CAN A WIND MODEL MIMIC
A CONVECTION-DOMINATED ACCRETION FLOW MODEL?

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ABSTRACT

In this paper we investigate the properties of advection-dominated accretion flows (ADAFs) in case that outflows carry away infalling matter with its angular momentum and energy. Positive Bernoulli numbers in ADAFs allow a fraction of the gas to be expelled in a form of outflows. The ADAFs are also unstable to convection. We present self-similar solutions for advection-dominated accretion flows in the presence of outflows from the accretion flows (ADIOS). The axisymmetric flow is treated in variables integrated over polar sections and the effects of outflows on the accretion flow are parameterized for possible configurations compatible with the one dimensional self-similar ADAF solution. We explicitly derive self-similar solutions of ADAFs in the presence of outflows and show that the strong outflows in the accretion flows result in a flatter density profile, which is similar to that of the convection-dominated accretion flows (CDAFs) in which convection transports the angular momentum inward and the energy outward. These two different versions of the ADAF model should show similar behaviors in X-ray spectrum to some extent. Even though the two models may show similar behaviors, they should be distinguishable due to different physical properties. We suggest that for a central object of which mass is known these two different accretion flows should have different X-ray flux value due to deficient matter in the wind model.

1. INTRODUCTION

In recent years, X-ray and radio observations have provided increasing evidence that advection-dominated accretion flows (Ichimaru 1977, Narayan & Yi 1995b, Abramowicz et al. 1995) describe reasonably well low luminous black hole candidates in various mass scale from stellar objects to galactic objects such as Sgr A^* (Narayan et al. 1995, Manmoto et al. 1997, Narayan et al. 1998). The advection-dominated accretion flows (ADAFs) have the low luminosity since most of the energy in the flows is stored in hot ions due to the low efficiency of heat transfer from ions to electrons which cool the flows. Temperature of the accreting flows is nearly virial and the flows are quasi-spherical. The Bernoulli parameter is positive, implying that the gas may escape as outflows. Furthermore, the

ADAF is unstable to convection so that convection is likely to occur and transfer angular momentum and energy.

The standard ADAF picture has been modified in recent papers by adding some features, such as winds, truncation due to jets, and convection (Beckert 2000, Blandford & Begelman 1999, Hujeirat & Camenzind 2000, Quataert & Gruzinov 2000a, Turolla & Dullemond 2000, Narayan et al. 2000). Since, at least in self-similar ADAFs, the Bernoulli number is positive (e.g. Narayan & Yi 1994), Blandford & Begelman (1999) have suggested that outflows may form and matter should escape. They have shown that the mass carried out by the wind must exceed by orders of magnitude that which falls into the central object, turning ADAFs into advection-dominated inflow-outflow solutions (ADIOSs). Outflow models for ADAFs have been investigated and applied to several candidates (Quataert & Narayan 1999, di Matteo et al. 1999). The lower radio flux than expectations from an ADAF model seems to be explained by the fact that only a fraction of the mass would accrete onto the central object due to a strong wind. Nonetheless, it is inconclusive since there are qualitative degeneracies between the mass loss rate in the wind and microphysics parameters of the accretion flows, that is, the fraction of the turbulent energy which directly heats the electrons. Quataert & Gruzinov (2000a) and Narayan et al. (2000) also show that, when convection moves the angular momentum inward, opposite to *normal* viscosity, convection dominates the dynamics of the flows and a nonaccreting solution exist for the viscosity coefficient lower than a critical value. This solution is characterized by a flatter radial density profile than the one in ADAFs, that is, $\rho \propto r^{-1/2}$ instead of $\propto r^{-3/2}$. Agol (2000) and Quataert & Gruzinov (2000b) argued that the linear polarization due to Faraday polarization may be very useful to distinguish models.

Time-dependent, multi-dimensional calculations of accretion flows have been performed (Igumenshchev & Abramowicz 1999, 2000, Stone et al. 1999, Igumenshchev et al. 2000), which in some cases resemble convection-dominated accretion flows (CDAFs) for certain viscosity parameters $\alpha < 0.03$, but also suggest the production of outflows for larger α, $\alpha \sim 1$ (e.g. Igumenshchev & Abramowicz 1999). According to the numerical simulations, the type of the flows depends mainly on the value of α, and less on other parameters. In other words, the parameter α determines the fate of the accretion flows. The goal of this paper is to investigate how, and to what extent, the inclusion of wind in the ADAF solutions mimic the convection-dominated accretion flows. This paper describes advection-dominated accretion flows in polar-integrated variables, including outflows or winds. We restrict the discussion to an extension of the self-similar solutions given by Narayan & Yi (1994) for the Newtonian limit.

This paper begins with descriptions of basic equations of accreting flows in Section 2. We present a steady state, axisymmetric self-similar solutions of ADAFs with a mass loss resulting from winds in Section 3. We discuss observational implications and conclude in Section 4.

2. BASIC EQUATIONS

Our first step is to establish a set of equations that describe the accretion flow. Advection-dominated accretion flows are known to be quasi-spherical (Narayan & Yi 1995a), therefore, we will use spherical coordinates in our discussion. In fact, we discuss accretion flows as polar-averaged, one-dimension flows with only a radial coordinate r. The average is taken over sections of shells occupied by the flow. Consider a steady state, axisymmetric flow so that $\partial/\partial t = \partial/\partial\phi = 0$ and rotating flow with angular velocity Ω around a compact object of mass M. The effective turbulent viscosity ν in the flow will redistribute specific angular momentum by a local viscous torque between neighboring shells. Mass is accreted by the central object with a rate $\dot{M} = -4\pi r u \Sigma$, where Σ is a suitable polar integral of the density. We are now left with the angular velocity $\Omega = \Omega(r)$ and

the radial component of the velocity, which is the accretion velocity $u = u\,(r)$. Nonetheless, any mass loss due to winds has to have a vertical motion. Since we describe all the quantities in terms of the radial component alone, those quantities related with mass loss are considered as a sink of mass, momentum, and energy. We regard these sources as external to our description of the flow and call it an outflow.

For a nonrelativistic flow, the conservation of mass implies that the change in mass flux at every radius is balanced by mass exchange with the wind in the stationary case. The continuity equation reads

$$\frac{1}{r}\frac{d(ru\Sigma)}{dr} = \dot{\Sigma}_w,$$ (1)

where Σ is the surface density of mass of the flows, $\dot{\Sigma}_w$ is the mass per surface area lost from the flow per time at a given radius due to the outflows, the accretion velocity of the flows $u = u(r)$. Angular momentum is also a conserved quantity in accretion flows and is redistributed by torques generated by viscous stresses $t_{r\phi}$ and mass loss due to the outflows. The angular momentum equation is given by

$$\frac{1}{r}\frac{d}{dr}(ru\Sigma l - r^2 t_{r\phi}) = \dot{\Sigma}_w l_w,$$ (2)

where $t_{r\phi} = \nu\Sigma r\,(d\Omega/dr)$, l and l_w are angular momentum of the accretingg flows and the out-flows. The $(r\phi)$ component of the stress tensor is assumed to be proportional to the corresponding component of the shear tensor with the kinematic viscosity $\mu = \nu\rho$ as the factor of proportionality. For the viscosity ν, we adopt the α prescription introduced by Shakura & Sunyaev (1973). For the α viscosity $\nu = \alpha c_s^2/\Omega_K$. The $(r\phi)$ component of the viscous stress tensor becomes

$$t_{r\phi} = \nu\Sigma r\frac{d\Omega}{dr}.$$ (3)

The radial accretion velocity u follows from the balance of gravitational force, centrifugal barrier, and radial pressure gradient.

$$\frac{1}{r}\frac{d(ru\Sigma u)}{dr} = \Sigma\left(r\Omega^2 - r\Omega_K^2\right) - r\frac{d(\rho c_s^2)}{dr} + \dot{\Sigma}_w u_w$$ (4)

where c_s is the isothermal sound speed, Ω_K is the Keplerian angular velocity, and u_w is the radial velocity of the wind, which subtracts its momentum from the accretion flow. The change in specific radial momentum induced by winds is proportional to the velocity difference $u_w - u$. Finally, an energy equation must be given by,

$$\frac{3+3\epsilon}{2}2\rho Hu\frac{dc_s^2}{dr} - 2c_s^2 Hu\frac{d\rho}{dr} = Q^+ - Q^- + \dot{\Sigma}_w\left[\omega_w - \omega + \frac{(\mathbf{u_w} - \mathbf{u})^2}{2}\right],$$ (5)

where Q^+ is the viscous heating due to differential rotation of the accreting flows, Q^- is the radiative cooling. The heat generated by the described viscous forces has to be included in the energy equation and amounts to

$$Q^+ = \nu\Sigma\left(r\frac{d\Omega}{dr}\right)^2.$$ (6)

The internal energy is increased by viscous heat and compression and reduced by radiative cooling Q^-. Cooling occurs mainly by the electrons thermally and nonthermally. The enthalpy difference between flow ω and wind ω_w, and the kinetic energy associated with the velocity difference,

which has to be dissipated into heat, is included. Here u is the velocity vector of the flow and u_w is the corresponding vector for the wind. Note that we parameterize the right hand side of Eq. 5 such that self-similar solutions are allowed. Therefore, we refrain our discussions from detailed processes of cooling.

3. SELF-SIMILAR ADAF SOLUTIONS WITH A WIND

Now we are looking for self-similar solutions in which all the unknown quantities scale as powers of r in the accretion flows. The set of equations described in previous sections allow self-similar power-law solutions for density, accretion velocity, angular velocity, and sound speed in the way Narayan & Yi (1994) have shown provided that $\dot{\Sigma}_w \propto r^{p-2}$ where the mass accretion rate varies as $\dot{M} \propto r^p$ (Blandford & Begelman 1999), and that the angular velocity and radial velocity of winds is assumed to be a fraction of those of the accretion flow itself. The rate of mass subtracted by the outflow per surface is constrained to steep radial profiles and introduces one free parameter p. Note that Blandford & Begelman (1999) confine the parameter p less than unity. Positive values of p correspond to outflows generated by the accretion flow. Similarly, infall case can be considered if we take p negative. For infalling material, we expect it to be in free fall so that the total velocity $u_w = u_{ff}$. In addition, we assume that the right hand side in Eq. 5 can be rewritten by $f' Q^+$, where f' is a similar quantity used in Narayan & Yi (1994) to describe the advection cooling. By substituting

$$\rho = Ar^a, u = Br^b,$$
$$\Omega = Cr^c, c_s^2 = Dr^d \tag{7}$$

into equations in the last section, and by equating the exponents of r in the various terms we obtain sets of algebraic equations,

$$a + b + \frac{d+5}{2} = p, \tag{8}$$
$$a + \frac{3d}{2} = p - 3,$$
$$d = -1, b = c + 1.$$

By solving those equations one can show that a self similar solutions exist if

$$\rho = \rho_0 r^{p-3/2}, u = -u_0 r^{-1/2}, \tag{9}$$
$$\Omega = \Omega_0 r^{-3/2}, c_s^2 = c_{s,0}^2 r^{-1},$$

with the radial coordinate scaled to the gravitational radius of the central mass. Solutions are reduced to the solutions obtained by Narayan & Yi (1994) if $p = 0$, and $\rho = \rho_0 r^{-1/2}$ as in the CDAF if $p = 1$.

4. DISCUSSION AND CONCLUSION

Blandford & Begelman (1999) constructed self-similar advection-dominated solutions for which the Bernoulli number is negative, assuming that $\dot{M}_{ADAF} \propto r^p$ with $p > 0$. They concluded that all the mass that does not reach the horizon escapes in a wind more massive than the ADAF by orders of magnitude. Although no detailed model including the wind has been presented as yet, preliminary hydrodynamical calculations seem indeed to support the original suggestion that the mass inflow rate

increases with radius (Stone et al. 1999). In addition, two-dimensional simulations by Igumenshchev & Abramowicz (1999) have shown that ADIOS-like solutions are present for large α.

Convective accretion flows are quite different from the standard self-similar ADAF solutions in several points. First, convective flows have a flattened density profile, $\rho \propto r^{-1/2}$, whereas $\rho \propto r^{-3/2}$ in the case of the self-similar ADAFs. Secondly, there is a net outward energy flux and an inward angular momentum flux in these flows provided by convective motions, whereas the self-similar ADAFs have a zero net energy flux. These effects have important implications for the spectra and luminosities of accretion flows. Since $\rho \propto r^{-1/2}$ and $T \propto r^{-1}$, the bremsstrahlung cooling rate per unit volume varies as $q_{br} \propto r^{-3/2}$. Most of the energy losses in convective accretion flows occurs in the outside, whereas most of the energy losses in standard ADAFs takes place in the innermost region. The CDAF solutions terminate at a critical α_c, which depends strongly on the ratio of specific heats so that the greatest possible α tends to zero for a nonrelativistic ideal gas (Narayan et al. 2000). At the critical α_c, the rotation of the flow vanishes and a purely radial inflow appears, which is not only supported by a pressure gradient but also by the viscous braking force.

We note that the important result of outflow model is that a radial density profile can be described as $\rho \propto r^{p-3/2}$. Although the physics is completely different, the density profile can be reduced to the case of CDAFs if $p = 1$. Therefore, when $p = 1$ the ADIOSmodel spectra can mimic those of the CDAF model. This flatter density profile would have important observational implications in common since the X-ray spectrum of accretion flows is sensitive to the variation of the density profile. For flatter density profile, a larger X-ray to radio flux ratio is expected and a harder X-ray spectrum. The X-ray spectrum is dominated by bremsstrahlung process. Several low-luminosity nearby AGNs seem to show this characteristics (di Matteo et al. 2000).

We show that the ADAF with a strong outflow is practically indistinguishable with the ADAF with convection in the sense that two models result in flatter density profiles. We find that not only the viscosity parameter α in the flows but also wind parameter p in the wind model, if any outflows are present and if it is a proper parameter for outflows, is an important physical parameter to govern the structure of the flows. Currently available X-ray observation cannot tell a CDAF model from an ADIOS model. However, it is not impossible that two model can be distinguished. One possible difference could be an absolute value of the X-ray flux provided that the mass of the accretor is known, or in other words, the energy spectrum in broad energy bands is obtained. Even if the slope of the density profile is same, in CDAFs it is due to the mass transferred from inner regions to outer regions so that the value of the density at larger radii is large than one in ADIOSs in which the flatter slope is due to reductions of matter inside the flows by winds. That is, the density of outer part is higher in CDAFs than in ADIOSs and consequently the higher X-ray flux results in CDAFs (for the model spectra of ADIOS and CDAF, see Quataert & Narayan 1999, Ball et al. 2000). In this sense X-ray observations provide a boundary condition for a model of the accretion flows. The deficiency of X-ray flux can be another criteria to distinguish models in addition to the linear poraization measurements (Agol 2000, Quataert & Gruzinov 2000b).

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