WHY IS SUPERCRITICAL DISK ACCRETION FEASIBLE?

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Received 2006 October 6; accepted 2007 August 9

ABSTRACT

Although the occurrence of steady supercritical disk accretion onto a black hole has been speculated about since the 1970s, it has not been accurately verified so far. For the first time, we previously demonstrated it through two-dimensional, long-term radiation-hydrodynamic simulations. To clarify why this accretion is possible, we quantitatively investigate the dynamics of a simulated supercritical accretion flow with a mass accretion rate of $\sim 10^2 L_\text{E}/c^2$ (with $L_\text{E}$ and $c$ being, respectively, the Eddington luminosity and the speed of light). We confirm two important mechanisms underlying supercritical disk accretion flow, as previously claimed, one of which is the radiation anisotropy arising from the anisotropic density distribution of very optically thick material. We qualitatively show that despite a very large radiation energy density, $E_0 \simeq 10^2 L_\text{E}/4\pi r^2 c$ (with $r$ being the distance from the black hole), the radiative flux $F_0 \sim cE_0/\tau$ could be small due to a large optical depth, typically $\tau \sim 10^3$, in the disk. Another mechanism is photon trapping, quantified by $rE_0$, where $r$ is the flow velocity. With a large $|r|$ and $E_0$, this term significantly reduces the radiative flux and even makes it negative (inward) at $r < 70r_\text{S}$, where $r_\text{S}$ is the Schwarzschild radius. Due to the combination of these effects, the radiative force in the direction along the disk plane is largely attenuated so that the gravitational force barely exceeds the sum of the radiative force and the centrifugal force. As a result, matter can slowly fall onto the central black hole mainly along the disk plane with velocity much less than the free-fall velocity, even though the disk luminosity exceeds the Eddington luminosity. Along the disk rotation axis, in contrast, the strong radiative force drives strong gas outflows.

Subject headings: accretion, accretion disks — black hole physics — hydrodynamics — radiative transfer

1. INTRODUCTION

Recently, very bright objects which may be undergoing supercritical (or super-Eddington) accretion flows have successfully been found. Good examples are ultraluminous X-ray sources (ULXs; Watarai et al. 2001; Ebisawa et al. 2003; Okajima et al. 2006). These are pointlike off-center X-ray sources whose X-ray luminosity significantly exceeds the Eddington luminosity of a neutron star (Fabbiano 1989). Because of substantial variations, it is reasonable to assume that the ULXs are single compact objects powered by accretion flows (Makishima et al. 2000). If so, there are two possibilities to account for large luminosities exceeding the Eddington luminosity for a mass of $100 M_\odot$: subcritical accretion onto an intermediate-mass black hole (IMBH) and supercritical accretion onto a stellar-mass black hole. We support the latter possibility, since through the fitting to several XMM-Newton EPIC data of ULXs, which have been claimed as good IMBH candidates, we have found evidence of supercritical flows (Vierdayanti et al. 2006). Another interesting group is narrow-line Seyfert 1 galaxies (see Boller 2004 for a review). Because of their relatively small black hole masses, they have in general large Eddington ratios ($L/L_\text{E}$ with $L$ and $L_\text{E}$ being the luminosity and the Eddington luminosity, respectively), and some of them seem to fall in the slim-disk regimes (Mineshige et al. 2000; Kawaguchi 2003; see also Wang et al. 1999).

Despite growing evidence indicating the existence of supercritical accretion flows in the universe, theoretical understanding is far from being complete. It is well known that any spherically accreting object, irrespective of the nature of the central source, cannot emit above the Eddington luminosity, since otherwise significant radiative force will prevent accretion of the gas. If we examine detailed radiation-matter interactions in the interior, however, we notice that the situation is not so simple. Actually, radiation produced at the very center cannot immediately reach the surface (i.e., photosphere), since photons generated at the center should suffer numerous scatterings with accreting material and thus take a long time to reach the surface. If the matter continuously falls, and if the mass accretion timescale is shorter than the mean travel time for photons to reach the surface (the diffusion timescale), photons at the core may not be able to go out. This is the so-called photon-trapping effect (e.g., Begelman 1978; Houck & Chevalier 1991). Here we define the trapping radius, inside which radiation-matter interaction is so frequent that photons are trapped within the accretion flow. Inside this trapping radius, therefore, radiative flux can be negative (i.e., inward). Thus, the apparent luminosity is reduced as compared with the case without photon trapping. Nevertheless, the concept of the Eddington luminosity is still valid, since far outside the trapping radius radiative flux should be outward and its absolute value should be less than $L_\text{E}/4\pi r^2$, where $r$ is the distance from the central black hole, in the quasi-steady state. Radiation-hydrodynamic (RHD) simulations of spherically symmetric supercritical accretion flows have been performed by Burger & Katz (1983).

The situation may differ in the case of disk accretion, since the radiation field is not isotropic due to inhomogeneous matter distribution. That is, matter can fall predominantly along the disk plane, whereas radiation can go out along its rotating axis, where matter density is low. In other words, the main directions of the
inward matter flow and the outward radiative flux are not parallel to each other in disk accretion, leading to a situation in which the radiative force does not completely counteract the gravitational force. There is room for the possibility of a supercritical accretion flow with super-Eddington luminosity.

Based on such an argument, many researchers have speculated about the occurrence of supercritical flows in disk accretion systems. Shakura & Sunyaev (1973) discussed the possibility of supercritical disk accretion based on a one-dimensional steady model (see also Maraschi et al. 1976). They mentioned that the mass accretion rate would not be steady but oscillate if the mass accretion rate exceeded the critical rate; otherwise, a part of the accreting matter might be ejected from the disk as a disk wind. Radiatively driven outflows from supercritical disks were investigated by Meier (1979), Jones & Raine (1979), and Icke (1980).

Despite a long history in the study of supercritical disk accretion flows, the occurrence of steady supercritical disk accretion has not yet been accurately verified. Similar simulations have been performed since the 1980s, but all of them calculated only the initial transient phase. Their conclusions then were not general, since the back-reactions (i.e., enhanced radiation pressure), which may inhibit steady flow, were not accurately evaluated. Although the radiative force predominantly has an effect in the vertical direction, it should also have an effect on the material within the disk. Hence, in the direction parallel to the disk plane, the situation may be similar to or more severe than the case of spherical accretion. This is because the radiative force, together with the centrifugal force, may possibly overcome the gravitational force. To study the possibility of supercritical disk accretion flows, precise and quantitative research treating both supercritical disks and outflows, and which also takes into consideration multidimensional effects, is needed.

Ohsuga et al. (2005, hereafter Paper I) have confirmed the occurrence of quasi-steady supercritical disk accretion onto a black hole by two-dimensional RHD simulations. The motivation of the present study is to investigate the physical mechanisms which make supercritical disk accretion possible. For this purpose we examine quantitatively the flow motion and force fields via the radiative flux, rotation, and gravity of a supercritical disk accretion flow onto a central black hole, based on the two-dimensional RHD simulation data from Paper I. Through detailed inspection of the results, it will be possible to clarify the physics behind supercritical disk accretion flows. In § 2 we plot the spatial distributions of several key quantities which control flow dynamics. A discussion is given in § 3.

2. DYNAMICS OF A SUPERCRITICAL DISK ACCRETION FLOW

2.1. Basic Considerations

Here we adopt the spherical coordinates \((r, \theta, \varphi)\), with \(\theta = \pi/2\) corresponding to the disk plane and the origin being set at the central black hole. The momentum equation for the radial component of the flow is

\[
\frac{dv_r}{dt} = f_{\text{grav}} + f_{\text{rad}}^r + f_{\text{pres}}^r + f_{\text{cent}}^r. \tag{1}
\]

Here \(v_r\) is the radial component of the flow velocity, \(d/dt \equiv \partial/\partial t + v_r \partial/\partial r\) is the Lagrangian derivative, \(f_{\text{grav}}\) is the gravitational force by the central black hole, \(f_{\text{rad}}^r = \chi F_0^r/c\) is the radiative force with \(\chi\) being absorption and scattering coefficients, \(c\) being the speed of light, and \(F_0^r\) representing the radial component of the radiative flux in the comoving frame, \(f_{\text{pres}}^r\) is the radial component of the gas pressure force, and \(f_{\text{cent}}^r = v_r^2/r\) is the radial component of the centrifugal force. We adopt a pseudo-Newtonian potential, thus having \(f_{\text{grav}} = -GM/(r - r_s)^2\) with \(M\) being the mass of the black hole and \(r_s \equiv 2GM/c^2\) (Paczyński & Wiita 1980).

To proceed, it is important to distinguish two different views: the view from an observer comoving with the accreting gas (i.e., the comoving frame) and the view from an observer standing at infinity (the rest frame). The \(r\)th component of radiative flux in the comoving frame, \(F_0^r\), is related to that in the rest frame, \(F^r\), on the order of \(v/c\),

\[
F^r = F_0^r + v_r E_0 + v_r P_0^r, \tag{2}
\]

where \(E_0\) and \(P_0^r\) are the radiation energy density and the radiation stress tensor in the comoving frame, respectively. Here the final term in equation (2) is equal to \(v/r E_0/3\) in the optically thick diffusion limit.

In § 2.3 we show that the gas accretes toward the black hole in the disk region. In this region, even if the radiative flux in the comoving frame is positive, \(F_0^r > 0\) (i.e., outward flux), \(F^r\) can be negative, \(F^r < 0\) (inward flux), because \(v_r < 0\). The term \(v_r E_0\) thus represents photon trapping. In § 2.5 we explicitly show this effect in the simulation data.

In contrast, the flow dynamics in the direction perpendicular to the disk plane is distinct. In particular, the centrifugal force has no effect in this direction. In addition, the matter density is significantly smaller along the rotation axis. Hence, the radiative flux can be much more effective in the vertical direction, thus driving strong outflows, as we see in § 2.3.

2.2. Overview of the Simulated Flow

Our present analysis is based on the two-dimensional RHD simulation data from Paper I. These are the first simulations of supercritical accretion flow in the quasi-steady state. Although the research history of such simulations stems back to the late 1980s, when Eggum et al. (1987) performed numerical simulations for the first time, their calculations were restricted to the first few seconds (see also Kley 1989; Okuda et al. 1997; Kley & Lin 1999; Okuda 2002). Back-reactions were not fully taken into account in their simulations. In our simulations presented in Paper I, matter is added continuously from the outer disk boundary at \(r = 500r_s\) to the initially (nearly) empty space at the rate of \(10^7L_E/c^2\). The injected mass has a small specific angular momentum so that it first free falls but then forms a rotating disk at \(r \sim 100r_s\). Mirror symmetry is assumed with respect to the disk (equatorial) plane. The \(a\)-prescription of the viscosity is employed, in which the viscosity is set to be proportional to the total pressure in the optically thick limit and the gas pressure only in the optically thin region. Hence, the viscosity is more effective in the disk region than in the outflow regions above and below the disk. The viscosity parameter is assumed to be \(\alpha = 0.1\). Except for the radial-azimuthal component, all components of the viscous stress tensor are set to be zero.

The radiative transfer was solved under the flux-limited diffusion approximation (Levermore & Pomraning 1981). The central object is taken to be a nonrotating stellar-mass black hole \((M = 10 M_\odot)\), generating a pseudo-Newtonian potential. Only 10% of the inflowing matter finally reaches the inner boundary \((3r_s)\); i.e., 90% of the mass input gets stuck in the dense, disklike structure around the equatorial plane, or transforms into the known collimated high-velocity outflows perpendicular to the equatorial plane or into low-velocity outflows with wider opening angles.
The resulting luminosity is about 3 times larger than the Eddington luminosity.

Figure 1 indicates the time-averaged contours of the matter density (left panel) and the radiation energy density (right panel) on the $R$-$z$ plane ($R = r \sin \theta$ and $z = r \cos \theta$), where both axes are normalized by the Schwarzschild radius ($r_s$). Note that these panels are similar to Figures 3 and 5 of Paper I, except that Figure 1 of the present paper has contours which are time-averaged over $t = 20$–$50$ s, whereas those in Paper I are snapshots at $t = 10$ s (i.e., in a quasi-steady phase). The high concentration of gas and radiation in the region near the black hole on the equatorial plane is clear.

2.3. Dynamics of the Simulated Flow

First we plot the time-averaged radiation energy density normalized by $L_E/4\pi r^2 c$ in Figure 2. We find that this value is larger than unity in most regions. In particular, we have $E_0 \gtrsim 10^2 L_E/4\pi r^2 c$ in the disk region. This means that there exists so large a number of photons that if we simply assume $F_0 \sim cE_0$ as in the optically thin region, the radiative force should highly exceed the gravity, which inevitably prevents the inflow motion. The simulation data, however, do show inflow motion (discussed below).

Figure 3 illustrates the time-averaged force balance in the radial ($r$) directions with various $\theta$-values from the origin. (It should be noted that since force is a vector, we need to specify the direction to draw such contours. Here we only plot the radial component of the forces.) Figure 3 (left) represents the ratio of the radial component of the radiative force to the gravitational force. Especially surprising is that most regions are turquoise, indicating that the radiative force is outward and less than the gravitational force. Why is the radiative force so weak, even though the radiation energy density is very large, $E_0 \gtrsim 10^2 L_E/4\pi r^2 c$ (see Fig. 2), and even though the total luminosity exceeds the Eddington luminosity,
$L > L_e$? This is because the disk is very optically thick. Although the absolute value of the radiative flux is equal to $cE_0$ in the optically thin limit, it is roughly given by $cE_0/\tau$, and hence, $F_0$ can be very small, $F_0 \ll cE_0$, in the optically thick region ($\tau \gg 1$), where $\tau$ is the optical thickness. Approximately, we find $\tau = \rho \chi r \sim 10^{1}(\rho/10^{-4.5} \text{ g cm}^{-3})(r/30r_s)$, where $\rho$ is the gas density. Thus, flux is attenuated a great deal. We thus have a relatively small radiative flux within the disk in spite of a large $E_0$ (see §2.4 for more detail). There are two exceptions: the color of the region in the vicinity of the black hole is blue, which means that the radiative force is inward. In this region, a large number of photons are swallowed by the black hole, $F_0^r < 0$, so that the gas is accelerated inward. The region near the rotation axis, in contrast, has a white color, which means that the radiative force exceeds the gravitational force.

To discuss how matter flows, we also need to consider the centrifugal force. (Note that the gas pressure is negligible in the present case.) Figure 3 (right) illustrates the ratio of the sum of the radial components of the radiation and centrifugal forces to the gravitational force. Certainly, the repulsing force is enhanced along the disk plane. However, this force ratio is still around unity in most regions except in the very vicinity of the black hole. That is, the gas is nearly in a balance of forces in wide regions. The regions near the rotation axis again have white colors, which means that the radiative force dominates, as in Figure 3 (left). (Note that the centrifugal force is not effective near the rotation axis.)

Since there are regions with a negative effective force in the radial direction, we expect regions with negative velocity (i.e., inflow). Figure 4 shows the spatial distribution of the radial component of the matter velocity in units of the free-fall velocity. Interestingly, the flow is inward in the disk region, but the infall velocity is much smaller than the free-fall velocity. Along the rotation axis, conversely, the flow is outward, and its magnitude is larger than the free-fall velocity.
Let us have a more quantitative discussion based on the one-dimensional distributions of these quantities, since it is difficult to obtain their precise values from the color contours. We calculate several quantities along two radial lines: one at 0.45π (close to the equatorial plane) and the other at θ = 2.3 × 10^{-2}π (nearly along the rotation axis). They are illustrated in the top and bottom panels of Figure 5, respectively.

We see in the top panel that the radiative force is not negligible, although it is smaller than the centrifugal force. The sum of the radiative and centrifugal forces is nearly balanced with the gravitational force. Radiation does work as a “radiation cushion,” which decelerates the accretion of the gas in cooperation with the rotation (centrifugal force). Deceleration via radiative flux was also reported by Burger & Katz (1980, 1983). Figure 5 (top) also shows that the radial velocity is much smaller than the free-fall velocity and only barely below zero (inflow), although there also exist regions with v_r ≈ 0 (no inflow).

In contrast, Figure 5 (bottom) shows that the ratio of the radiative force to the gravitational force grows as the distance increases. The outward velocity thus grows rapidly upward. We confirm again that the strong outflow around the rotation axis is produced by the strong radiative force. However, the velocity is negative in the very vicinity of the hole. This means that the radiation which produces the huge radiative force in the vertical direction does not originate from the region just outside the event horizon but from the region with θ < 5 r_s at maximum [at (5–10)r_s].

Here we note that the angular momentum is very small around the rotation axis, leading to a negligible centrifugal force (dotted line). This is because a significant amount of material exists even inside the radius of the marginally stable orbit, R < 3 r_s, in the supercritical flow, so the matter can lose angular momentum there (Kato et al. 1998; Watarai & Mineshige 2003). This situation contrasts with that of the subcritical flow, in which there is a sharp density drop at R = 3 r_s.

Our computational domain covers exactly down to the rotation axis. Numerical simulations show that most of the outflow matter is blown away into an oblique direction by the radiative force in cooperation with the centrifugal force.

2.4. Geometric Effect

Here we consider the reason why the radiative force in the radial direction does not dominate over the gravitational force inside the disk, even though E_0 is larger than 10^3 L_€/4πr^2 c as shown in Figure 2. The radial component of the radiative flux is evaluated as F_0^r ≈ (c/3 θ G)∂E_0/∂r in the disk region. It is attenuated since the disk is dense and very optically thick (τ ≫ 1). That is, even though the radiation energy density itself is large, the high matter density significantly suppresses the radiative flux inside the disk. However, the high density (large optical thickness) is not the only condition for the occurrence of supercritical accretion. In the case of a spherical system, the radiative flux should be L/4πr^2 even if the matter is very optically thick. The radiative force dominates over the gravitational force when L > L_€, preventing the accretion of matter. Hence, there should be another reason that supercritical disk accretion is realized in spite of L > L_€.

Whereas the radiation field is isotropic in the spherical case by definition, it can be anisotropic in the disk case. Indeed, the simulated profile of the radiation energy density is highly anisotropic (Fig. 1, right). Unlike in spherical geometry, photons can escape from the less dense region around the rotation axis without thrusting through the dense disk region. Thus, the effective radiative force is attenuated in the disk region. Here we note that, even in the presence of an anisotropic matter distribution, L cannot exceed L_€ if the medium is optically thin. To sum up, supercritical disk accretion with super-Edington luminosity is realized due to a large optical thickness and anisotropy of the radiation field.

2.5. Photon-trapping Effects

Photon-trapping effects assist the occurrence of supercritical accretion. Figure 6 (top) indicates the radiative fluxes in the comoving and rest frames inside the disk. As shown in this figure, the radial component of the radiative flux in the rest frame (dotted line) is negative in the region of r < 70 r_s, whereas that in the comoving frame (solid line) is positive except in the vicinity of the black hole. This means that the radiation energy is transported inward via photon trapping, v_r E_0 < 0 (see eq. [2]). Some part of this radiation energy is swallowed by the black hole, whereby the luminosity is reduced. This effect attenuates the radiative force, supporting the accretion.

The anisotropy of the radiation field is enhanced by photon trapping. This is another important role of the photon trapping. The radiation energy, which is advected inward with the matter by the photon trapping but not swallowed by the black hole, is transported to the vertical direction and finally released from the disk surface. It is shown in Figure 5 (bottom), which plots the θ-components of the radiative fluxes in the comoving (solid line) and the rest (dotted line) frames along a radial line at θ = 0.3π, that the entire region is below the photosphere. In this figure we can see that the radiation energy is transported toward the disk surface, F^θ < 0, in most of the region. We also find F^θ < F^r in this figure. This implies that the gas motion contributes to the transport of radiation energy toward the disk surface, v_r E_0 < 0.

To conclude, the photon-trapping effect enhances the anisotropy of the radiation field, assisting the occurrence of supercritical accretion.
Here we note that the gas motion in the vertical direction seems to be driven by convection in cooperation with the radiative force. In fact, we find that the adiabatic conditions for radiation-pressure-dominated matter are roughly satisfied along the vertical line in the disk region, $\partial \ln P / \partial \ln \rho \sim 4/3$ and $\partial \ln T / \partial \ln P \sim 1/4$, where $P$ is the total pressure and $T$ is the temperature.

3. DISCUSSION

3.1. Structure of the Supercritical Disk Accretion Flow

We summarize our simulation results in a schematic picture (see Fig. 7). In this figure the radiative flux in the comoving frame, $F'_0$, is positive (outward) except in the vicinity of the black hole. However, the radiative flux in the rest frame, $F'\sim F'_0 + 4\nu E_0$, is negative (inward) via photon trapping, $\nu E_0 < 0$, in the trapping region. In the vicinity of the black hole, both $F'_0$ and $F'$ are negative. Matter slowly accretes inside the disk, since the sum of the radiative and centrifugal forces is nearly balanced with the gravitational force. Here we stress again that the radiative force counteracts the gravitational force in spite of the trapping region because $F'_0 > 0$. Radiatively driven high-velocity outflows appear above and below the disk. In the very vicinity of the black hole, the gas is accelerated inward by the radiative force and the gravitational force.

As far as the physical quantities around the equatorial plane are concerned, the simulated profiles of the density, temperature, and radial as well as rotational velocities roughly agree with the prediction of the slim-disk model (Abramowicz et al. 1988). Such features have already been shown in Figure 11 in Paper I. However, only about 10% of the injected mass can accrete onto the black hole, and an almost equal amount of matter is ejected as high-velocity outflows. The mass accretion rate is not constant in the radial direction and decreases near the black hole (see Fig. 6 in Paper I). Thus, we conclude that the simulated flows do not perfectly agree with the slim-disk model with regard to the whole structure of the flow.

Heinzeller & Duschl (2007) have investigated local maximum values of the accretion rate in supercritical disk accretion flows. In their paper they focused only on the force balance in the vertical and radial directions around the equatorial plane. Multidimensional effects were not taken into consideration. They revealed that the vertical radiative force limits the maximum accretion rate at the inner disk region, leading to a decrease of the accretion rate with a decrease of the radius. Their results imply that the disk loses mass via the radiatively driven outflows and the mass accretion rate decreases at the inner region. Such tendencies agree with our results. As shown in Figure 4, our simulations show that radiatively driven outflows form above and below the disk. The mass accretion rate decreases with a decrease of the radius (see Fig. 6 in Paper I).

3.2. Dependency of the Mass Accretion Rate

In the present study, focusing on numerical simulations in which the mass input rate at the outer boundary is set to be $M_{\text{input}} = 10^2 L_{\text{E}} / c^2$, we show that the radiative force is attenuated in the disk region via large optical thickness, which makes supercritical disk accretion possible. Such dilution of the radiative force would effectively operate even if the mass input rate (mass accretion rate) varied. In fact, simulations with mass input rates of $3 \times 10^2 L_{\text{E}} / c^2$ and $3 \times 10^3 L_{\text{E}} / c^2$ show that $E_0 / \rho$ is almost independent of the mass input rate, although the radiation energy density goes up as the mass input rate increases. That is, the dynamics is not sensitive to the precise value of $M_{\text{input}}$ as long as it largely exceeds the critical value.

So far we have studied steady accretion flows. Although a highly supercritical disk ($M_{\text{input}} > 3 \times 10^2 L_{\text{E}} / c^2$) is quasi-steady, it has been revealed that a moderately supercritical disk [$M_{\text{input}} = (10-10^2) L_{\text{E}} / c^2$] is unstable and exhibits limit-cycle behavior (Ohsuga 2006, 2007; see also Shibazaki & Hoshi 1975; Shakura & Sunyaev 1976). The luminosity goes up and down around the Eddington luminosity.

Ohsuga (2007) has reported that the time-averaged mass, momentum, and kinetic energy output rates via the outflow, the mass accretion rate, and the disk luminosity increase as the mass input rate increases, $\propto M_{\text{input}}^{0.7} M_{\text{input}}^{1.0}$ for $\alpha = 0.5$ and $\propto M_{\text{input}}^{0.4} M_{\text{input}}^{0.6}$ for $\alpha = 0.1$.

3.3. Future Work

As we have already mentioned in § 3.1, the sum of the accreting matter and the matter ejected as high-velocity outflows is 20% of the injected mass, and 80% of the injected matter is ejected from the computational domain as low-velocity outflows, whose velocities do not exceed the escape velocity at the outer boundary. Since such outflowing matter tends to be accelerated by the radiative force even at the outside of the computational domain, it would be blown away from the system. However, a part of the outflowing matter might return to the vicinity of the black hole through the disk region, since the radiative force does not exceed the gravity near the equatorial plane. Numerical simulations with larger computational domains would make this point clear.

Whereas the resulting mass accretion rate onto the black hole is around $10^2 L_{\text{E}} / c^2$ in the present simulations, Heinzeller & Duschl (2007) have indicated that the mass accretion rate can increase up to $10^4 L_{\text{E}} / c^2$. They have reported that the vertical force balance breaks down via a strong radiative force if the mass accretion rate exceeds this limit. However, even in such a case, the matter might accrete onto the black hole, although the strong radiative force would produce powerful outflows. To investigate the
maximum value of the accretion rate is an outstanding issue. We should perform numerical simulations with larger computational domains, since the trapping region is expected to expand with the increase of the mass accretion rate.

We reveal in the present paper that photons generated deep inside the disk are effectively trapped in the flow, leading to supercritical disk accretion. Although the magnetic fields are not solved in our simulations, magnetic buoyancy might play an important role in the transportation of matter, as well as photons, toward the disk surface (Parker 1975; Stella & Rosner 1984; Sakimoto & Coroniti 1989). Magnetic buoyancy might lead to photon generation near the disk surface if the magnetic fields rise quickly without dissipation deep inside the disk. Thus, magnetic buoyancy would dilute the photon-trapping effect. A photon bubble instability, which is induced in the magnetized, radiation-pressure-dominated region, might also suppress the photon trapping (Begelman 2002; Turner et al. 2005). In these cases the enhanced radiative force would more effectively accelerate the matter around the disk surface, working to decrease the mass accretion rate. However, the magnetic fields might prevent such acceleration if they
strongly tie the matter near the disk surface with the disk matter. In the disk region the matter might easily accrete toward the black hole, since the radiation energy density decreases. Global radiation-magnetohydrodynamic (RMHD) simulations would make these points clear. Local RMHD simulations of accretion flows have been performed by Turner et al. (2003) and Hirose et al. (2006). In addition, it is thought that disk viscosity has magnetic origins (Hawley et al. 2001; Machida et al. 2001; for a review see Balbus 2003). Hence, we should stress again that RMHD simulations are very important to more realistically investigate viscous accretion flows, although an $\alpha$-viscosity model is employed in the present study.

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We would like to thank the anonymous reviewer for many helpful suggestions. The calculations were carried out by a parallel computer at Rikkyo University and the Institute of Natural Science, Senshu University. This work was supported in part by a special postdoctoral researchers program in the Institute of Physical and Chemical Research (K. O.), by a research grant from the Japan Society for the Promotion of Science (17740111; K. O.), by Grants-in-Aid from the Ministry of Education, Science, and Sports (14079205, 16340057; S. M.), and by the Grant-in-Aid for the 21st Century COE “Center for Diversity and Universality in Physics” from the Ministry of Education, Culture, Sports, Science, and Technology of Japan.