THE INFLUENCES OF OUTFLOW ON THE DYNAMICS OF INFLOW

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ABSTRACT

Both numerical simulations and observations indicate that in an advection-dominated accretion flow most of the accretion material supplied at the outer boundary will not reach the inner boundary. Rather, it is lost via outflow. Previously, the influence of outflow on the dynamics of inflow had been taken into account only by adopting a radius-dependent mass accretion rate \( \dot{M} = \dot{M}_0(r/r_{\text{out}})^s \) with \( s > 0 \). In this paper, based on a one-and-a-half-dimensional description of the accretion flow, we investigate this problem in more detail by considering the interchange of mass, radial and azimuthal momentum, and the energy between the outflow and inflow. The physical quantities of the outflow are parameterized based on our current understandings of the properties of outflow mainly from numerical simulations of accretion flows. Our results indicate that under reasonable assumptions about the properties of outflow, the main influence of outflow has been properly included by adopting \( \dot{M} = \dot{M}_0(r/r_{\text{out}})^s \).

Subject headings: accretion, accretion disks — black hole physics — hydrodynamics — ISM: jets and outflows

1. INTRODUCTION

There is now strong observational evidence for the existence of outflow in the accretion flow system. One of the best examples comes from Sgr A*, the supermassive black hole located at our Galactic center. The accretion flow in this source is likely to be in the form of the advection-dominated accretion flow (ADAF, or radiatively inefficient accretion flow; Yuan et al. 2003). From the observational results from Chandra combined with the Bondi accretion theory we can calculate the value of the mass accretion rate at the outer boundary—the Bondi radius. Radio polarization observations constrain the accretion rate at the innermost region of the accretion flow nearly 2 orders of magnitude lower than that determined at the Bondi radius (e.g., Marrone et al. 2006). This implies that about 99% of the material available at the Bondi radius will not finally enter into the black hole horizon, rather, it must be lost in the form of outflow. Outflow seems to exist also in more luminous sources whose accretion mode is different from the ADAF. For example, the blueshifted absorption lines, which indicate the existence of outflowing materials, have been detected in the X-ray spectrum of some Seyfert 1 sources (e.g., NGC 3783; Kaspi et al. 2001) and more spectacularly in quasars (e.g., PG 1115+80; Chartas et al. 2003). The existence of outflow has been paid more and more attention recently in the field of galaxy formation because of its feedback effect in the coevolution of galaxies and the central active galactic nuclei (e.g., Silk & Rees 1998; Granato et al. 2004; Springel et al. 2005).

Much work has been done on the origin and dynamics of outflow (e.g., Xu & Chen 1997; Blandford & Begelman 2004; Xue & Wang 2005) in the frame of a self-similar hydrodynamical solution. Magnetic field, especially its poloidal component, may presumably serve as the most promising mechanism on producing outflow, as proposed by, e.g., Blandford & Payne (1982). This has been confirmed in nonradiative magnetohydrodynamical (MHD) numerical simulations of accretion flows (e.g., Stone & Pringle 2001; Igumenshchev et al. 2003; Vlahakis & Königl 2003; McKinney 2006). Radiation pressure could be another important mechanism in luminous accretion disks (Proga 2003). But even in the absence of magnetic field and strong radiation, outflow is likely present in ADAFs. This was first proposed from an analytical argument that the Bernoulli parameter of an ADAF is large or even positive because of the small radiative energy loss. This implies that the gas is inclined to escape once it is perturbed (Narayan & Yi 1994; Blandford & Begelman 1999). This suggestion was later confirmed through numerical simulation by Stone et al. (1999).

Since the outflow is likely very strong (Misra & Taam 2001), it may provide an additional important sink of angular momentum and energy. So it is important to investigate its dynamical influence on inflow. This problem has been investigated by Kuncic & Bicknell (2007) in the context of the standard thin disk. In this paper we focus on ADAFs. Blandford & Begelman (1999, hereafter BB99) examined this question through a one-dimensional self-similar approach. A phenomenological method was adopted in which they parameterized the rate at which mass, angular momentum, and energy were extracted through outflow, regardless of the mechanism for the formation of outflow.

BB99 give a quite general description, covering a broad kind of outflow, including Poynting flux whose mass flux is zero while its energy flux is not. It is based on a self-similar assumption. For the purpose of application and comparison with observation, however, we need to discuss it based on global solutions, because a self-similar solution is too simplified to be used to calculate the emitted spectrum. Quataert & Narayan (1999) presented the first effort on this aspect. They calculate the global solution of inflow when strong outflow is present by using a radius-dependent mass accretion rate, \( \dot{M} \propto r^s \), while keeping all other equations describing inflow such as the momentum and energy equations unchanged. This is roughly equivalent to assuming that the specific angular momentum and energy of the outflow are identical to the inflow at the same radius where outflow is launched (see, e.g., eqs. [1]–[5]). This approach is subsequently adopted in almost all following works (e.g., Yuan et al. 2003). In this paper we refer to this treatment as the standard treatment.

While the approximation of Quataert & Narayan (1999; see also Yuan et al. 2003) may capture the most important influence of outflow on inflow, it is not obvious in what degree we can use this approximation or how good this approximation is when we compare the theoretical prediction, such as the spectrum, to
observations. This is the aim of the present paper. More specifically, by considering the conservations of fluxes of mass, momentum, and energy of the combined inflow/outflow system, we focus on the influence of outflow on the dynamics of inflow. We use a “one-and-a-half-dimensional” description of the accretion flow, which means the height-integrated equations are used instead of a fully two-dimensional description, but the conservation equations take into account the outflow in the vertical direction as well. The paper is organized as follows. In §2 we present basic equations for our model and discuss the main properties of outflow. The calculation results are presented in §3. The last section is devoted to a summary.

2. ACCRETION MODEL WITH OUTFLOW

2.1. Basic Equations

We adopt a cylinder coordinate system \((r, \phi, z)\) to describe a steady axisymmetric \((\partial/\partial t = \partial/\partial \phi = 0)\) accretion flow. The Paczyński & Wiita potential (Paczyński & Wiita 1980) \(\psi = -GM_{BH}/(r - r_g)\) is adopted to mimic the geometry of a Schwarzschild black hole, where \(M_{BH}\) is the mass of the black hole and \(r_g \equiv 2GM_{BH}/c^2\) is the Schwarzschild radius of the black hole. As shown in Figure 1, we divide the whole accretion flow at each radius into two parts, i.e., inflow and outflow. For the inflow, we assume a hydrostatic balance in the vertical direction \((e_z = 0\) for the inflow) and assume all quantities such as the radial and azimuthal velocities \((v_r\) and \(v_\phi\)), ion and electron temperatures \((T_i\) and \(T_e\)), and the sound speed \((c_s)\) are only functions of radius \(r\). Such an isothermal assumption in the vertical direction results in a density distribution \(\rho(r, z) = \rho(r, 0) e^{(-z^2/2H^2)}\) in the inflow, where \(H = c_s/\Omega_k\) is the vertical scale height of the inflow.4 We set \(z = H\) as the surface from which an outflow launches. The vertical gradients of the above quantities are absorbed by their discontinuity between the inflow and outflow at this surface, except that the density distribution is continuous and the density of outflow at \(z = H\) is then \(e^{-1/2}\rho(r, 0)\). Note that the vertical velocity of the outflow \(v_{z,w}\) will “compress” the inflow because of momentum conservation; thus, the vertical scale height may be smaller. We neglect this effect here.

From compressible Navier-Stokes equations, we can write the equations of the conservations of mass, momentum, and energy for the inflow as follows (see the Appendix for details),

\[
\frac{dM(r)}{dr} = \eta_1 4\pi r \rho v_{z,w},
\]

\[
v_r \frac{dv_r}{dr} + \eta_1 v_r w - \frac{v_r}{H} = r(\Omega^2 - \Omega_k^2) - \frac{1}{\rho} \frac{dP}{dr} - \frac{1}{2} \frac{dc_s^2}{dr},
\]

\[
\rho v_r \frac{dv_r}{dr} \left( r^2 \Omega \right) + \eta_1 \rho v_r w - \frac{v_r}{H} = \frac{d}{dr} (r^2 H \tau_{\phi r}),
\]

\[
\rho v_r \frac{d\epsilon_v}{dr} - \frac{p_r}{\rho^2} \frac{dp_r}{dr} + \eta_1 \rho v_r w \frac{\epsilon_{\phi,w} - \epsilon_v}{H} = \delta q^r + q_{\epsilon_v} - q^r,
\]

\[
\rho v_r \frac{d\epsilon_\phi}{dr} - \frac{p_\phi}{\rho^2} \frac{dp_\phi}{dr} + \eta_1 \rho v_r w \frac{\epsilon_{\phi,w} - \epsilon_\phi}{H} = (1 - \delta) q^r - q_{\epsilon_\phi}.
\]

Here, all quantities have their usual meanings. The specific internal energy of electrons and ions are \(\epsilon_e\) and \(\epsilon_i\), respectively. The pressure \(P\) is the sum of the gas and magnetic pressures \(P = P_{gas} + P_{mag}\). The inflow’s accretion rate is defined as \(\dot{M}(r) = -4\pi r \rho v_r H\), and \(\eta_1 = \rho v_r / \bar{p}\) is the density ratio of outflow to inflow (Appendix). The parameter \(\delta\) describes the fraction of the turbulent energy dissipation rate \(q^{\prime} (\equiv \tau_{\phi r} r dV/dr)\) that heats electrons directly. Energy transfers from ions to electrons through Coulomb collisions at a volume rate \(q_{\epsilon_e}\), and radiative cooling rate is denoted by \(q^r\). The quantities with subscript \(w\) denote the quantities of wind/outflow just away from the launching surface \(z = H\). We take the \(\alpha\) viscosity description for the stress tensor \(\tau_{\phi r}\) (Shakura & Sunyaev 1973),

\[
\tau_{\phi r} = -\alpha P,
\]

where \(\alpha\) is the dimensionless viscosity parameter. Other stress tensor components are neglected for simplicity, except that the \(\phi z\)-component is considered by taking into account the angular momentum exchange between inflow and outflow at \(z = H\).

Obviously, it is impossible to directly solve equations (1)–(5). We therefore introduce the following parameters “\(\xi\)” to evaluate the radial, azimuthal, and vertical velocities and the ion and electron temperatures of outflow in terms of inflow,

\[
v_{r,w} = \xi_r v_{\phi f},
\]

\[
v_{\phi,w} = \xi_\phi v_{\phi f},
\]

\[
v_{z,w} = \xi_z c_t,
\]

\[
T_{i,w} = \xi_T T_i,
\]

\[
T_{e,w} = \xi_T c_t,
\]

where \(v_{\phi f}\) is the free-fall velocity, and \(v_{\phi f}\) and \(c_t\) are the azimuthal velocity and the sound speed of the inflow, respectively. We assume that these parameters are independent of radius. While this assumption is simple, we think it can capture the main physics of the influence of outflow in a reasonable way. Specifically, this simple assumption does not mean all quantities are a power-law function of radius as the usual “power-law” assumption of the mass flux of inflow. If we know the values of these parameters, we will be able to get the global solution of equations (1)–(5).
2.2. Outflow’s Properties

We now estimate the properties of outflow. Generally, all these quantities should be a function of $z$. Here, we consider the properties of outflow when it is just launched or detached from inflow. All its subsequent evolution should be due to outflow itself and does not affect the inflow any longer.

The first quantity is the strength of the outflow, or the mass-loss rate. BB99 assume $M \propto r^3$ with $0 < s < 1$. This ensures that the mass accretion rate decreases, while the released energy increases with accretion (BB99). The strength of outflow in our notation is mainly governed by $\xi_0$. The above range corresponds to $0 < \xi_0 < -v_e/\eta_1 c_s \approx 0.2$ [eq. (12), but note $s(r)$ now is a function of $r$].

We next consider the value of $\xi_0$. The vertical distribution of the angular momentum of the accretion flow is complicated. Two-dimensional self-similar analysis on ADAF based on hydrodynamics shows that the specific angular momentum of outflow is lower than that of inflow (Narayan & Yi 1995; Xu & Chen 1997; Blandford & Begelman 2004). This result is confirmed later by numerical simulations (e.g., Stone et al. 1999). However, any magnetic coupling between inflow and outflow will likely lead to transportation of angular momentum from the former to the latter (Spruit 1996; Stone & Pringle 2001; BB99; Blandford & Begelman 2004). Therefore, in this paper we explore $\xi_0$ in a range around unity, $0.8 < \xi_0 < 1.2$.

Hydrodynamical and MHD simulations also reveal that the specific internal energy or the temperature of the gas increases from the equator to higher altitudes (e.g., Stone et al. 1999; De Villiers et al. 2005; Beckwith et al. 2008). One underlying reason may be that the gas with higher internal energy may escape more easily. We therefore consider $\xi_T = 1.5$, 1.15, and $\xi_T = 1.15$.

The radial velocity of outflow when they are just launched is highly uncertain, although we somehow know how they will be accelerated later. But we speculate that it should be positive and should not be larger than a fraction of the local Keplerian or free-fall velocity $v_T$. Fortunately, although it may be important for the dynamics of outflow itself, we find that the value of $\xi_v$ has a minor effect on the inflow. We simply set $\xi_v \equiv 0.2$ in our calculations.

3. RESULTS

For our specific model, we adopt the black hole mass $M_{BH} \equiv 4.0 \times 10^6 M_\odot$, and the accretion rate at the outer boundary $\dot{M}_{out} = 10^4 r_\odot$, is $\dot{M} = 1.3 \times 10^{-3} M_{\odot} / \text{edd}$, where $M_{\text{edd}} = 10 L_{\text{edd}} / c^2$ is the Eddington accretion rate. The values for other parameters are $\alpha = 0.1, \beta \equiv P_{\text{gas}} / P_{\text{total}} = 0.9$, and $\delta = 0.3$. These parameters are close to those in Yuan et al. (2003) for modeling the supermassive black hole in our Galactic center. There, they assume $M \propto r^5$ with $s = 0.27$ being a constant. Under our notation, we have

$$s(r) = \frac{d \ln \dot{M}(r)}{d \ln r} = \frac{v_K}{c_s} \left( \frac{v_T}{v'} \right)$$

where $v_K$ is the Keplerian velocity. We would like to note that $s(r)$ now is not a constant as in Yuan et al. (2003; or Quataert & Narayan 1999). The slope of $\dot{M}(r)$ now is steeper at large radius while flatter at small radius because of the quicker increase of $v_r$ compared to $v_K$. This is shown in Figure 2, where we adjust the parameter $\xi_v$ so that the accretion rates at $r_{out}$ and the horizon are the same as those for the case of $M \propto r^8$ with $s = 0.48$.

We first investigate the effect of $\xi_v$. Figure 3 shows the effects of various $\xi_v$ on inflow, with other outflow parameters fixed at $\xi_0 = \xi_T = 1.0$ and $v_{\text{sw}} = v_T$. The four plots show the Mach number, profiles of density, temperature, and specific angular momentum. The dotted, dashed, and long-dashed lines correspond to $\xi_v = 0.01, 0.05$, and 0.15, respectively. As the outflow becomes stronger ($\xi_v$ increases), the gas density decreases while the ion temperature decreases. This is very similar to the case of the standard treatment (with increasing $s$). The decrease of ion temperature is because when more and more accretion material is lost via the outflow, the density profile becomes flatter; thus, the compression work which is an important heating mechanism for ions becomes weaker. Different from the ions, the electron temperature has no obvious relation to the strength of the outflow. This is because, unlike the ions, the compression work in the electron energy equation is about 1 order of magnitude smaller due to the lower electron temperature (eq. [4]).

We mentioned above that the value of the radial velocity of outflow, or equivalently $\xi_v$, has a minor effect on the dynamics of inflow. The “kick back” force due to the discrepancy of the radial velocity between the inflow and outflow is manifested by the second term in equation (2). Since $v_{\text{sw}} = \xi_v c_s, H = c_s / \Omega_K$, and $v_r \sim \alpha v_K$, this term is roughly $\alpha \xi_z (\approx 1)$ times the gravitational force and, thus, can be neglected. So we simply fix $\xi_v = 0.2$ in this paper.

We now check how good the standard treatment is. For this purpose, we first get the global solution with the standard treatment with $M = 2 \times 10^{-8} (r/r_{out})^{0.25}$. We then get the global solution of equations (1)–(5) for various sets of outflow parameters, $\xi_0 = 0.8, 1.0$, and $1.2$, $\xi_T = 1.0$ (referred to as case A) and $1.5$ (referred to as case B), and $\xi_T = 1.5$. For each set of these parameters, we adjust the value of $\xi_z$ so that the mass accretion rates at $r_{out}$ and the black hole horizon are equal to the values in the above standard treatment. By doing this, we want to focus on the influence on inflow of the transportation of angular momentum and internal energy between inflow and outflow, which is neglected in the standard treatment. Note the profile of accretion rate in this case is similar to Figure 2.

Figure 4 shows the comparison of case A with the standard treatment. We can see that our models tend to have lower densities compared to the standard treatment, although the accretion rates at the outer and inner boundaries are the same. We can easily...
understand this by looking at the bottom left panel of Figure 4. Our solutions have higher ion temperatures and lower electron temperatures at the inner region of the inflow. The higher ion temperatures are because the density profile in the inner region is steeper; thus, the compression heating is stronger. The lower electron temperature is because $\xi_T = 1.5 > 1$, which implies that some internal energy is transferred into the outflow from the inflow (eq. [4]).

Figure 5 shows the dynamical influences of outflow for case B. Compared to case A, the ion temperatures are lower. This is obviously because $\xi_T$ is larger, $\xi_T = 1.5$, so some internal energy is transferred from inflow to outflow. The lower ion temperatures result in a smaller $H$. This, combined with the smaller radial velocity, makes the density of inflow higher compared to case A and almost identical to that of the standard treatment, as shown in the figure. We also see from the figure that both the value of the specific angular momentum and its slope are higher compared to the standard treatment. This results in a stronger viscous heating, which somehow cancels the effect of $\xi_T = 1.5 > 1$. This is why the electron temperatures are roughly the same with the standard treatment while higher than those of case A.

From Figures 3–5, we find that within the range of the values of parameters we adopt to describe the outflow, the strength of the outflow has the most significant influence on the dynamics of
the inflow (i.e., Fig. 3). The influences of all other properties of outflow, namely, the angular momentum, temperature, and radial velocity, are much smaller (Figs. 4 and 5). This is the reason why the discrepancy between our model (with different properties of outflow) and the standard treatment, which only considers the strength of outflow but assumes the properties of the outflow are the same as the inflow, is small.

4. SUMMARY

Outflow is now believed to be very significant in advection-dominated accretion flow; thus, it is important to investigate its influence on the dynamics of inflow. Previously, this was done by using a rather simple method. In the “standard treatment,” the only change compared to the case of no outflow is that the mass accretion rate is not a constant, but a power-law function of radius, \( \dot{M} \propto r^s \) (\( s > 0 \)). All other equations describing the accretion flow remain unchanged (e.g., Quataert & Narayan 1999; Yuan et al. 2003).

In this paper we investigate the influence of outflow in more detail to check how good the above “standard treatment” is. We have derived the height-integrated accretion equations, including the coupling between the inflow and outflow, to investigate...
the influence of outflow on the dynamics of inflow. We assume hydrostatic equilibrium for the inflow. For the outflow, we assume it is launched just above the surface of the inflow. We parameterize and estimate the quantities of outflow in terms of the quantities of inflow mainly from the results of numerical simulations. In this way, we reduce the number of unknown quantities in the above inflow/outflow equations; thus, we are able to get their global solution.

We have studied the influences on the dynamics of inflow of the strength (via vertical velocity), the (ion and electron) temperature, specific angular momentum, and the radial velocity of the outflow. We find that among them the strength of the outflow is the most important quantity. It can produce orders of magnitude difference for the density of inflow. If the strength of outflow is fixed, all other quantities of outflow can only produce a difference for the density and temperature within a factor of ~2, if our estimations of the properties of outflow are correct. Therefore, the "standard treatment" is usually a good approximation.

The largest uncertainty in our model comes from the estimations of the properties of outflow, such as their temperature, specific angular momentum, and azimuthal and radial velocities. We estimate these values from numerical simulations to accretion flows which is still not exact. With the rapid development of numerical simulations, our results will be significantly improved. Especially, if the properties of outflow are found to be far more deviated from the inflow than those adopted in the present paper (e.g., $\xi_{Te} > 1$),

![Fig. 5. Same as Fig. 4 (case A), but for $\xi_{Te} = 1.5$.](image-url)
the standard treatment will not be enough, although we believe that our conclusion that the strength of outflow is the most influential quantity should remain correct. In that case, the influence of the other properties of outflow must be taken into account as well.

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APPENDIX
THE HEIGHT-INTEGRATED EQUATIONS DESCRIBING INFLOW/OUTFLOW

For a steady axisymmetric accretion flow, the equation of mass conservation is
\[
\frac{1}{r} \frac{\partial}{\partial r} \left( r \rho v_r \right) + \frac{\partial (\rho v_\phi)}{\partial z} = 0. \tag{A1}
\]
Defining the mass accretion rate \( \dot{M} \equiv -4\pi \rho v_r H \), we integrate equation (A1) in \( z \) from 0 to \( H^+ \), where \( H^+ \) denotes just above the surface \( z = H \) where the outflow is launched. Noting \( v_z = 0 \) for inflow and \( v_z = v_{z,w} \) for outflow at \( H^+ \), we get
\[
\frac{d\dot{M}}{dr} = \eta_1 4\pi \rho v_{z,w}, \tag{A2}
\]
where
\[
\eta_1 = \frac{\rho_w}{\rho} = \frac{e^{-1/2} \rho(r,0)}{(1/H) \int_0^H \rho(r,0) \exp[-z^2/(2H^2)] dz} = 0.7089, \tag{A3}
\]
which gives the ratio of the density of outflow and height-averaged inflow.

The radial and azimuthal momentum equations read as follows,
\[
\rho \left( \frac{\partial v_r}{\partial r} - \frac{v_r^2}{r} + v_z \frac{\partial v_r}{\partial z} \right) = -\frac{\partial P}{\partial r} + \rho g_r, \tag{A4}
\]
\[
\rho \left( \frac{\partial v_\phi}{\partial r} + \frac{v_r v_\phi}{r} + v_z \frac{\partial v_\phi}{\partial z} \right) = \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \rho v_\phi \right), \tag{A5}
\]
where \( g_r \) is the radial component of the gravitational force. The energy equation is
\[
\rho T \frac{ds}{dt} \equiv \rho \left[ \frac{dU}{dt} - \left( \frac{P}{\rho^2} \right) \frac{d\rho}{dt} \right] = q^+ - q^-, \tag{A6}
\]
which for steady flow reduces to
\[
\rho \left( \frac{v_z}{\rho} \frac{\partial U}{\partial r} - \frac{P}{\rho^2} \frac{\partial \rho}{\partial r} \right) + \frac{v_z}{\rho} \left( \frac{\partial U}{\partial z} - \frac{P}{\rho^2} \frac{\partial \rho}{\partial z} \right) = q^+ - q^- \tag{A7}
\]
We integrate the above equations (A4)–(A7) for \( z \) from 0 to \( H^+ \) using the following general result,
\[
\int_0^{H^+} f v_z \frac{\partial q}{\partial z} dz = f v_{z,w} (g_{w} - g_{z=H}), \tag{A8}
\]
where \( f \) and \( g \) are functions of \( (r, z) \). Note that if \( g(r, z) \) is continuous at \( z = H \) (e.g., density \( \rho \)), the right-hand side of equation (A8) is equal to 0. Then we get equations (2)–(5).

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