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Mode Transitions of Black Hole Accretion Disks

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Abstract. The model of a bimodal accretion disk, which consists of an Shakura-Sunyaev disk (SSD) as the outer part and an advection-dominated accretion flow (ADAF) as the inner part, has been quite successfully applied to many black hole X-ray binaries. However, the precise physical mechanism through which such a transition occurs remains a matter of debate. We review briefly SSD-ADAF transition mechanisms presented in the literature, and offer a proposal that in the case of moderately strong viscosity, the thermal instability of a radiation pressure-supported SSD can trigger the transition.

There are four known self-consistent solutions of differentially-rotating, viscous accretion flows around black holes, namely the Shakura-Sunyaev disk (SSD, Shakura & Sunyaev 1973), the Shapiro-Lightman-Eardley (SLE) disk (Shapiro, Lightman, & Eardley 1976), the slim disk (Abramowicz et al. 1988), and the advection-dominated accretion flow (ADAF, Narayan & Yi 1994; Abramowicz et al. 1995). Among these solutions the most famous one is SSD, as it has provided an excellent description of cataclysmic variables, i.e. the case of white dwarf accretion (Frank, King, & Raine 1992). ADAF, on the other hand, has received much attention in recent years, as it did give a totally new picture of accretion (Kato, Fukue, & Mineshige 1998). It seems that SSD and ADAF are adequate for the outer and the inner region of black hole accretion flows, respectively, and the model of a bimodal accretion disk, which consists of an SSD as the outer part and an ADAF as the inner part, has been quite successfully applied to many black hole X-ray binaries, e.g. quiescent soft X-ray transients A0620-00, V404 Cyg, GRO J1655-40, and luminous X-ray binaries GRO J0442+32, Nova Muscae 1991, Cyg X-1 (Narayan, Mahadevan, & Quataert 1998). Such a bimodal disk model is, however, only a phenomenological one, in the sense that it artificially joins an SSD to an ADAF at some transition radius R_{tr}, and remains basic questions as to what (if any) the SSD-ADAF transition mechanism is, and how to determine the transition radius R_{tr}.

To our knowledge, there have been four answers to these basic questions. The first is called 'strong ADAF principle' (Narayan & Yi 1995), it states that whenever the accretion flow has a choice between an SSD and an ADAF, the ADAF mode is always preferred; and accordingly, it gives an estimation of R_{tr} (cf. Abramowicz et al. 1995):

$$\begin{aligned} R_{tr} &\sim 1.9 \times 10^4 \alpha^4 \dot{m}^{-2} R_g \\ &\sim 10^4 R_g \quad \text{for } \alpha \sim 0.1,\ \dot{m} \sim 0.01, \end{aligned}$$

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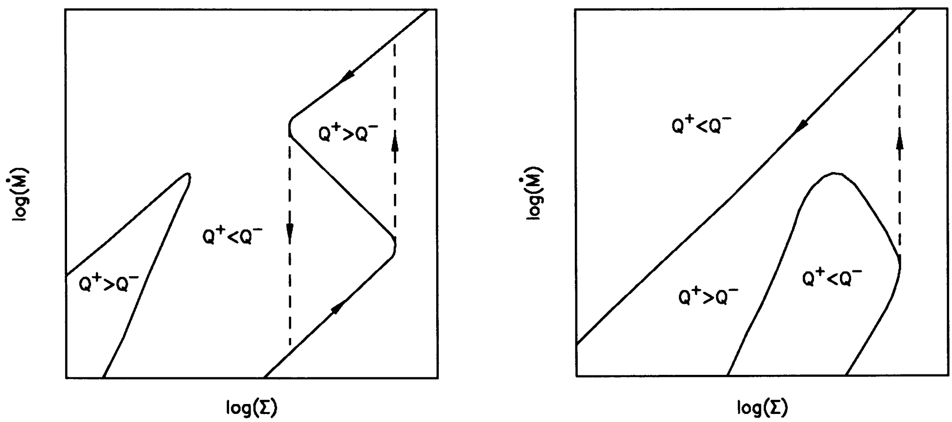

Figure 1. Unified description of accretion flows at a fixed radius. The solid lines mark thermal equilibrium solutions. The arrows show the behavior of the flow resulting from the thermal instability of a radiation pressure-supported SSD. Left: At $\alpha < \alpha_{crit}$, a limit cycle occurs; Right: At $\alpha > \alpha_{crit}$, an SSD-ADAF transition occurs.

where α is the constant viscosity parameter, $\dot{m} = \dot{M}/\dot{M}_{Edd}$, with $\dot{M}$ and $\dot{M}_{Edd}$ being respectively the mass accretion rate and the Eddington accretion rate, and R_g is the black hole's gravitational radius. The second answer suggests that the SSD-ADAF transition is due to the evaporation of the disk material into the hot corona through thermal conduction in the vertical direction, with an estimation of R_{tr} similar to that of 'strong ADAF principle' (Liu et al. 1999):

$$R_{tr} = 18.3(M/M_{\odot})^{0.17/1.17}\dot{m}^{-1/1.17}R_g \sim 10^4 R_g \ ,$$

where M is the black hole mass. Different from the evaporation mechanism, the third answer considers thermal conduction in the radial direction, and the resulting R_{tr} has a very wide range (Honma 1996):

$$R_{tr} = 1.08\alpha^4\dot{m}^{-2}R_g$$
$$\text{from} \ \sim 3R_g \ \text{to} \ \sim 10^4 R_g \quad \text{for} \ \alpha = 0.2 - 0.4, \ 10^{-3} \le \dot{m} \le 10^{-1} \ .$$

We think that the first answer is only a principle, without giving the underlying physical mechanism, while both the second and the third answer involve extra process of thermal conduction. The fourth answer to the question of SSD-ADAF transition (Takeuchi & Mineshige 1998; Gu & Lu 2000) is, in our opinion, clear in physics, and simple in the sense that it is within the framework of standard accretion disk theory, without involving any extra processes. The physics of this answer is seen from Fig. 1, which shows all known thermal equilibrium solutions of black hole accretion flows at a fixed radius, with the vertical and the horizontal axis being $\dot{M}$ and the flow's surface density Σ, respectively (Chen et al. 1995; Gu & Lu 2000). For each radius there exists a critical viscosity parameter α_{crit}. The left panel of Fig. 1 is for $\alpha < \alpha_{crit}$, where the S-shaped solid curve consists of three branches, of which the lower one is for gas pressure-supported SSDs, the middle one for radiation pressure-supported SSDs, and the

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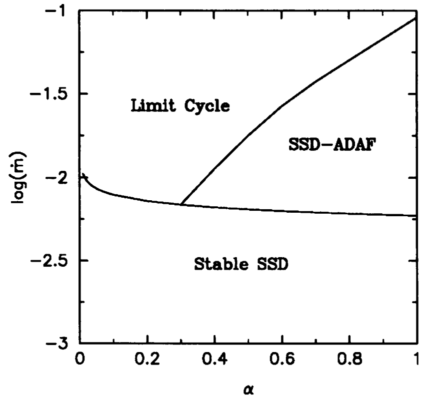

Figure 2. Dependence of the possible behavior of an original SSD flow on α and $\dot{m}$.

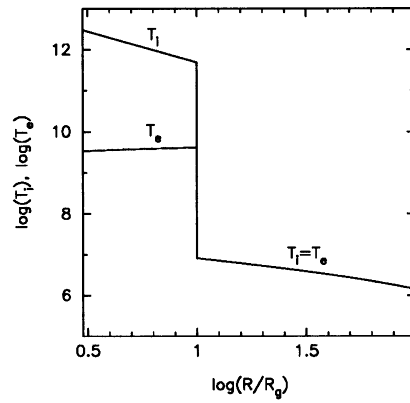

Figure 3. Radial variations of T_i and T_e of a global bimodal SSD-ADAF solution with $\alpha = 0.7$ and $\dot{m} = 0.03$.

upper one for slim disks; while the left solid curve consists of two branches, of which the lower one is for SLE disks and the upper one is for ADAFs. It is well known that gas pressure-supported SSDs, slim disks, and ADAFs are thermally stable, whereas radiation pressure-supported SSDs and SLE disks are thermally unstable (Kato, Fukue, & Mineshige 1998), thus the figure predicts a limit cycle behavior of the flow, i.e. that the flow oscillates between the gas pressure-supported SSD mode and the slim disk mode, as indicated by the four arrows in the figure.

In the right panel of Fig. 1 which is for $\alpha > \alpha_{crit}$, the straight solid line is for slim disks (higher $\dot{M}$) and ADAFs (lower $\dot{M}$), while the n-shaped solid curve consists of three branches, of which the two branches on the right are the same as the lower and middle branches of the S-shaped curve in the left panel of Fig. 1, and the branch on the left is for SLE disks. The thermal instability of a radiation pressure-supported SSD plays a key role again, but in a different way: The flow first jumps to the slim disk mode and becomes thermally stable, but because $\dot{M}$ does not match that of the outer SSD, the flow must evolve into the ADAF mode, for which $\dot{M}$ matches that of the outer SSD. The whole behavior is indicated by the two arrows in the figure. Since the radiation pressure region is the inner part of SSD (Frank, King, & Raine 1992), the position of SSD-ADAF transition should be close to the central black hole. R_{tr} can be calculated from the standard accretion disk theory as

$$R_{tr} = 1.2 \times 10^2 \alpha^{2/21} (M/M_\odot)^{2/21} \dot{m}^{16/21} R_g \sim 10 R_g \ .$$

The fate of an original SSD flow depends on two parameters, α and $\dot{m}$, as shown in Fig. 2 (Lu & Pan 2001). It is seen that of three possible cases, namely, the entirely stable SSD, the limit cycle behavior, and the SSD-ADAF transition, each occupies a certain region of the parameter space and that the SSD-ADAF transition occurs for $\alpha > 0.3$ and a definite range of $\dot{m}$. Fig. 3 gives an example of a global solution of a bimodal SSD-ADAF accretion flow, which draws the radial variation of the ion temperature T_i and the electron temperature T_e (Lu & Pan 2001). The parameters corresponding to this solution are $\alpha = 0.7$ and $\dot{m} = 0.03$. It is seen that during the SSD mode the flow is of one temperature ($T_i = T_e$), and the temperature is low. At $R_{tr} = 10R_g$ the SSD becomes unstable and switches to the two-temperature ADAF mode, T_i reaches the virial temperature, and T_e is of the order of 10^9K.

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