Hot accretion with outflow and thermal conduction

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Abstract We present self-similar solutions for advection-dominated accretion flows with thermal conduction in the presence of outflows. Possible effects of outflows on the accretion flow are parametrized and a saturated form of thermal conduction, as is appropriate for the weakly-collisional regime of interest, is included in our model. While the cooling effect of outflows is noticeable, thermal conduction provides an extra heating source. In comparison to accretion flows without winds, we show that the disc rotates faster and becomes cooler because of the angular momentum and energy flux which are taking away by the winds. But thermal conduction opposes the effects of winds and not only decreases the rotational velocity, but increases the temperature. However, reduction of the surface density and the enhanced accretion velocity are amplified by both of the winds and the thermal conduction. We find that for stronger outflows, a higher level of saturated thermal conduction is needed to significantly modify the physical profiles of the accretion flow.

Keywords Accretion · Accretion discs · Black hole physics

1 Introduction

The thin accretion disk model describes flows in which the viscous heating of the gas radiates out of the system imme-

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diately after generation (Shakura and Sunyaev 1973). However, another kind of accretion has been studied during recent years where radiative energy losses are small so that most of the energy is advected with the gas. These Advection-Dominated Accretion Flows (ADAF) occur in two regimes depending on the mass accretion rate and the optical depth. At very high mass accretion rate, the optical depth becomes very high and the radiation can be trapped in the gas. This type of accretion which is known under the name ‘slim accretion disk’ has been studied in detail by Abramowicz et al. (1988). But when the accretion rate is very small and the optical depth is very low, we may have another type of accretion (Narayan and Yi 1994; Abramowicz et al. 1995; Chen 1995). However, numerical simulations of radiatively inefficient accretion flows revealed that low viscosity flows are convectively unstable and convection strongly influences the global properties of the flow (e.g., Igumenshchev et al. 2000). Thus, another type of accretion flows has been proposed, in which convection plays as a dominant mechanism of transporting angular momentum and the local released viscous energy (e.g., Narayan et al. 2000).

This diversity of models tells us that modeling the hot accretion flows is a challenging and controversial problem. We think, one of the largely neglected physical ingredient in this field, is thermal conduction. But a few authors tried to study the role of “turbulently” heat transport in ADAF-like flows (Honma 1996; Manmoto et al. 2000). Since thermal conduction acts to oppose the formation of the temperature gradient that causes it, one might expect that the temperature and density profiles for accretion flows in which thermal conduction plays a significant role to appear different compared to those flows in which thermal conduction is less effective. Just recently, Johnson and Quataert (2007) studied the effects of electron thermal conduction on the properties of...
hot accretion flows, under the assumption of spherical symmetry. In another interesting analysis, Tanaka and Menou (2006) showed that thermal conduction affects the global properties of hot accretion flows substantially. They generalized standard ADAF solutions to include a saturated form of thermal conduction. In the second part of their paper, a set of two dimensional self-similar solutions of ADAFs in the presence of thermal conduction has been presented. The role of conduction is in providing the extra degree of freedom necessary to launch thermal outflows according to their 2D solutions.

On the other hand, ADAFs with winds or outflows have been studied extensively during recent years, irrespective of possible driven mechanisms of winds. But thermal conduction has been neglected in all these ADAFs solutions with winds. In advection-dominated inflow-outflow solutions (ADIOS), it is generally assumed that the mass flow rate has a power-law dependence on radius, with the power law index, $s$, treated as a parameter (e.g., Blandford and Begelman 1999; Quataert and Narayan 1999; Beckert 2000; Misra and Taam 2001; Fukue 2004; Xie and Yuan 2008). Beckert (2000) presented self-similar solutions for ADAFs with radial viscous force in the presence of outflows from the accretion flow or infall. Turolla and Dullemond (2000) investigated how, and to what extent, the inclusion of the source of ADAF material affects the Bernoulli number and the onset of a wind. In their model, the accretion rate decreases with radius ($s < 0$). Misra and Taam (2001) studied the effect of a possible hydrodynamical wind on the nature of hot accretion disc solutions. They showed that their solutions are locally unstable to a new type of instability called wind-driven instability, in which the presence of a wind causes the disc to be unstable to long-wavelength perturbations of the surface density. Kitabatake et al. (2002) studied supercritical accretion disc with winds, though angular momentum loss of the disc, because of the winds, has been neglected. Comparisons with observations reveal that the X-ray spectra of such a wind-driven self-similar flow, can explain the observed spectra of black hole candidates in quiescence (Quataert and Narayan 1999; Yuan et al. 2002). Lin et al. (2001) find that the spectral characteristics of high-luminosity black hole systems suggest that winds may be important for these systems as well.

Considering extensive works on hot accretion flows with winds and significant role of thermal conduction in deriving outflows (Tanaka and Menou 2006), we study ADAFs with outflows and thermal conduction using height-integrated set of equations. A phenomenological way is adopted in which we parameterize the rate at which mass, angular momentum and energy are extracted by outflow or wind. In the next section, we present basic equations of the model. Self-similar solutions are investigated in Sect. 3. The paper concludes with a summary of the results in Sect. 4.

### 2 General formulation

We consider an accretion disc that is axisymmetric and geometrically thin, i.e. $H/R < 1$. Here $R$ and $H$ are, respectively, the disk radius and the half-thickness. The disc is supposed to be turbulent and possesses an effective turbulent viscosity. Consider stationary height-integrated equations described an accretion flow onto a central object of mass $M_\bullet$. The continuity equations reads

$$\frac{\partial}{\partial R}(R \Sigma v_R) + \frac{1}{2\pi} \frac{\partial M_w}{\partial R} = 0,$$

where $v_R$ is the accretion velocity ($v_R < 0$) and $\Sigma = 2\rho H$ is the surface density at a cylindrical radius $R$. Also, $\rho$ is the midplane density of the disc and the mass loss rate by outflow/wind is represented by $M_w$. So,

$$\dot{M_w}(R) = \int 4\pi R'\dot{\nu_w}(R')dR',$$

where $\dot{\nu_w}(R)$ is mass loss rate per unit area from each disc face.

Xie and Yuan (2008) derived the height-integrated accretion equations including the coupling between the inflow and outflow, to investigate the influence of outflow on the dynamics of hot inflow. They showed that under reasonable assumptions to the properties of outflow, the main influence of outflow can be properly included by adopting a radius dependent mass accretion rate. We write the dependence of the accretion rate $\dot{M}$ as follows (e.g., Quataert and Begelman 1999)

$$\dot{M} = -2\pi R \Sigma v_R = \dot{M}_0 \left( \frac{R}{R_0} \right)^s,$$

where $\dot{M}_0$ is the mass accretion rate at the outer boundary $R_0$. The parameter $s$ describes how the density profile and the accretion rate are modified. In this paper, typical values of $s$ considered are between $s = 0$ (no winds) and $s = 0.3$ (moderately strong wind). The above prescription for mass accretion rate has been used widely for $s > 0$ (e.g., Quataert and Narayan 1999; Beckert 2000; Misra and Taam 2001; Fukue 2004) or $s < 0$ (Turolla and Dullemond 2000). Considering equations (1), (2) and (3), we can obtain

$$\dot{\nu_w} = \frac{s}{4\pi R_0^2} \dot{M}_0 \left( \frac{R}{R_0} \right)^{s-2}.$$

The equation of motion in the radial direction is

$$v_R \frac{dv_R}{dR} = R(\Omega_2 - \Omega_K^2) - \frac{1}{\rho} \frac{d}{dR}(\rho c_s^2),$$

where $\Omega$ is angular velocity and $\Omega_K = \sqrt{GM_\bullet/R^3}$ represents Keplerian velocity. Also, $c_s$ is sound speed and from vertical hydrostatic equilibrium, we have $H = c_s/\Omega_K$. 

\[ \square \]