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The Connection of Standard Thin Disk With Advection-dominated Accretion Flow† *

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Abstract Using the standard Runge-Kutta method, a global solution of the basic equations describing black hole accretion flows is derived. It is proved that transition from a standard thin disk to an advection-dominated accretion flow is realizable in case of high viscosity, without introducing any additional mechanism of energy transfer or specifying any ad hoc outer boundary condition.

Key words: black hole physics—accretion —accretion disks—hydrodynamics

1. INTRODUCTION

So far, there are four types of models of black hole accretion disk in α viscosity description, namely, the standard thin disk (Shakura-Sunyaev disk, hereinafter SSD for short)[1], the SLE (Shapiro-Lightman-Eardley) disk[2], the slim disk[3], and the optically thin advection-dominated accretion flow (ADAF)[4]. Of these, the more successful ones are the SSD model which was the first one proposed, and the ADAF model which has been a hot topic of recent studies. The SSD model has scored great success in explaining some of the observed phenomena, but its rather high luminosity and relatively low temperature can not explain the high-energy radiation of the black hole candidates. On the other hand, because of its rather low total luminosity and very high temperature, the ADAF model can be used to explain the high-energy radiation. It seems that the SSD and ADAF suit respectively the outer and inner regions of the black hole accretion flow. So, if we combine them together, i.e., if we take a double structure for the accretion disk, namely, an SSD for the outer part and an ADAF for the inner part, with transition taking place at some radius $R_{\rm tr}$, then the observed spectra of many black hole X-ray double stars and low-luminosity active galactic

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nucleuses can be very well matched[5]. But such a connection is phenomenological, i.e., it is simply assumed that the SSD goes over into the ADAF at some radius $R_{\rm tr}$ without considering the underlying physical mechanism or how $R_{\rm tr}$ is to be determined.

Some authors don't think the connection of SSD with ADAF possible[6,7], but the reasoning is based on certain conditions: Ref.[6] considered only the low-viscosity case (α=0.1) and Ref.[7] did not take into consideration the mechanism of radiation cooling. Other authors have given an affirmative answer and have obtained an SSD-ADAF connection by introducing the radial (Refs.[8-10]) or the vertical (Refs.[11-12]) thermal flux due to thermal conduction. But the premises for such an answer are the introduction of an additional mechanism of energy transfer, thermal conduction, and the introduction of a new unknown parameter α_T describing the conduction. A third answer is that the transition from an SSD to an ADAF is triggered by an instability of the radiation pressure-dominated SSD in the inner region[13,14]. This also gives an affirmative answer but introduces no additional mechanism of energy transfer.

This paper will study further the SSD-ADAF transition. We will prove that in cases of high-viscosity (which is not considered in Ref.[6]) and non-zero radiation cooling (not considered in Ref.[7]), such transition is possible. But we shall not introduce any additional mechanism of energy transfer, such as thermal conduction; in this we differ from the second type of answer, and are similar to the third. And we will discuss in detail the differences and similarities with the third type of answer, as exemplified by Refs.[13,14].

2. BASIC EQUATIONS

The basic equations for a stationary, axisymmetric accretion flow, the equations of mass conservation, of radial momentum, of vertical balance, of angular momentum, and of energy conservation, and the equation of state are as follows:

(1) The mass conservation equation:

$$\dot{M} = -4\pi RH\rho v\,, \tag{1}$$

in which, $\dot{M}$, R, H, ρ and v are, respectively, the mass-accretion rate, radius, vertical half-thickness of accretion flow, density and radial velocity of the accretion fluid, the last positive outward.

(2) The equation of radial momentum:

$$v\frac{\mathrm{d}v}{\mathrm{d}R} = \Omega^2 R - \Omega_K^2 R - \frac{1}{\rho}\frac{\mathrm{d}p}{\mathrm{d}R}\,, \tag{2}$$

in which Ω and Ω_K are the angular velocity and Keplerian angular velocity of the fluid, respectively. The Keplerian angular velocity has as expression

$$\Omega_K^2 = GM/(R-R_g)^2 R\,.$$

The gravitational force of the central black hole is described by the pseudo-Newton potential[15], with M the mass of the central black hole, R_g the gravitational radius, $R_g \equiv 2GM/c^2$, and c the velocity of light.