Maximal Possible Accretion Rates for Slim Disks

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Abstract. By adopting the correct vertical gravitational force in studies of thermal equilibrium solutions, we find that there exists a maximal possible accretion rate for each radius in the outer region of optically thick accretion flows, such that only the inner regions of these flows can possibly take the form of slim disks.

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INTRODUCTION

The slim disk model is one of the popular models for accretion flows around black holes, and it has been applied in recent years to many energetic astrophysical systems, such as narrow-line Seyfert 1 galaxies, Galactic black hole candidates, and ultraluminous X-ray sources. Despite its growing importance in the observational sense, we note that some theoretical problems regarding this model in the fundamental sense have been ignored. Here we address one such problem, namely the inaccurate calculation of the gravitational force in dealing with the hydrostatic equilibrium in the vertical direction of slim disks. We work in the cylindrical coordinate system (r, z, φ) throughout.

VERTICAL GRAVITATIONAL FORCE

Both the Shakura-Sunyaev disk model and Hōshi (1977) reduced the vertical hydrostatic equilibrium into a very simple but very useful relation: $c_s/\Omega_{\rm K}H =$ constant. This relation was adopted in the slim disk model in the following way. First, vertical hydrostatic equilibrium was still assumed, even though slim disks are not geometrically thin, i.e., they may have $H \leq r$ or $H \sim r$. Second, although the pseudo-Newtonian potential introduced by Paczyński & Wiita (1980, hereafter the PW potential), i.e.,

$$\psi_{\rm PW}(r,z) = -GM_{\rm BH}/(\sqrt{r^2+z^2} - r_g) \ , \tag{1}$$

was widely used to simulate the general relativistic effect of a central black hole, it was again treated in the form of Hōshi (1977), i.e.,

$$\psi_{\rm PW}(r,z) \simeq \psi_{\rm PW}(r,0) + \Omega_{\rm K}^2 z^2/2 \ . \tag{2}$$

Using equation (2) and keeping the assumption of polytropic relation, we refined the relation $c_s/\Omega_{\rm K}H =$ constant with the sound speed c_s being defined either in terms of the

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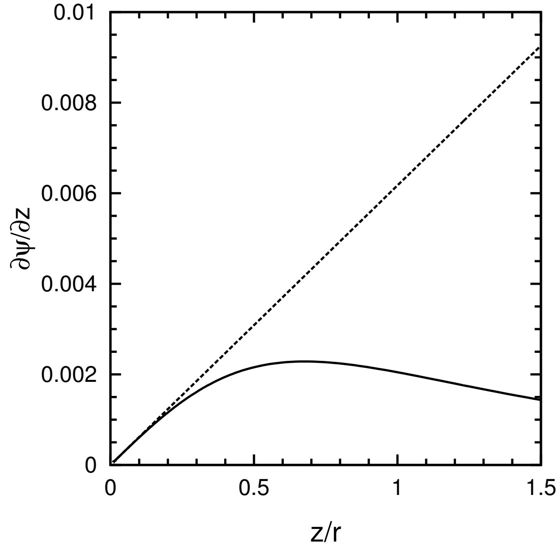

FIGURE 1. Vertical gravitational force $\partial\psi/\partial z$ for varying z/r at $r = 10r_g$, calculated using the explicit form of the PW potential (solid line) and the Hōshi form of this potential (dashed line) (Gu & Lu 2007).

pressure and mass density on the equatorial plane (Abramowicz et al. 1988), or in terms of the vertically integrated pressure and density (Kato et al. 1998, p. 242). To check the validity of the Hōshi form of the potential, we show in Figure 1 the gravitational force in the vertical direction $\partial\psi_{\rm PW}/\partial z$ in units of c^2/r_g for varying values of z/r at a fixed radius $r = 10r_g$, calculated from equations (1) (solid line) and (2) (dashed line). As expected, the Hōshi form of the potential, equation (2), is valid only for $z/r \leq 0.2$, while for $z/r \sim 1$ it greatly magnifies the vertical gravitational force in comparison with the correct result according to the explicit form of the PW potential, equation (1).

THERMAL EQUILIBRIA

We present in Figure 2 a united description of thermal equilibrium solutions of optically thick accretion flows around black holes in the form of $\dot{m} - r$ plane. The solid line in the figure shows $\dot{m}_{\rm max}$ for each radius, above which no thermal equilibrium solutions exist at all. The rest of the plane is further divided into three regions on the basis of the local stability analysis. The region below the dotted line is for stable SSDs, which are radiative cooling-dominated and gas pressure-supported. The region between the dotted and the dashed lines is for unstable SSDs, which are radiation pressure-supported but not yet advective cooling-dominated. These two regions were already known in the literature. The region between the dashed and the solid line is obviously for slim disks, which are advective cooling-dominated and radiation pressure-supported and are stable. What is new is that, because of the limitation of $\dot{m}_{\rm max}$, accretion flows can possibly take the form

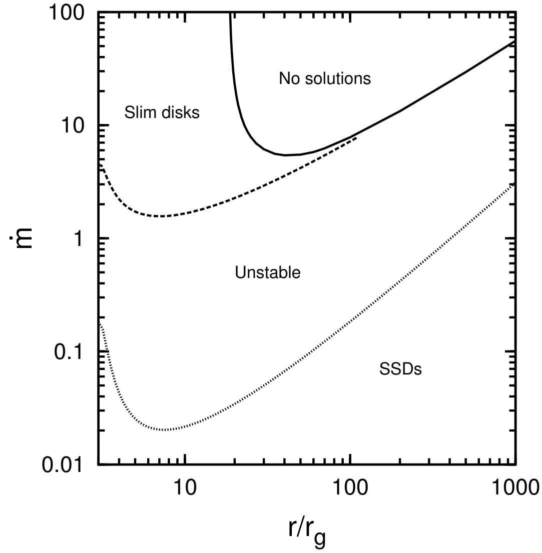

FIGURE 2. Distribution of thermal equilibrium solutions (Gu & Lu 2007).

of slim disks only in the inner regions of the flows.

We stress that only one change has been made in obtaining these results, i.e., using the explicit form of the PW potential, instead of the Hōshi form of this potential, to calculate the vertical gravitational force, while all the assumptions, equations, and methods for solutions are kept exactly the same as in the slim disk model (e.g., in the excellent book of Kato et al. 1998).

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