Three-Dimensional Magnetohydrodynamical Accretion Flows into Black Holes

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Abstract

Outflows and convective motions in accretion flows have been intensively discussed recently in the context of advection-dominated accretion flow (ADAF) based on two-dimensional (2D) and three-dimensional (3D) hydrodynamical simulations. We, however, point that without proper treatments of the disk magnetic fields, a major source of viscosity, one can never derive general, firm conclusions concerning the occurrence of outflows and convection. We analyzed the 3D MHD numerical simulation data of magnetized accretion flows initially threaded by weak toroidal magnetic fields, finding large-scale convective motions dominating near the black hole. In contrast, outflows occur only temporarily and are not very significant in our simulations. If there grow strong vertical fields somehow, however, formation of bi-polar jets is inevitable. It is claimed that radiation could be dominant at the outermost zones of the convective disks because of outward energy flow by convection, however, this is no longer the case in convective MHD flows, since accretion energy can be released via magnetic reconnection in the inner parts. Such reconnection leads to sporadic flare events, thus producing substantial variability in out-going radiation.

Key words: Accretion, accretion disks — Black holes — Convection — Outflow — Magnetohydrodynamics

1. Introduction

Rapid progress has been made recently in the research field of black-hole accretion flow and our knowledge about flow properties has been remarkably enriched. In addition to the standard disk (Shakura, Sunyaev 1973), the existence of a distinct type of flow, advection-dominated accretion flow (ADAF) has been widely recognized. Although ADAF was proposed long time ago by Ichimaru (1977), its significance is only recently fully appreciated (Narayan and Yi 1994, 1995; Abramowicz et al. 1995; for a review, see Kato et al. 1998).

Narayan and Yi (1994) made two important pieces of predictions: possible occurrence of convection (in the radial direction) and outflows. Since radiative cooling is inefficient, entropy of accreting gas should monotonically increase towards a black hole (i.e., in the direction of gravity), a condition for a convective instability. Convection was later confirmed numerically (e.g. Igumenshchev et al. 1996; Stone et al. 1999). The occurrence of outflow is, on the other hand, still open to question; the self-similar model points an advection-dominated flow having positive Bernoulli parameter, $Be$, meaning that matter is gravitationally unbound and can form outflows (see also Blandford, Begelman 1999). However, matter with positive $Be$ may not necessarily produce powerful unbound outflows (Abramowicz et al. 2000). Certainly, the traditional, radially one-dimensional treatments are inappropriate to discuss this issue.

Through extensive 2D hydrodynamical simulations, Igumenshchev and Abramowicz (2000, hereafter IA00) have found different modes of accretion flow realizing in advection-dominated regimes, depending on the magnitude of the viscosity parameter, $\alpha$. They found outflows for a moderately large $\alpha$ ($\sim 1$) and convection and/or large-scale circulations for small $\alpha \lesssim 0.1$ (see also Igumenshchev et al. 2000 for 3D calculations).

However, the magnitude of viscosity is not a free parameter in real situations but should be determined in a self-consistent way. It is now widely believed that magnetic fields provide a major source of disk viscosity. If so, without proper treatment of disk magnetic fields one can never derive solid conclusions concerning flow patterns. Dynamics of magnetically dominated accretion is in question. This prompted us to examine the three-dimensional data of the global, MHD disk calculations first made by Machida et al. (2000), aiming to establishing a general, new view of accretion flow in advection-
dominated regimes. The results of MHD flow structures are presented in section 2. The final section is devoted to discussion.

2. Three-Dimensional Flow Structure

Machida et al. (2000) calculated how magnetic field evolves in a rotating MHD torus with its center at \( r = r_0 \) initially threaded by toroidal \((B_\theta)\) fields under the Newtonian potential (Okada et al. 1989) with cylindrical coordinate \((r, \phi, z)\). They solved ideal MHD equations, but entropy can increase by shock heating. Since no cooling is taken into account in the computations, the simulated disk is of an ADAF type. They assumed the adiabatic index, \( n = 5/3 \), and no heat conduction. The numbers of mesh points are \((n_r \times n_\phi \times n_z) = (200 \times 64 \times 240)\). The outer boundaries at \( r = 6.4 \, r_0 \) and at \( z = 11.8 \, r_0 \) are free boundaries at which waves can transmit. A periodic boundary condition is imposed for \( \phi \)-direction. The grid size is \( \Delta r = \Delta z = 0.01 \, r_0 \) for \( 0 \leq r \leq 1.2 \, r_0 \) and \( 0 \leq z \leq r_0 \) and otherwise increases with \( r \) and \( z \). We imposed absorbing boundary condition at \( r = 0.1 \, r_0 \) where \( r \equiv (r^2 + z^2)^{1/2} \). To initiate non-axisymmetric evolution, small-amplitude, random perturbations are imposed at \( t = 0 \) for azimuthal velocity. Although the initial torus has a flat angular-momentum distribution, the angular-momentum profile soon approaches that of the Keplerian \((\sim 1/r^{1/2})\) after several rotations. Since it is difficult to add gas threaded by magnetic fields, we assume no mass input. However, the flow can be regarded as being quasi-stationary inside \( r_0 \), since the total calculation time is \( t \sim 22 \) (in a unit of the rotation period at \( r_0 \)) which by far exceeds the mass-flow timescale \((\sim |v_r|)\) in the inner zone.

As time goes on, each component of magnetic fields is rapidly amplified via a number of MHD instabilities together with the differential rotation. The maximum field strength is determined either by field dissipation by reconnection or field escape from accretion flow via Parker instability. As a result, the plasma \( \beta \) (\( \equiv p_{\text{gas}}/p_{\text{mag}} \), the ratio of gas pressure to magnetic pressure) finally reaches \( \sim 2 - 10 \) on average, irrespective of the initial \( \beta \). The corresponding \( \alpha \) value is \( \alpha \sim 0.01 - 0.1 \). Even lower-\( \beta \) (\(< 1\)) values are observed in the regions with filamentary shapes. Although the spatial distribution of the fields is quite inhomogeneous (Kawaguchi et al. 2000), matter distribution is somewhat smoother. In the following, we analyze the case with initial \( \beta_0 = 100 \) at \((r, z) = (r_0, 0)\).

Figure 1 displays the snapshots (left and middle) and the time averages (right) of density contours and momentum vectors on the \((r, z)\) plane. Note that each quantity is averaged over azimuthal angles. Large-scale convective motions, which look very similar to those of IA00 (their figure 15) are evident in these panels; that is, the accretion is suppressed in the equatorial plane and the mass inflows concentrate mainly along the upper and lower surfaces of the torus-like accretion disk. The polar inflows are highly supersonic, although accompanying mass flux is small because of low density. Note that we assume equatorial symmetry, thus large-scale motion penetrating the equatorial plane is artificially suppressed in our simulations, while it is allowed in IA00.

In figure 2, we plot various physical quantities averaged over a spherical shell with a constant \( r \):

\[
\bar{q}(r) = \frac{\int \int q(r, \theta, \phi) \sin \theta \, d\theta \, d\phi}{\int \int \sin \theta \, d\theta \, d\phi}
\]

for \( q = \rho, T, B^2, \alpha, \) and

\[
\bar{v}(r) = \frac{\int \int \rho v(r, \theta, \phi) \sin \theta \, d\theta \, d\phi}{\int \int \rho \sin \theta \, d\theta \, d\phi}.
\]

The results are summarized in Table 1, in which we also compare radial dependences of various quantities for vari-
Fig. 2. Various physical quantities averaged over angles as functions of radius ($r$): matter density (upper-left), temperature (upper-middle), magnetic energy (upper-right), radial velocity $v_r$ (lower-left), azimuthal velocity (lower-middle), and viscosity parameter, $\alpha \equiv -\langle B_r B_\phi / 4\pi \rangle / \langle p_{\text{gas}} \rangle$ (lower-right), respectively, at different epochs, (a) at $t = 10.5$ and (b) at $t = 19.7$, respectively. The dashed curves represent power-law relations, such as $\rho \propto r^{-0.5}$, $T \propto r^{-1.0}$, $B^2 \propto r^{-1.5}$, $v_r \propto r^{-1.5}$, and $v_\phi \propto r^{-0.5}$. Long dashed curves in the lower-left panels indicate portions of negative $v_r$ (inflow). The unit of velocity is the Keplerian rotation speed at $r_0$.

ious types of accretion. Note that outer parts of the simulated disks are formed by out-going motions of the disk material as a result of re-distribution of the initial disk angular momenta as is indicated by positive radial velocities. In the MHD flow, we concentrate on the flow structure at $r \leq r_0$, where inflow motions dominate (indicated by long-dashed lines in the $v_r$ distribution).

In general, our numerical results remarkably agree well with those of the convective disk at least at $t = 10.5$, confirming that convection dominates the flow dynamics. It is interesting to note that density profiles differ at $t = 10.5$ (named as early stage) and at $t = 19.7$ (late stage). We notice that entropy [$\propto \ln(p_{\text{gas}}/\rho^\gamma)$] with $\gamma = 5/3$] increases with decreasing $r$ in the early stage (namely, the flow is certainly convectively unstable), whereas it is nearly flat (i.e., the flow is isentropic) in the later stage. This indicates that convection efficiently works in the early stage to smooth out entropy profile, leading to a flat entropy profile in the late stage. The plasma $\beta$ is roughly constant radially, whereas electron drift velocity ($\propto j/\rho \propto |\nabla \times B|/\rho$), a key factor to turn on anomalous resistivity, increases with a decreasing $r$ as $\propto r^{-1}$. Magnetic reconnection, hence, preferably occurs at small radii. We also notice that $\alpha$ has a weak radial dependence; roughly, $\alpha \propto r^{0.5}$.

3. Discussion

Magnetic fields play many crucial roles in activating accretion disks: source of viscosity (Shakura, Sunyaev 1973), producing rapid fluctuations (e.g. Kawaguchi et al. 2000), jet formation (e.g. Matsumoto 1999), and so on. Nevertheless, our knowledge about the disk magnetic fields still remains poor mainly because of their
highly nonlinear and global nature, requiring sophisticated multi-dimensional simulations which are only recently available. A number of questions have been addressed: is the field strength strong enough to account for observed rapid accretion? Does convection really occur in a magnetized disk? Or is it more likely for an ADAF to produce outflows/jets?

Although we have not run many models, we obtain a sort of answers for some cases. The field strength can indeed grow to be strong enough explain observed accretion phenomena. Convective motions are evident in the simulations, indicating that convection may be rather general phenomena in accretion flows. The estimated viscosity parameter is, \( \alpha \sim 0.01 - 0.1 \), for which we indeed expect the onset of convection from 2D/3D hydrodynamical simulations. More precisely, we find \( \alpha \propto r^{0.5} \). However, we should keep in mind that the presence of patchy low-\( \beta \) regions implies that simple \( \alpha \)-type prescription may not perfectly work.

As Machida et al. (2000) already noted, outflow is temporarily observed, although it is not very significant; the mass outflow rate is less than the mass accretion rate by some factor. Although we began calculations with weak toroidal fields, if we start with strong vertical fields, magnetically-driven bi-polar jets are evident (e.g. Matsumoto 1999). The flow pattern of MHD disks may depend on the initial field configurations. On the other hand, injection of a magnetized, differentially rotating buoyant element naturally can drive outflows (Turner et al. 1999). We need further MHD studies before finally settling down the issue of convection/outflows.

It is suggested (Igumenshchev 2000) that since energy can be carried outward by convective motions, radiation could be dominant at the outermost zones. We, however, point out that magnetic reconnection is likely to occur in the inner zones and to release substantial fraction of the total energy of accretion flows in the inner zone. This is a very likely possibility, if indeed magnetic flares are responsible for variability (e.g. Kawaguchi et al. 2000). In fact, we find large field energy in the inner zone, which can be released in a sufficiently short time before fields are brought outward by convective gas motions. That is, the computed spectra on the basis of the ADAF model will not need significant changes even in the presence of large-scale circulations.

We have not yet included conductive energy transport, although two-dimensional hydrodynamical simulations found significant changes in flow structure caused by conduction; any conductive models did not show bipolar outflows nor convection, since the thermal conduction mainly acts as a cooling agent (IA00). It is tempting to check if this is the case in MHD disks, as well.

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### Table 1. Various types of accretion flow.

| accretion mode | \( \rho(r) \) | \( T(r) \) | \( v_r(r) \) | \( B^2(r) \) |
|----------------|-------------|-------------|--------------|--------------|
| ADAF           | \( \propto r^{-3/2} \) | \( \propto r^{-1} \) | \( \propto r^{-1/2} \) | \( \cdots \) |
| outflow        | \( \propto r^{-1} \) | \( \propto r^{-1} \) | \( \propto r^{-1} \) | \( \cdots \) |
| convection     | \( \propto r^{-1/2} \) | \( \propto r^{-1} \) | \( \propto r^{-3/2} \) | \( \cdots \) |
| MHD flow       | \( \propto r^{-0.5} \) | \( \propto r^{-1.0} \) | \( \propto r^{-1.5} \) | \( \propto r^{-1.5} \) |
| (at \( t = 10.5 \)) | \( \propto r^{-0.8} \) | \( \propto r^{-0.5} \) | \( \propto r^{-1.3} \) | \( \propto r^{-1.6} \) |
| MHD flow       | \( \propto r^{-0.8} \) | \( \propto r^{-0.5} \) | \( \propto r^{-1.3} \) | \( \propto r^{-1.6} \) |

### References

Abramowicz M. A., Chen X. M., Kato S., Lasota J.-P., Regev O. 1995, ApJL, 438, 37
Abramowicz M.A., Lasota J.-P., Igumenshchev I.V. 2000, MNRAS, 314, 775
Blandford R.D., Begelman M.C. 1999, MNRAS 303, L1
Ichimaru S. 1997, ApJ, 214, 840
Igumenshchev I.V. 2000, MNRAS in press
Igumenshchev I.V., Abramowicz M.A. 2000, astro-ph/0003397 (IA00)
Igumenshchev I.V., Chen X., Abramowicz M.A. 1996, MNRAS 278, 236
Igumenshchev I.V., Abramowicz M.A., Narayan R. 2000, ApJL, 537, 27
Kato S., Fukue J., & Mineshige S. 1998, Black-Hole Accretion Disks (Kyoto Univ. Press, Kyoto)
Kawaguchi T., Mineshige S., Machida M., Matsumoto R., and Shibata K. 2000, PASJ 52, L1
Machida M., Hayashi M. R. & Matsumoto R. 2000, ApJL, 532, 67
Matsumoto R. 1999, Numerical Astrophysics, ed. Miyama S., Tomisaka K., and Hanawa T. (Kluwer Academic Publishers), p.195
Narayan R., Yi I. 1994, ApJ 428, L13
Narayan R., Yi I. 1995, ApJ 452, 710
Okada R., Fukue J., Matsumoto R. 1989, PASJ 41, 133
Shakura N. I., Sunyaev R. A. 1973, A&A, 24, 337
Stone J.M., Pringle J.E., Begelman M.C. 1999, MNRAS 310, 1002
Turner N. J., Bodenheimer P., Rozyczka M. 1999, ApJ, 524, 129