DYNAMICS OF ROTATING ACCRETION FLOWS IRRADIATED BY A QUASAR

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ABSTRACT

We study the axisymmetric, time-dependent hydrodynamics of rotating flows that are under the influence of supermassive black hole gravity and radiation from an accretion disk surrounding the black hole (BH). This work is an extension of the earlier work presented by Proga, in which nonrotating flows were studied. Here, we consider effects of rotation, a position-dependent radiation temperature, density at large radii, and uniform X-ray background radiation. As in the nonrotating case, the rotating flow settles into a configuration with two components, (1) an equatorial inflow and (2) a bipolar inflow/outflow with the outflow leaving the system along the pole. However, with rotation the flow does not always reach a steady state. In addition, rotation reduces the outflow collimation and the outward flux of mass and kinetic energy. Moreover, rotation increases the outward flux of the thermal energy and can lead to fragmentation and time variability of the outflow. We also show that a position-dependent radiation temperature can significantly change the flow solution. In particular, the inflow in the equatorial region can be replaced by a thermally driven outflow. Generally, as has been discussed and shown in the past, we find that self-consistently determined preheating/cooling from the quasar radiation can significantly reduce the rate at which the central BH is fed with matter. However, our results also emphasize a little-appreciated feature. Namely, quasar radiation drives a nonspherical, multitemperature, and very dynamic flow. These effects become dominant for luminosities in excess of 0.01 of the Eddington luminosity.

Subject headings: accretion, accretion disks — galaxies: active — galaxies: nuclei — methods: numerical — quasars: general

1. INTRODUCTION

The key property of active galactic nuclei (AGNs) is that they emit an enormous amount of electromagnetic radiation over a very broad energy range. The central location of AGNs in their host galaxies implies that AGN radiation can play a very important role in determining the ionization structure and dynamics of matter not only near the AGN but also on galactic and even intergalactic scales (Ciotti & Ostriker 1997, 2001, 2007; Silk & Rees 1998; King 2003; Murray et al. 2005; Sazonov et al. 2005; Springel et al. 2005; Hopkins et al. 2005; Wang et al. 2006; Fabian et al. 2006; Thacker et al. 2006, and references therein). In the first paper of this series (Proga 2007, hereafter Paper I), we reported on results from the first phase of our gas dynamics studies of AGNs on subparsec and parsec scales. This is a complex problem, as it involves many aspects of physics such as multidimensional fluid dynamics, radiative processes, and magnetic processes. Therefore, our approach was to set up simulations as simply as possible and to start by exploring the effects of X-ray heating (which is important in the so-called preheated accretion; e.g., Ostriker et al. 1976; Park & Ostriker 2001, 2007) and radiation pressure on gas that is gravitationally captured by a black hole (BH). We adopted the numerical methods developed by Proga et al. (2000, hereafter PSK00) for studying radiation-driven disk winds in AGNs. Generally, our simulations cover a relatively unexplored range of the distance from the central BH; we end where models of galaxies begin (e.g., Ciotti & Ostriker 2007; Springel et al. 2005), and we begin where models of BH accretion end (e.g., Hawley & Balbus 2002; Ohsuga 2007).

In Paper I, we presented results from axisymmetric time-dependent hydrodynamical (HD) calculations of gas flows. The flows were nonrotating and exposed to quasar radiation. We took into account X-ray heating and the radiation force due to electron scattering and spectral lines. To compute the radiation field, we considered an optically thick, geometrically thin, standard accretion disk as a source of UV photons and a spherical central object as a source of X-rays (a corona). The gas temperature, $T$, and ionization state in the flow were calculated self-consistently from the photoionization and heating rate of the central object.

We found that for a $10^8 M_\odot$ black hole with an accretion luminosity of 0.6 of the Eddington luminosity, the flow settles into a steady state and has two components: (1) an equatorial inflow and (2) a bipolar inflow/outflow with the outflow leaving the system along the rotational axis of the disk. The inflow is a realization of a Bondi-like accretion flow. The second component is an example of a nonradial accretion flow that becomes an outflow once it is pushed close to the rotational axis, where the radiation pressure accelerates it outward. In some cases, the outflow is heated by radiation so that it can also be accelerated by thermal expansion. Our main result was that the existence of the two above-mentioned flow components is robust to the outer boundary conditions, the geometry, and the spectral energy distribution of the radiation field. However, the flow properties are not robust. In particular, the outflow power and collimation is higher for the radiation dominated by the UV/disk emission than for the radiation dominated by the X-ray/central engine emission. Our most intriguing result was that a very narrow outflow driven by radiation pressure on lines can carry more energy and mass than a broad outflow driven by thermal expansion.

Here, we report on results from simulations that are basically run-offs of those presented in Paper I, but with the inclusion of gas rotation. Our goal is to assess how rotation changes the flow solution. In particular, we study how rotation changes the flow pattern, mass and energy fluxes, and temporal behavior. We also present results from a new set of simulations that illustrate how complex and dynamic the flow evolution can be, even for relatively
simple initial and boundary conditions. We describe our calculations in §2 and present our results in §3. The paper ends in §4, with discussion and our conclusions.

2. METHOD

In this paper, we extend the work presented in Paper I by relaxing some assumptions and simplifications. Our numerical HD calculations are in most respects as described by Paper I. Here we only describe the key elements of the calculations and list the changes we made. We refer the reader to Paper I and PSK00 for details.

We consider an axisymmetric HD flow accreting onto a supermassive black hole (SMBH). The flow is nonspherical because it is irradiated by an accretion disk. The disk radiation flux, $F_{\text{disk}}$, is highest along the disk rotational axis and gradually decreases with increasing polar angle, $\theta$: $F_{\text{disk}} \propto |\cos \theta|$. The flow is also irradiated by a corona. We account for some effects of photoionization. In particular, we calculate the gas temperature assuming that the gas is optically thin to its own cooling radiation. We include the following radiative processes: Compton heating/cooling, X-ray photoionization heating and recombination, bremsstrahlung, and line cooling. We also take into account some effects of photoionization on radiation pressure due to lines (line force). Namely, we compute the line force using the value of the photoionization parameter, $\xi$, and the analytical formulae of Stevens & Kallman (1990). This procedure is computationally efficient and gives good estimates for the number and opacity distribution of spectral lines for a given $\xi$ without detailed information about the ionization state (see Stevens & Kallman 1990). In addition, we take into account the attenuation of the X-ray radiation by computing the X-ray optical depth in the radial direction. To be consistent with our gas heating rates, for which we include X-ray photoionization but not UV photoionization, we do not account for attenuation of the UV radiation.

We assume that the total accretion luminosity, $L$, has two components, $L_{\text{disk}} = f_{\text{disk}}L$ due to the accretion disk, and $L_s = f_sL$ due to the corona. For simplicity, we assume that the disk emits only UV photons, whereas the corona emits only X-rays, i.e., the system UV luminosity, $L_{\text{UV}} = f_{\text{UV}}L = L_{\text{disk}}$, and the system X-ray luminosity, $L_X = f_sL = L_s$ (in other words $f_{\text{UV}} = f_{\text{disk}}$ and $f_s = f_s$).

With the above simplifications, only the corona radiation is responsible for ionizing the flow to a very high ionization state. In our calculations, the corona contributes to the radiation force due to electron scattering but does not contribute to line driving. We note that metal lines in the soft X-ray band may have an appreciable contribution to the total radiation force in some cases. On the other hand, the disk radiation contributes to the radiation force due to both electron and line scattering.

We perform our calculations in spherical polar coordinates $(r, \theta, \phi)$ assuming axial symmetry about the rotational axis of the accretion disk ($\theta = 0^\circ$). Our computational domain is defined to occupy the angular range $0^\circ \leq \theta \leq 90^\circ$ and the radial range $r_i = 500r_s \leq r \leq r_o = 2.5 \times 10^5 r_s$, where $r_s = 3\gamma S_3$ is the inner radius of the disk around a Schwarzschild BH with a mass $M_{\text{BH}}$ and a radius $r_S = 2GM_{\text{BH}}/c^2$. The $r - \theta$ domain is discretized into zones. Our numerical resolution in the $r$-direction consists of 140 zones. We fix the zone size ratio, $dr_{z+1}/dr_z = 1.04$ (i.e., the zone spacing increases with increasing radius). Gridding in this manner ensures good spatial resolution close to the inner boundary, $r_i$. In the $\theta$ direction, our numerical resolution consists of 50 zones. The zone size ratio is always $d\theta_i/d\theta_{i+1} = 1.0$ (i.e., grid points are equally spaced).

For the initial condition in Paper I, we assumed spherical symmetry and set all HD variables to constant values everywhere in the computational domain. Here we will allow the gas to rotate.

2.1. Gas Rotation

In simulations with rotation, we break the spherical symmetry of the initial and boundary conditions by introducing a small, latitude-dependent angular momentum. Namely, for large radii we assume that the specific angular momentum, $l$, depends on the polar angle, $\theta$, as

$$l(\theta) = l_0 f(\theta),$$

where $f = 1$ on the equator ($\theta = 90^\circ$) and monotonically decreases to zero at the poles (at $\theta = 0^\circ$ and $180^\circ$). The initial distribution of the rotational velocity is

$$v_\phi(r, \theta) = \begin{cases} 0 & \text{for } r < 10^5 r_s, \\ 1/r \sin \theta & \text{for } r \geq 10^5 r_s. \end{cases}$$

We express the specific angular momentum on the equator as

$$l_0 = cr_s \sqrt{r_s^3/6},$$

where $r_s$ is the “circularization radius” on the equator in units of $r_s$ for the Newtonian potential (i.e., $GM/r^2 = v_\phi^2/r$ at $r = r_s$).

We adopt two forms for the function $f(\theta)$:

$$f_1(\theta) = \begin{cases} 0 & \text{for } \theta < \theta_o \text{ and } \theta > 180^\circ - \theta_o, \\ l_0 & \text{for } \theta_o \leq \theta \leq 180^\circ - \theta_o, \end{cases}$$

and

$$f_2(\theta) = 1 - |\cos \theta|.$$
the X-ray and UV fluxes can decrease if the X-ray optical depth is high. To test how important these effects are, we allow the X-ray and UV fluxes can decrease if the X-ray optical depth is high. To test how important these effects are, we allow $T_R$ to vary with position.

We introduce the position dependence of $T_R$ in the following way. We start with the standard expression for the net Compton heating rate,

$$ L = n_e \frac{\sigma}{m_e c^2} F (kT_R - 4kT), $$

where $F$ is the radiation flux and $n_e$ is the electron number density (other symbols have their usual meaning).

As mentioned above, we consider two sources of radiation: a disk that emits UV photons with energies between 0 and 50 eV, and a corona that emits photons with energies above 50 eV. Each of these sources has its own mean photon energy, $\langle \varepsilon \rangle$, or equivalently, radiation temperature, $\langle \varepsilon \rangle = kT_R$. The radiation temperature of these two sources can be computed from

$$ kT_{\text{disk}} = \frac{\int_{0}^{50} \nu \mathcal{F}_{\text{disk}, \nu} d\nu}{\int_{0}^{50} \mathcal{F}_{\text{disk}, \nu} d\nu}, $$

and

$$ kT_{X} = \frac{\int_{50}^{\infty} \nu \mathcal{F}_{X, \nu} d\nu}{\int_{50}^{\infty} \mathcal{F}_{X, \nu} d\nu}. $$

We consider these temperatures as additional free parameters. We chose the radiation temperature of the disk to be $2 \times 10^4$ K and of the corona to be $2.9 \times 10^6$ K.

Having set the radiation temperature of the disk and corona radiation, we can compute the radiation temperature of the total radiation field from

$$ T_R(\theta) = T_{\text{UV}} f_X R_T \exp(-\tau_X) + 2 f_{\text{UV}} \cos \theta f_X \exp(-\tau_X) + 2 f_{\text{UV}} \cos \theta, $$

where $R_T = T_{X, \text{max}}/T_{\text{UV}}$. To obtain the expression above, we used the definition of $T_R$ and the formulae for the radiation fluxes from the disk and corona (eqs. [6] and [15] in Paper I). Practically, to account for the position-dependent radiation temperature, we adopt the same formulae for the radiative heating/cooling rates as in Paper I but replace $T_X$ with $T_R$ (see eqs. [19] and [20] in PSK00). The seventh column in Table 1 shows the value of the adopted $T_R$ or its range for cases where we use equation (9).

We finish this section with a note about the gas temperature at the outer radius. This temperature is typically set to the Compton temperature, assuming that the central X-rays heat a gas up to an equilibrium Compton temperature. However, in some of our simulations, the optical depth toward the radiation source or the local density in the flow is so high that radiation cannot heat a gas at large radii to the Compton temperature. In such cases, there is a mismatch between the gas temperature assumed at $r_o$ (i.e., $T_{\theta}$) and that computed for $r$ close to $r_o$.

It is possible that gas at large radii is heated not only by the central source but also by shocks or other sources such as supernovae. To mimic such sources of heating, we introduce a uniform background X-ray radiation, $\mathcal{F}_{X,b}$, in some of our simulations. We illustrate effects of this radiation by showing results of one model (run Crbgd), where we assumed $\mathcal{F}_{X,b} = 1.2 \times 10^7$ erg cm$^{-2}$ s$^{-1}$, for which the gas with relatively low density is Comptonized, e.g., for $\rho = 1 \times 10^{-20}$ g cm$^{-3}$ and $\xi = 2.5 \times 10^4$ (we assume that the $T_R$ of the background radiation is the same as that of the central source, that is, $8 \times 10^7$ K.)

3. RESULTS

As in Paper I, we assume the mass of the nonrotating BH, $M_{\text{BH}} = 10^8 M_{\odot}$, and the disk inner radius, $r_s = 3.8 \times 10^{13}$ cm throughout this paper. We compute the total accretion luminosity as $L = \eta M_{\text{BH}} c^2 = 2 \eta GM_{\text{BH}} M_{\text{in}} / r_s$, where $\eta$ and $M_{\text{in}}$ are the rest-mass conversion efficiency and the mass accretion on the BH, respectively. We assume a relatively high conversion efficiency appropriate for disk accretion onto a nonrotating BH, i.e., $\eta = 0.0833$.

We express the accretion luminosity in units of the Eddington luminosity for the Schwarzschild BH, i.e., $L_{\text{Edd}} = 4\pi c G M_{\text{BH}} / \sigma_t$. We refer to this normalized luminosity as the Eddington number, $\Gamma = L / L_{\text{Edd}} = (\sigma_t M_{\text{in}}) / (8\pi c r_s)$. Table 1 summarizes the properties of models from Paper I (runs A, B, B1, B2, B3, and C) and our new models (the other models listed in the table). Columns (2)–(11) give the input parameters that we varied: the Eddington number $\Gamma$, the disk contribution to the total luminosity $f_{\text{disk}}$, the corona contribution to the total luminosity $f_{\text{cor}}$, the UV contribution to the total luminosity $f_{\text{UV}}$, the X-ray contribution to the total luminosity $f_X$, the radiation temperature $T_R$, the X-ray background radiation flux $\mathcal{F}_{X,b}$, the gas temperature at the outer boundary $T_{\theta}$, the gas density at the outer boundary $\rho_o$, and the circularization radius $r_c$. Columns (12)–(17) give some of the gross properties of the solutions: the mass inflow rate through the outer boundary $M_{\text{in}}(r_o)$, the net mass flux rate through the inner boundary $M_{\text{out}}(r_c)$, the mass outflow rate through the outer boundary $M_{\text{out}}(r_o)$, the maximum outflow velocity at the outer boundary $v_o$, the outflow power carried out through the outer boundary in the form of kinetic energy $P_k(r_o)$, and in the form of thermal energy $P_{th}(r_o)$. Table 1 also explains our convention of labeling our runs. All other model parameters not listed in Table 1 are as in Paper I.

3.1. Effects of Gas Rotation

Simulations without rotation, presented in Paper I, show that an infalling gas collimates an outflowing gas and that the collimation increases with increasing radius. In addition, for a given $\Gamma$, the collimation increases as the ratio between $f_X$ and $f_{\text{UV}}$ decreases. Out of three cases explored in Paper I, case C, which has the smallest $f_{\text{UV}}/f_X$, shows the strongest collimation and the highest efficiency in turning an inflow into an outflow. Figure 1 in Paper I and Figure 1 here show that in run C the gas is siphoned off within a very narrow channel along the pole.

In Paper I, we argued that the collimation, outflow power, and other results will likely change if one allows for significant gas rotation. One would expect the gas to converge toward the equator due to the combination of the centrifugal and gravitational forces. This, in turn, will likely broaden and weaken the outflow in the polar region because less gas will be pushed toward the polar region.

To test the effects of rotation, we rerun models presented in Paper I with rotation. We set $r_c = 300$, i.e., near the maximum value for which the flow will not circularize inside our computational domain. We do not consider higher $r_c$ at the moment because we want to avoid the complexities that will result from the formation of a rotationally supported torus or disk inside the computational domain (e.g., Hawley et al. 1984a, 1984b; Clarke et al. 1985; Hawley 1986; Molteni et al. 1994; Ryu et al. 1995; Chen et al. 1997; Toropin et al. 1999; Kryukov et al. 2000; Igumenshchev & Narayan 2002; Proga & Begelman 2003; Chakrabarti et al. 2004, and references therein). In these exploratory simulations, our choice...
TABLE 1
Summary of Results

| Run   | $\Gamma$ | $f_{\text{disk}}$ | $f_r$ | $f_{\text{UV}}$ | $T_R$ | $F_X$ | $T_e$ | $\rho_0$ | $r_e'$ | $M_{\text{in}}(r_e)$ | $M_{\text{tot}}(r_e)$ | $M_{\text{out}}(r_e)$ | $v_r$ | $P_{\text{t}}(r_e)$ | $P_{\text{d}}(r_e)$ |
|-------|---------|-----------------|------|---------------|------|------|------|--------|-------|-------------------|-------------------|-------------------|------|----------------|----------------|
| A..... | 0.6     | 0.5             | 0.5  | 0.5           | 4    | 0    | 1    | 1      | 1     | 0                | -4                | -1                | 3    | 700             | 4               |
| AX.....| 0.6     | 0.5             | 0.5  | 0.5           | 4.8-14.5 | 0    | 1    | 1      | 1     | 0               | -0.8              | -0.1 | 0.7             | 400             | 0.1             | 2    |
| B..... | 0.6     | 0.8             | 0.2  | 0.8           | 0.2   | 4    | 0    | 1      | 1     | 0               | -8                | -3               | 5               | 4000            | 100             | 0.8 |
| BR.....| 0.6     | 0.8             | 0.2  | 0.8           | 0.2   | 4    | 1/10 | 1      | 1     | 0               | -0.5              | -0.09 | 0.41            | 1500            | 0.5             | 0.8 |
| B1.....| 0.6     | 0.8             | 0.2  | 0.8           | 0.2   | 4    | 1/3  | 1      | 1     | 0               | -2                | -0.4 | 1.6             | 1700            | 2               | 2    |
| B3.....| 0.6     | 0.8             | 0.2  | 0.8           | 0.2   | 4    | 3    | 1      | 1     | 0               | -9                | -5               | 4               | 400             | 3               | 0.8 |
| C..... | 0.6     | 0.95            | 0.05 | 0.95          | 0.05  | 4    | 0    | 1      | 1     | 0               | -9                | -1              | 8               | 6700            | 700             | 0.03 |
| CR.....| 0.6     | 0.95            | 0.05 | 0.95          | 0.05  | 4    | 0    | 1      | 1     | 1               | 300               | -10             | -8              | 3               | 600             | 3               | 0.2 |
| Cr.....| 0.6     | 0.95            | 0.05 | 0.95          | 0.05  | 4    | 0    | 1      | 1     | 1               | 300               | -10             | -4              | 6               | 1000            | 10              | 0.2 |
| Cx.....| 0.6     | 0.95            | 0.05 | 0.95          | 0.05  | 0.3-14.5 | 0    | 1      | 1     | 0               | -11               | -0.15 | 10.85           | 7000            | 300             | 0.03 |
| Crx.....| 0.6    | 0.95           | 0.05 | 0.95          | 0.05  | 0.3-14.5 | 0    | 1      | 1     | 1               | 300               | -11             | -2              | 3               | 500             | 10              | 0.01 |
| Crgd.....| 0.9   | 0.95           | 0.05 | 0.95          | 0.05  | 4    | 0    | 10     | 10    | 300             | -115              | -5              | 110             | 2500            | 1000            | 10 |
| Crgd.....| 0.9 | 0.95           | 0.05 | 0.95          | 0.05  | 4    | 1.2  | 10     | 10    | 300             | -150             | -120            | 30              | 3700            | 30              | 5   |

Notes.—We use the following convention to label our runs. The first character refers to the values of $f_X$ and $f_{\text{UV}}$: A is for $f_{\text{UV}} = 0.5$ and $f_X = 0.5$, B is for $f_{\text{UV}} = 0.8$ and $f_X = 0.2$, and C is for $f_{\text{UV}} = 0.95$ and $f_X = 0.05$. Runs A, B, and C are the fiducial runs. If the first character is followed by a letter (or letters) or a number, it means that it is the same run, but modified by the introduction of rotation (letter “R” if we use eq. [4] or “r” if we use eq. [5]), the position-dependent $T_R$ (letter “x”), the X-ray background radiation (letter “b”), a higher $\Gamma$ (letter “g”), and a higher $\rho_0$ (letter “d”). The numbers 1, 2, and 3 correspond to $T_R = 1/10, 1/3$, and 3, respectively, in units of $2 \times 10^7$ K.
of high $r'$, yielding low $l$, allows us to first study relatively simple flows and to set a stage for modeling more complex flows with high $l$. We assume that the circularized gas will accrete onto the SMBH on a viscous timescale. However, as we do not model this part of the flow, we do not consider any details of an actual process or processes that leads to the transport of angular momentum. The transport is most likely due to magnetorotational instability (Balbus & Hawley 1991), but a contribution from the photon viscosity can be important in the case of high radiation luminosity.

We note that our choice of low $l$ can be relevant to real QSOs because feeding a SMBH in a QSO with gas of high $l$ can be problematic. Namely, for high $l$, an accretion disk would form at large radii and be self-gravitating (e.g., Paczynski 1978; Shlosman & Begelman 1987). Converting disk material to stars could then starve the SMBH, and the QSO would be quenched (e.g., Goodman 2003). After reviewing a variety of possibilities, Goodman (2003) suggested that QSO disks do not extend beyond a thousand $r_s$, enabling them to be gravitationally stable. If this is correct, the disks must be replenished with gas of small $l$, a scenario we explore here.

Figure 1 presents the results for runs C, CR, and Cr. For run CR, a step function describes the angular distribution of angular momentum on the outer boundary (we set $\theta_0$ to 45°; see eq. [4]). For $45° \leq \theta$, we assume that the specific angular momentum at the outer boundary equals $l_0$, whereas for $\theta < 45°$, we assume that $l = 0$. For run Cr, a smooth function describes $l$ (see eq. [5]). The figure shows the instantaneous density and temperature distributions, and the poloidal velocity field of the models. In addition, it shows the Compton radius corrected for the effects of radiation pressure due to electrons (see eq. [19] in Paper I) and the contours where the Mach number equals 1, $[M \equiv (v_r^2 + v_\theta^2)^{1/2}/c_s = 1$, where $c_s = \gamma P/\rho$ is the speed of sound].

The detailed calculations confirm our general expectations: compared to the nonrotating case, the outflow in the rotating case is less collimated and weaker. As Table 1 shows, in the runs with rotation (runs CR and Cr), the outflow power, $M_{\text{out}}(r_s)$, and $v_r$ are lower than those in the run without rotation (run C; compare also Fig. 4 in Paper I with Figs. 2 and 3 here). Another difference is that in runs CR and Cr, gas does not cool as much as in run C, especially at small radii (i.e., $r' < 1 \times 10^5$). Comparison between runs C, CR, and Cr shows that in run CR the solution is an
intermediate one between runs C and Cr. This is not too surprising, given that the step function is an intermediate distribution between \( f_l = 0 \) and the distribution described by function \( f_l \). In particular, the outflow in run CR is less collimated than in run C and more collimated than in run Cr. One of the new unexpected features that we found in run Cr is that the relatively cold outflow is fragmented and time-variable.

Although the flow in run Cr settles down into a time-averaged steady state, it is not as steady as in run C. An indication of this behavior can be found in Figure 3, which shows three radial mass flow rates as a function of radius, the net rate \( \dot{M}_{\text{net}}(r) \), the inflow rate \( \dot{M}_{\text{in}}(r) \), and the outflow rate \( \dot{M}_{\text{out}}(r) \) (see eqs. [22], [23], and [24] in Paper I for formal definitions). For a perfect steady state, one expects \( \dot{M}_{\text{net}}(r) = \dot{M}_{\text{in}}(r) + \dot{M}_{\text{out}}(r) = \text{const} \) at all radii, as in run C (see Fig. 4 in Paper I). However, in run Cr, the above equation holds only at small radii, \( r' \leq 10^4 \). We note that unlike \( \dot{M}_{\text{out}} \), \( \dot{M}_{\text{in}} \) is a smooth function of radius. Thus, the unsteadiness of the flow appears to be caused by the unsteady behavior of the outflow, especially the outflow at large radii where it can cool down.

We relate the fragmentation and time variability of the outflow to the abrupt turning on of the line force when \( T \) decreases below \( \sim 5 \times 10^4 \) K and its turning off when \( T \) increases again. Figure 1 shows that \( T \) decreases in the regions where the inflow sharply turns into the outflow. The density there increases, and the gas radiatively cools. The turning on of the line force leads to an enhanced acceleration of the outflow, but this alone is not sufficient to fragment the outflow. For example, in runs C and Cr, the cold outflow is not fragmented and is quite steady. Thus, there must be another factor or factors that may contribute to fragmentation and time variability. We note that in run C, the outflow is nearly radial; hence its inner parts shield the outer parts from the central radiation. Consequently, the outflow cannot be heated downstream by the central radiation. However, in run Cr the outflow is not radial, and the flow can be heated up downstream because, as its density decreases during acceleration, it is irradiated by stronger unattenuated X-ray flux. There the outflow orientation with respect to the radiation flux appears to be one of the key factors causing the fragmentation and time variability of the outflow. This conclusion is supported by the fact that even in run Cr, the outflow is not fragmented at large radii, where the outflow becomes almost radial, and where clumps merge with each other.

To show the variable solution in more detail, in Figure 4 we present a sequence of density maps of the inner part of the flow in run Cr at four different times. The left panel shows the flow at a time when a clump breaks from a high-density filament at \( z' \approx 1.5 \times 10^4 r_\star \). Subsequent panels show how this and other clumps move outward and how they are stretched. Figure 4 also shows the formation of a new clump (the second panel from the right). We find that clumps usually form at the same location (i.e., at \( r' \approx 5 \times 10^3 r_\star \) and \( z' \approx 1.5 \times 10^4 r_\star \)) every \( 10^{14} \) s or so, which is on the order of a dynamical timescale at the radius where the clumps form. Generally, despite the time variability, the instantaneous maps shown in Figure 1 are representative of run Cr because they show an example of a large-scale inflow and outflow with continuous production of small-scale clumps that merge at large radii (i.e., beyond \( r' \gtrsim 10^5 \)).

Figures 3 and 4 show that in runs CR and Cr, the outflow power is dominated by the kinetic energy, not the thermal energy. However, the dominance is not as strong compared to run C (see Fig. 4 in Paper I).

We conclude that in case C, rotation reduces the outflow collimation and the outward flux of mass and kinetic energy. Rotation also leads to fragmentation and time variability of the outflow, and an increase of the outward flux of the thermal energy. As expected, rotation does not significantly change the mass inflow rate through the outer boundary.

Figures 5 and 6 show results for case B with and without rotation, i.e., runs B and Br (see also Fig. 3 in Paper I). In this case, rotational effects are almost the same as in case C. The main difference is that in run Br, an outflow does fragment, and the overall flow settles down into a steady state. This is understandable, however: in run Br, radiative heating is strong, and the gas does not cool; therefore, the line force does not turn on.
3.2. Effects of the Position-dependent Radiation Temperature

We return now to case C and consider effects of the position-dependent $T_R$. Figure 7 (left) and Figure 8 show results for run Cx. In comparison with run C, the outflow in run Cx is broader. The mass outflow rate in run Cx is only slightly higher than in run C. However, the outflow rate almost cancels out the inflow rate, so that the net rate is 2 orders of magnitude smaller than the mass flux through the outer boundary. Run Cx is a good example of how AGN irradiation can significantly reduce the rate at which the central engine is fed with matter.

In run Cx, $T_R$ is lower near the poles than near the equator. In addition, $T_R$ near the pole is lower in run Cx than $T_R$ in run C. The latter difference explains why the outflow in run Cx is so strong: the relatively low $T_R$ in the polar region leads to a lower gas temperature in this region. This in turn leads to more mass being pushed toward the pole. This mass can then be effectively turned into an outflow, because in the polar region the radiation flux is sub-Eddington; furthermore, line force turns on there because the gas temperature is low enough. In other words, the siphon effect seen in many of our simulations is very strong in run Cx.

Figure 7 (right) and Figure 9 show results for run Crx, which is a rerun of run Cx, but with rotation added. Comparing these two runs, we find that the effects of rotation in the simulations with the position-dependent $T_R$ are similar to those in the simulations with constant $T_X$. Namely, rotation decreases the degree of the outflow collimation and decreases the outward flux of mass and kinetic energy. In addition, rotation leads to an increase of the outward flux of the thermal energy. In run Crx, the cold outflow is nearly radial and does not fragment as much as in run Cr.

In this paper, we do not present results for case A with rotation because in this case the flow is dominated by thermal effects, and
rotation does not significantly change the solution. However, we present here results for case A with the position-dependent $T_R$ (run Ax) because they show new effects.

Figure 10 compares results for runs A and Ax. In run Ax, the flow pattern is different from that seen in runs presented in Paper I and from the runs presented here so far. The dramatic difference is that in run Ax, the equatorial inflow is replaced by an equatorial outflow. Generally in run Ax there are equatorial and polar outflows that are both fed by an inflow of gas at intermediate polar angles. The equatorial outflow is a simple consequence of the
higher radiation temperature near the equator, which leads to a high gas temperature and an enhanced thermal expansion. In the polar region, where the gas temperature is lower, an outflow is driven by thermal expansion assisted by radiation pressure on electrons.

Overall, the flow pattern in run Ax is dominated by the outflow. This leads to the net mass inflow rate at small radii being 1 order of magnitude lower than the inflow rate at large radii (see Fig. 11).

We conclude that both rotation and position-dependent $T_R$ lead to qualitative and quantitative changes in the flow. Most prominent of these are weaker collimation and fragmentation of the outflow in cases with rotation, and the production of a thermal equatorial outflow in cases with position-dependent $T_R$.

3.3. Complex Case

A realistic model of accretion flows should include many physical effects. Here, we focused on the role of gas rotation and position-dependent $T_R$. We consider our simulations as just exploratory tests. These tests support the notion that AGN radiation can play a very important role in determining the ionization structure and dynamics of matter on subparsec and parsec scales. We finish the presentation of our models with results for two runs Ax.
that illustrate how complex the flow dynamics can be, even in a very simple setup such as the one we focus on here.

One of our motivations is to understand gas dynamics in the broad-line regions (BLRs) and narrow-line regions (NLRs) so characteristic of AGNs. These regions are thought to be made of cold gas clouds that move randomly or nearly randomly and have a small filling factor (e.g., Krolik 1999, and references therein). Formation, evolution, and other key aspects of these clouds are not well understood. Our simulations show that an accretion flow that is initially smooth and spherical can break into inflows and outflows. In cases with rotation, we have seen outflows fragmented due to line force and X-ray irradiation. These results raise the following question: Can we produce many cold clouds with a small filling factor? The answer seems to be “yes,” as we show in Figures 12, 13, and 14.

Figures 12, 13, and 14 compare results for case C with $\Gamma_C = 0.9$ and $\rho_C = 10^{-20}$ g cm$^{-3}$. Figure 12 (left) shows results for run Crgd. The density and temperature distribution, as well as some other properties of this run differ a lot from other runs shown here. The main difference is a much larger dynamical range in the temperature and density, plus the fact that the flow is far from reaching any steady state. However, close inspection of the results from run Crgd shows that the flow pattern is similar to that seen in most other runs: there is an equatorial inflow and a bipolar outflow. The latter is not fragmented because it is radial, in agreement with our explanation of the outflow fragmentation. The large dynamical range in the density and temperature in run Crgd is a simple consequence of the higher density at the outer boundary. A high-density gas can cool much faster than a low-density gas. In this run, the gas is also heated by shocks because for $\Gamma_C = 0.9$, radiation pressure of electrons alone can drive a powerful and broad outflow that collides with an inflowing gas.
As we discussed in § 2.2, an accretion flow at large radii does not have to be heated by the central radiation source. Figure 12 (bottom left) illustrates this point, as one can see that near the equator a good fraction of the inflow is relatively cold. One of the predictions of such a model is that for a wide range of inclination angles, this cold gas should produce absorption lines redshifted with respect to the systemic velocity. However, such lines are not observed.

The problem of large-scale accretion of cold gas can be easily overcome by the introduction of a noncentral source of heating. Figure 12 (right) shows results for run Crbgd, which is a rerun of model Crgd with X-ray background radiation (see § 2.2).

In run Crbgd, there are no large regions of shock-heated gas. The only region where shock heating is important is a narrow polar region of low density. The background radiation heating in this run keeps the gas from undergoing rapid cooling, which in turn can lead to an abrupt turn on of line driving and a strong expulsion of gas, as seen in run Crgd. Comparing runs Cr and Crbgd, we see that an outflow tends to fragment more if the gas density is higher. The density and temperature maps show that the outflow occupies a relatively large fraction of the computational domain. However, Figure 14 shows that this outflow does not significantly change the overall mass budget. As in run Cr, this is caused by rotation that reduces the amount of gas that is pushed toward the polar region, where it can be siphoned off.

4. CONCLUSIONS

We have calculated a series of models for rotating flows that are under the influence of SMBH gravity and radiation from an accretion disk surrounding the BH. We seek to determine self-consistently what fraction of the flow is gravitationally captured by the BH, or what fraction is driven away by thermal expansion and radiation pressure. This work is an extension of the work presented in Paper I, where nonrotating flows were studied. Here, we consider effects of rotation and of a position-dependent radiation temperature, density at large radii, and a uniform X-ray background radiation.

As in the nonrotating case, the rotating flow settles into a configuration with two components: (1) an equatorial inflow and (2) a bipolar inflow/outflow with the outflow leaving the system along the pole. However, the rotating flow does not reach a steady state. In addition, rotation reduces the outflow collimation and the outward flux of mass and kinetic energy. Moreover, rotation increases the outward flux of the thermal energy and can lead to fragmentation and time variability of the outflow. In the future, we plan to check whether thermal instability can contribute to fragmentation and time variability of the outflow. As expected, rotation does not significantly change the mass inflow rate through the outer boundary.

In our model, the radiation comes from a UV-emitting disk and an X-ray-emitting spherical corona. As a result, the radiation temperature is position dependent: in the polar region, radiation is dominated by a softer disk component, whereas near the equator, radiation is dominated by a harder corona component. The two main changes due to this position dependence are (1) an increase in the power of the outflow in the polar region and (2) the development of a large-scale thermally driven outflow in the equatorial region.

Overall, we conclude that our exploratory study provides additional support to the idea that AGN radiation can significantly change gas dynamics and photoionization structure on subparsec and parsec scales. As has been discussed and shown in the past, we found that AGN radiation can significantly reduce the rate at which the central BH is fed with matter (e.g., Figs. 8 and 13).

This result should not depend on the inner radius of the computational domain because most of the outflow is launched from a radius larger than the inner radius. However, we note that when reducing the inner radius of the computational domain, one should also consider additional processes, in particular disk accretion and disk winds and jets. Thus, our mass inflow rate should be viewed only as an upper limit for the BH accretion rate.

Our results also emphasize a little-appreciated feature, i.e., that AGN radiation can drive a nonspherical, multitemperature, and very dynamic flow pattern. This result may have implications for the problem of AGN feedback and the problem of the origin, geometry, and physics of NLRs and BLRs.

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REFERENCES

Allen, S. W., Dunn, R. J. H., Fabian, A. C., Taylor, G. B., & Reynolds, C. S. 2006, MNRAS, 372, 21
Balsara, S. A., & Hawley, J. F. 1991, ApJ, 376, 214
Chakrabarti, S. K., Acharyya, K., & Molteni, D. 2004, A&A, 421, 1
Chen, X., Taam, R. E., Abramowicz, M. A., & Igumenshchev, I. V. 1997, MNRAS, 285, 439
Ciotti, L., & Ostriker, J. P. 1997, ApJ, 487, L105
———. 2001, ApJ, 551, 131
———. 2007, ApJ, 665, 1038
Clarke, D., Karpik, S., & Henriksen, R. N. 1985, ApJS, 58, 81
Fabian, A. C., Celotti, A., & Erlund, M. C. 2006, MNRAS, 373, L16
Goodman, J. 2003, MNRAS, 339, 937
Hawley, J. F. 1986, in IAU Colloq. 89, Radiation Hydrodynamics in Stars and Compact Objects, ed. D. Mihalas & K. H. Winkler (New York: Springer), 369
Hawley, J. F., & Balbus, S. A. 2002, ApJ, 573, 738
Hawley, J. F., Smarr, L. L., & Wilson, J. R. 1984a, ApJ, 277, 296
———. 1984b, ApJS, 55, 211
Hopkins, P. F., Hernquist, L., Cox, T. J., Di Matteo, T., Martini, P., Robertson, B., & Springel, V. 2005, ApJ, 630, 705
Igumenshchev, I. V., & Narayan, R. 2002, ApJ, 566, 137
King, A. 2003, ApJ, 596, L27
Krolik, J. H. 1999, Active Galactic Nuclei: from the Central Black Hole to the Galactic Environment, (Princeton: Princeton Univ. Press)
Kryukov, I. A., Pogorelov, N. V., Bisnovatyi-Kogan, G. S., Anzer, U., & Börner, G. 2000, A&A, 364, 901
Molteni, D, Lanzafame, G., & Chakrabarti, S. 1994, ApJ, 425, 161
Murray, N., Quataert, E., & Thompson, T. A. 2005, ApJ, 618, 569
Ohsuga, K. 2007, ApJ, 659, 205
Ostriker, J. P., Weaver, R., Yahil, A., & McCray, R. 1976, ApJ, 208, L61
Paczynski, B. 1978, Acta Astron., 28, 91
Park, M.-G., & Ostriker, J. P. 2001, ApJ, 549, 100
———. 2007, ApJ, 655, 88

———. 2007, ApJ, 661, 693 (Paper I)
Proga, D., & Begelman, M. C. 2003, ApJ, 582, 69
Proga, D., Stone, J. M., & Kallman, T. R. 2000, ApJ, 543, 686 (PSK00)
Ryu, D., Brown, G. L., Ostriker, J. P., & Loeb, A. 1995, ApJ, 452, 364
Sazonov, S. Y., Ostriker, J. P., Ciotti, L., & Sunyaev, R. A. 2005, MNRAS, 358, 168
Shlosman, I., & Begelman, M. C. 1987, Nature, 329, 810
Silk, J., & Rees, M. J. 1998, A&A, 331, L1
Springel, V., Di Matteo, T., & Hernquist, L. 2005, ApJ, 620, L79
Stevens, I. R., & Kallman, T. R. 1990, ApJ, 365, 321
Thacker, R. J., Scannapieco, E., & Couchman, H. M. P. 2006, ApJ, 653, 86
Toropin, Y. M., Toropina, O. D., Savelyev, V. V., Romanova, M. M., Chechetkin, V. M., & Lovelace, R. V. E. 1999, ApJ, 517, 906
Wang, J.-M., Chen, Y.-M., & Hu, C. 2006, ApJ, 637, L85