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Cooling and black hole disk transitions

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Abstract. We investigate the role of radiative cooling in determining the geometric structure of accretion flows around black holes (BHs), and develop a model to explain the time evolution of observed transients in BH X-ray binaries (XRBs). Based on our numerical simulations, which include bremsstrahlung cooling, we arrive at the condition that the cooling time of the flow should be shorter than the viscous time, in order for a transition to occur from of a hot, geometrically thick, radiatively inefficient accretion flow (RIAF), to a cold, geometrically thin disk. We establish that variability in mass accretion rate ($\dot{M}$), together with viscous evolution, can explain BH state transitions. Interestingly, our model qualitatively reproduces the overall features of the observed state transitions in XRBs.

Keywords : accretion, accretion discs – hydrodynamics – cooling flows

1. Introduction

Accretion flows around BHs are interesting albeit complex phenomena (see Balbus & Hawley (1998) for a review). The two most dominant accretion flow states, observed in both stellar mass and supermassive BH systems, are: an optically thick, geometrically thin black-body-like disk state (Shakura & Sunyaev 1973); and an optically thin, geometrically thick radiatively inefficient state (Rees et al. 1982). Observationally, many BH XRBs are known to be transient sources, i.e., they exhibit variability in their luminosity due to transitions between different X-ray spectral states — a hard X-ray dominated state (under luminous) to a disk-dominated soft state (more luminous), and back to a hard state (Remillard & McClintock 2006). The black-body dominated soft state is well-fit by the standard Shakura-Sunyaev thin disk and the hard state can be described by a hot RIAF. Since the basic timescales involved in an accretion process are proportional to the mass of the BH, thus XRBs (stellar mass BH systems) are seen to undergo state transitions in humanly observable timescales.

Although the nature of individual outbursts may differ from source to source, the

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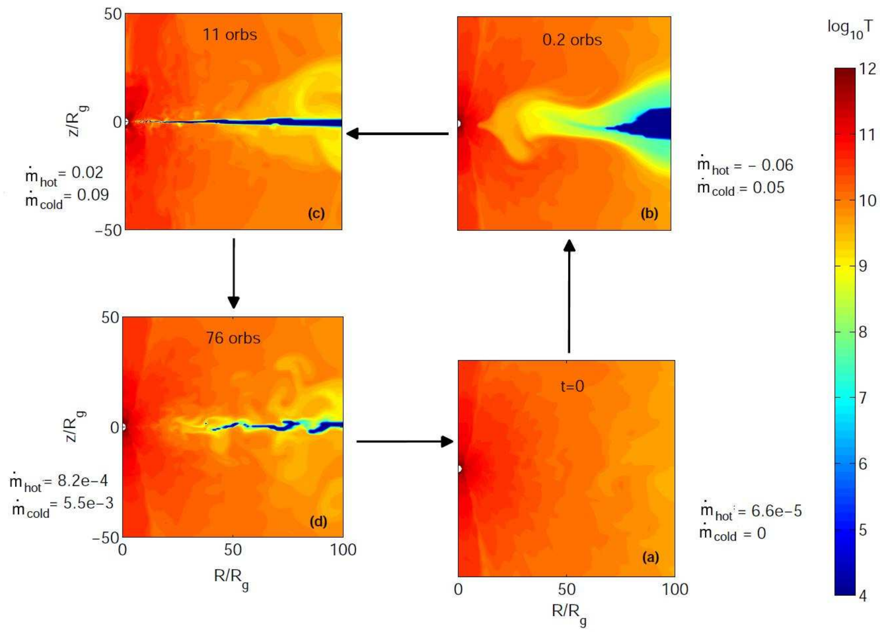

Figure 1. Complete state transition diagram from our idealized simulations. (a) Low-hard state (b) Intermediate hard state (c) High-soft state (d) Intermediate soft state. $\dot{m}_{\rm hot}$ and $\dot{m}_{\rm cold}$ are the accretion rates in units of $\dot{M}_{\rm Edd}$ of the hot and cold gas respectively. The grid resolution is 256^2 and $\alpha = 0.1$.

overall evolution of an outburst is remarkably uniform, as evident from the Hardness-Intensity diagram (HID) of XRBs. Typically in the HID, a BH transient source transitions between various spectral states classified according to their X-ray luminosity and X-ray hardness tracing a 'q'-shape, as shown, for example, by the 2002/2003 outburst of GX 339-4 (Belloni et al. 2005).

We have performed two-dimensional (axisymmetric) hydrodynamical simulations of accretion flow around a BH by including bremsstrahlung cooling. The main aim of this paper is to identify the physical processes responsible for the various state transitions in XRBs and hence, to construct a unified model explaining the global properties of BH transients. For details see our recently submitted paper (Das & Sharma 2013).

2. Effect of cooling on the structure of a RIAF

Our numerical simulations show that if the the cooling time is longer than the viscous timescale (i.e., $t_{\rm cool} \gtrsim t_{\rm visc}$), then the flow structure is geometrically thick, and independent of the gas density and cooling. Now, $t_{\rm cool}$ is inversely proportional to the density. Hence, a higher density, or equivalently a higher $\dot{M}$, corresponds to a shorter $t_{\rm cool}$ and an increase in the radiative efficiency of the flow. Thus, once $\dot{M}$ is high enough to trigger the onset of bremsstrahlung cooling, the gas cools before being accreted into the BH and forms the standard geometrically thin, optically thick Shakura-Sunyaev disk. Further, for $t_{\rm cool} \lesssim t_{\rm visc}$, the accretion flow separates into two phases — a radiatively inefficient hot coronal phase with long cooling times and a dense optically-thick, geometrically thin disk (Das & Sharma 2013).

The $t_{\rm cool}/t_{\rm visc}$ ratio leads to the condition for the formation of a cold, geometrically thin disk from a hot RIAF, which is $t_{\rm cool}/t_{\rm visc} \lesssim 1$. This condition can be expressed as $\dot{m} \lesssim 0.1\,\alpha^2$ (Rees et al. 1982), where $\dot{m}$ is the accretion rate in units of the corresponding Eddington accretion rate ($\dot{M}_{\rm Edd}$) and α is the Shakura-Sunyaev viscosity parameter.

3. State transitions

The transition from a RIAF to a thin disk state can be induced by an increase in $\dot{M}$. This in turn can be achieved by adding mass to the accretion flow, thereby increasing the density and decreasing $t_{\rm cool}$ for the accretion flow, such that the critical ratio $t_{\rm cool}/t_{\rm visc}$ becomes less than unity (see Das & Sharma (2013)).

The transition from a dense thin disk to a RIAF occurs simply due to viscous evolution. Once sufficient mass in the dense accretion flow is exhausted due to accretion, $t_{\rm cool}/t_{\rm visc}$ becomes $\gtrsim 1$ in the inner regions of the accretion flow. The thin disk recedes away from the BH giving way to a hot RIAF. However, this is possible only if $\dot{M}$ in the thin disk at inner radii is larger than the mass addition rate at outer radii.

4. A model for the time evolution of black hole transients

Fig. 1 summarizes the results of a single simulation, which captures the complete transition from a RIAF to a cold thin disk and back to a RIAF. The initial hot, low density RIAF has a very long $t_{\rm cool}$ (Fig. 1(a)). Mass is added to this flow, which brings about an increase in density, decrease in $t_{\rm cool}$ and the onset of a thin disk (Fig. 1(b)). As the mass accumulates (much) faster than the accretion time, the density of the flow keeps increasing and eventually a thin cold disk (Fig. 1(c)) is formed which extends very close to the BH. Once a steady thin disk is formed, the mass addition is stopped and the disk is simply allowed to evolve viscously. As accretion continues, sufficient mass is exhausted from the disk and the thin disk recedes far away from the central BH (Fig. 1(d)). As more and more mass is accreted into the BH, the density of the flow drops, causing $t_{\rm cool}$ to become longer than $t_{\rm viscs}$, eventually resulting in the formation of a RIAF. Thus we return to the original state with which we started (similar to Fig. 1(a)). We also note that the soft photons are radiated by a geometrically thin, optically thick multi-color black-body disk, while the hot RIAF is associated with hard X-rays and the corresponding spectrum is dominated by a power-law.

For the simulation in Fig. 1, the condition ($\dot{m} \lesssim 0.1\,\alpha^2$) for the flow to be a RIAF is $\dot{m} \lesssim 10^{-3}$, which is indeed satisfied. Fig. 1(a) shows no cold gas, and $\dot{m}_{\rm hot} \ll 10^{-3}$, establishing the flow to be a low-luminosity RIAF with a low accretion rate (the low-hard state). Fig. 1(c) corresponds to $\dot{m}_{\rm cold} > \dot{m}_{\rm hot}$; thus it is a cooling dominated flow. Also, $\dot{m} \approx 0.1 \gg 10^{-3}$ indicating that this state has a higher luminosity and a prominent thin disk (the high-soft state).

Thus putting it all together we find that the complete state transition in Fig. 1, (a) → (b) → (c) → (d) → (a), traces a ‘q’ as expected, which can be explained by variability in $\dot{M}$ and viscous evolution of the accretion flow. Thus, very interestingly, our model for state transitions qualitatively reproduces the features of the HID for observed XRBs.

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