et al. 2016; Garain et al. 2020; Singh et al. 2021), and the post-shock region is much hotter than other flows, which can produce very high energy radiations, like, hard X-ray, and soft $\gamma$-ray. This shock can be standing or quasi-steady or moving inward in accretion flow, and these kind of geometries is represented for the LHS and HISs. This geometry has total three-accretion components in the disk Fig.1(plots B,& C). Here, the upper hot component can act as corona as well as base of the outflows, and the KD can produce seed photons for Compton scattering, ADAF, and thermal component of the spectrum. When the upper hot flow is disappeared with launching off jet due to lack of the accretion gas at AB, then the transition happen from hard HIS to soft HIS stage. Now the KD with inner ADAF disk is remained and mostly the thermal photons can be seen in the observations during the HSS stage (Fig.1D). The KD is also gradually disappeared via ADAF due to absence of the accreting gas at AB (So, no further evolution of the KD), and source moves to the LISs then QS stage with increasing $R_t$.

Interestingly, It has been found in the MHD simulation that the magnetic field (both toroidal and poloidal) is rapidly evolved in the post-shock region of the hot component than other part of the disk, which will be helpful to $^2$ The KD formation rate may depend on $T_{AB}$ of the accreting gas. We believed that if $T_{AB} \ll T_{\text{vir}}$ then formation rate can be higher since this gas gives least advective and higher AM flow (Kumar & Yuan 2021).
make outflows faster and collimated (Garain et al. 2020). Moreover, if the ADAF can thread with the magnetic field lines then the field lines can be hold relatively against the gas of hot component, since the ADAF is always slow moving inward due to high AM. So, the possibility of interaction of field lines with the plasma is higher in the TCAM, over the co-moving of the plasma and lines in same component. Thus the chance of plasma of upper flow in the disk can move along the poloidal field lines is higher with support of the ADAF barrier. This scenario can also be suitable for the magnetic reconnection with the interception of the magnetic lines of fast and slow moving flows in the inner region (Fig.2). Moreover, as the KD approaches towards the BH with increasing accretion rate, so the ADAF reduces size, and becomes stronger. At the same time, momentum flux of the upper hot component is also increased with moving inward as decreasing the $R_H$ (see right panel of Fig.3). So, the impact of interaction of both flows will be stronger, which can turn the upper flow more strongly upward, so it can make the stronger jet when moving from LHS to HISs. So the ADAF component could be the key component in the TCAM, which created new possibilities of physical processes in the inner part of the disk together with the upper hot component for the understanding of the jet generation, launching and evolution of jet strength during LHS to HISs.

The presented model scenario can be tested in future with numerical simulation study of the accretion flow with the accreting gas at the AB, which has temperature distribution (can be magnetized/non-magnetized), broadly two types of gases ($T_{AB} \sim T_{vir}$ and cold $T_{AB} << T_{vir}$) with relevant radiative and viscous dissipations. We believed that a suitable numerical setup can generate hot sub-Keplerian and cool Keplerian disk flow with large AB locations due to their different viscous and radiative time scales. We are also expecting some modeling studies of the BXBs in near future.

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APPENDIX

A. BALLOON BURST ANALOGY

A balloon burst depends broadly on limits of maximum pressure, and expansion rate during air inflow. A burst would be strong if pressure reached to maximum capacity, otherwise weaker with limit of maximum expansion rate due to high inflow rate. In BH inflow-outflow, the jets can be weak or strong, and they can evolve with increasing inflow rate, so the balloon burst or burst analogy can not work in the BXBs! Moreover, It is also noticed that the inflow rate is highest during HSS in the modeling of the BXBs (Marcel et al. 2018) but no outflow, and the BHs are sink for everything. It means that the origin of jet is dependent on some extra factors. So, we believe that the extra factor can be one more accretion component with the radial coupling model, which should reach close to the BH, and can also carry evolving magnetic field. Additionally, this makes one more extra factor is the ADAF barrier. Thus, our proposed TCAM flow is more suitable for the jet generation.

B. COMPARISON OF BOTH ADVECTIVE FLOWS

We calculate the optical depth, $\tau_T = k_T \rho H$, and inward momentum flux, $\dot{P}_j = \rho u^2 + p$ of the flows, and represented in the Fig.3. Here, $\rho, H, u, p$ and $k_T$ are the mass density, half-height of disk, bulk velocity, gas pressure, and Thompson scattering cross section, respectively. Interestingly, we find that the momentum flux is much higher for the inner ADAF and increases with decreasing radius ($r$). So the inner ADAF barrier can not be destroyed by the fast moving upper hot component. Thus matter of the hot component can turn upward and form the spirally rotating jet close to the axis. Although the momentum flux of the both components is mostly dependent on the accretion rate and energy of the flow, so the difference of $\dot{P}_j$ of the flows can be higher or lower from the presented case.

Since the upper hot component is participated in the jet formation in our TCAM, therefore the local energy flux of the flow can determine the kinetic power of the emitted jet, which can also depends on the local momentum flux of the flows. Suppose, $\dot{P}_f$, and $\dot{P}_u$ are the local momentum fluxes of the inner ADAF, and upper hot component at the interaction radius of both flows, respectively. Now, the efficiency of the jet emission can be defined as $\eta_j = (\dot{P}_j - \dot{P}_u)/\dot{P}_f$, and the local energy flux of the upper flow is $\dot{B} = MB$, where $\dot{B} = \dot{m}M_{Edd}$, and $\dot{B} = Bc^2$ are the accretion rate, and local specific energy of the upper component flow, respectively. Thus the kinetic power of the emitted jet can be
Figure 1. An illustration of the HID (q–diagram) in middle of first column, and typical disk structures from A to E, which can represent the various spectral states of BXBs. The $H/r$ height profiles are obtained from theoretical solutions by numerically solving general relativistic fluid equations (Kumar & Yuan 2021), except the KD flow, which is sketched with a dash-dotted line. The vertical line (magenta color) is representing transition radius ($R_t$), and arrow is representing moving direction.

defined as

$$L_j = \eta_j \dot{B} = \eta_j \dot{m} B M_{\text{Edd}} c^2 = 1.26 \times 10^{38} \eta_j \dot{m} B \frac{M_b}{M_\odot} \text{ erg/s},$$  \hspace{1cm} (B1)$$

where $M_b$ is mass of BH, $\eta_j \in [0, 1]$, and $B > 1$ for the upper hot flow (Kumar & Yuan 2021). Maximum value of $B$ depends on the BH spin, local magnetic energy (if present), viscosity parameter of the flow, and OBCs. If $\eta_j < 0$ then no jet emission.
Figure 2. An illustration of the disk-jet system for proposed TCAM scenario.

Figure 3. A typical behavior of the Thompson optical depth ($\tau_T$) for the two different size of the inner ADAF in left panel. In right panel, a variation of the momentum flux ($\dot{P}_f$) of the upper hot component (dotted red) and inner ADAF component (dashed blue) is plotted in dimensionless geometric unit. Both figures are plotted for the accretion rate, $\dot{M} = 0.01\dot{M}_{Edd}$. These solutions are generated from the viscous GR fluid equations of motion (Kumar & Yuan 2021).

C. OBSERVATIONAL SUPPORTS OF INNER DISAPPEARANCE OF THE KD

Apart from the failed outburst and nature of the HID (as discussed in section 2), the full outburst can also give the evidence of the disappearance of the KD flow with looking the variation of the high soft peak in the multicolor blackbody spectrum during the HSS to LISs. It is widely understood that the most of the high energy blackbody radiations are come from the inner part of the disk. So if the inner part disappears firstly, then the high soft peak will move towards low energy with decreasing luminosity, otherwise the peak will hold in same position with outer disappearance of the KD. It has been more commonly observed in the BXBs that the soft state shows a strong decline
in high energy peak rather than pivoting around it (Hirsch et al. 2020), which also supports the inner disappearance of the KD and the radial coupling.

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