Radiation Hydrodynamic / Radiation Magnetohydrodynamic Simulations of Accretion Flows and Outflows around Black Holes

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Abstract

We perform global two-dimensional radiation hydrodynamic (RHD) and radiation magnetohydrodynamic (RMHD) simulations of accretion flows around black holes. Our RHD simulations reveal that the steady, supercritical accretion is feasible. The disk luminosity is several times larger than the Eddington luminosity. The disk is geometrically and optically thick. It is supported by the radiation pressure. The strong radiation pressure force drives the outflow above the disk. Our RMHD simulations demonstrate three distinct modes of accretion. When the density is large, a thick, very luminous disk forms. When the density is moderate, the accreting gas can effectively cool, thus generating a thin disk. When the density is too low for radiative cooling to be important, a disk becomes hot, thick, and faint. Strong outflows emerge, which are driven either by radiation pressure force for the dense disk or magnetic pressure force for the less dense disks.

Key words: black holes — accretion disks — numerical simulations

1. Introduction

It is widely believed that accretion flows onto black holes drives major activities of astrophysical black holes, such as active galactic nuclei, black hole binaries, and gamma-ray bursts. The basic accretion processes and radiation properties in moderate luminosity state can well be described by the standard-disk model by Shakura & Sunyaev (1973). This model was followed by the radiatively inefficient accretion flow (RIAF) model and the slim disk model for understanding accretion flow in low and very high luminosity states (Ichimaru 1977, Abramowicz et al. 1988, Narayan & Yi 1994).

These models can successfully account for many properties of accreting objects. However, they are (radially) one-dimensional models so that they cannot treat multi-dimensional motion, such as outflow and internal circulation. Such multi-dimensional motion would affect the dynamics and the structure of the accretion flows through the transportation of the mass, the momentum/angular momentum, and the energy. Thus, we need multi-dimensional approach to study accretion flows and outflows.

The conventional one-dimensional models do not solve the radiation fields and the magnetic fields. Therefore, they can not investigate the radiative and magnetic effects, such as the radiation pressure driven outflows as well as magnetic wind. In addition, the phenomenological viscosity model (so-called α model) is assumed, although the disk viscosity is thought to be of magnetic origin (Balbus & Hawley 1991).

Here, we take two independent, but complementary approaches to study the accretion flows. In section 2, we present our results of two-dimensional radiation hydrodynamic (RHD) simulations. The simulations are the first to clarify the structure of supercritical accretion flow in quasi-steady regimes. We, next, in section 3, present the results of global two-dimensional radiation-magnetohydrodynamic (RMHD) simulations. Our RMHD simulations demonstrate three distinct modes of accretion (corresponding to the standard disk model, RIAF model, and slim disk model) with the same code by varying mass density normalisations.

2. Radiation Hydrodynamic (RHD) Simulations

Two-dimensional RHD simulations of supercritical accretion disks were initiated by Eggum, Coroniti, & Katz (1988), who assumed the equilibrium between gas and radiation. The improved simulations, in which the energy of gas and radiation are separately treated, were performed by Okuda (2002). However, those simulations were computational-time limited and could not follow quasi-steady state of accretion.

We start simulations with an initially empty place and continuously add mass with angular momentum, which is 0.45 times Keplerian angular momentum, through the outer disk boundary at $r = 500 r_S$, where r_S is the Schwarzschild radius. The mass input rate is set to be

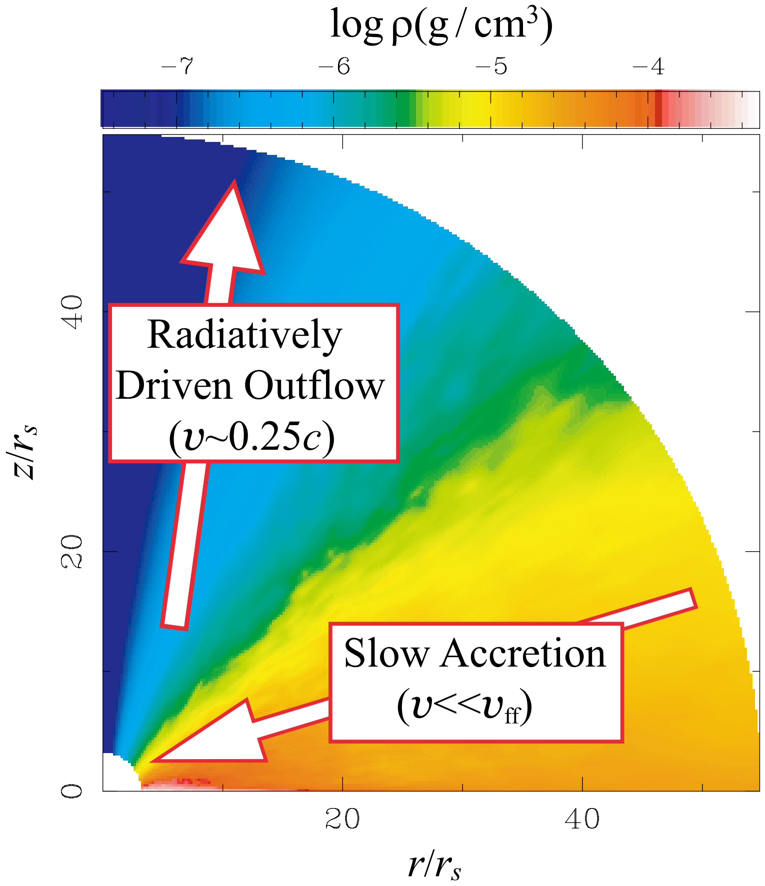

Fig. 1. the cross-sectional view of the density distributions in the quasi-steady state. The matter slowly accretes onto the black hole within the disk, while the high-velocity outflow appear around the rotation axis via the strong radiation force. The disk luminosity exceeds the Eddington luminosity. Our simulations, for the first time, reveals that the steady, supercritical accretion is feasible.

$10^3 L_{\rm E}/c^2$, where $L_{\rm E}$ is the Eddington luminosity and c is the speed of light. The black hole mass is assumed to be $10M_\odot$. To simplify the radiation processes and to save computational time, we adopt the flux-limited diffusion approximation. We employ the α viscosity model ($\alpha = 0.1$), since the magnetic fields are not solved in the RHD simulations (see Ohsuga et al. 2005, Ohsuga 2006 for more detail).

Overall evolution is divided into two distinct phases: the accumulation phase and the quasi-steady phase. The injected matter falls inward because of the gravity. Since angular momentum of the injected matter is set to be equal to the Keplerian angular momentum at $r = 100r_S$, it is natural that the gas tends to accumulate around the regions with the radius of $100r_S$ by degrees. This is the accumulation phase. Eventually, the viscosity starts to work so that the angular momentum of the gas can be transported outward, which drives inflow gas motion in a quasi-steady fashion. This is the quasi-steady phase. Then, the outflow driven by radiation pressure is generated around the rotation axis.

Figure 1 displays the cross-sectional view of the density distributions in the quasi-steady state. We understand with this figure that the flow structure is roughly divided into two regions: the disk region around the equatorial plane (characterised by orange color) and the outflow region above the inflow region (characterised by blue color).

The disk luminosity is several times larger than the Eddington luminosity. Our simulations, for the fist time, demonstrate that the steady, supercritical accretion is feasible. In addition, the emission of the supercritical accretion flows is moderately collimated, so that the apparent luminosity could become more than $10L_{\rm E}$ in the face-on view. It implies that the huge X-ray flux of the ultra-luminous X-ray sources is understood by the supercritical accretion onto the stellar mass black holes.

Here, we note that the energy conversion efficiency of the supercritical flows is smaller than the prediction of the standard disk model, 0.1. This is due to the photon-trapping. The huge amount of photons generated deep inside the disk is swallowed by the black hole with accreting matter, since the photon diffusion timescale exceeds the accretion timescale.

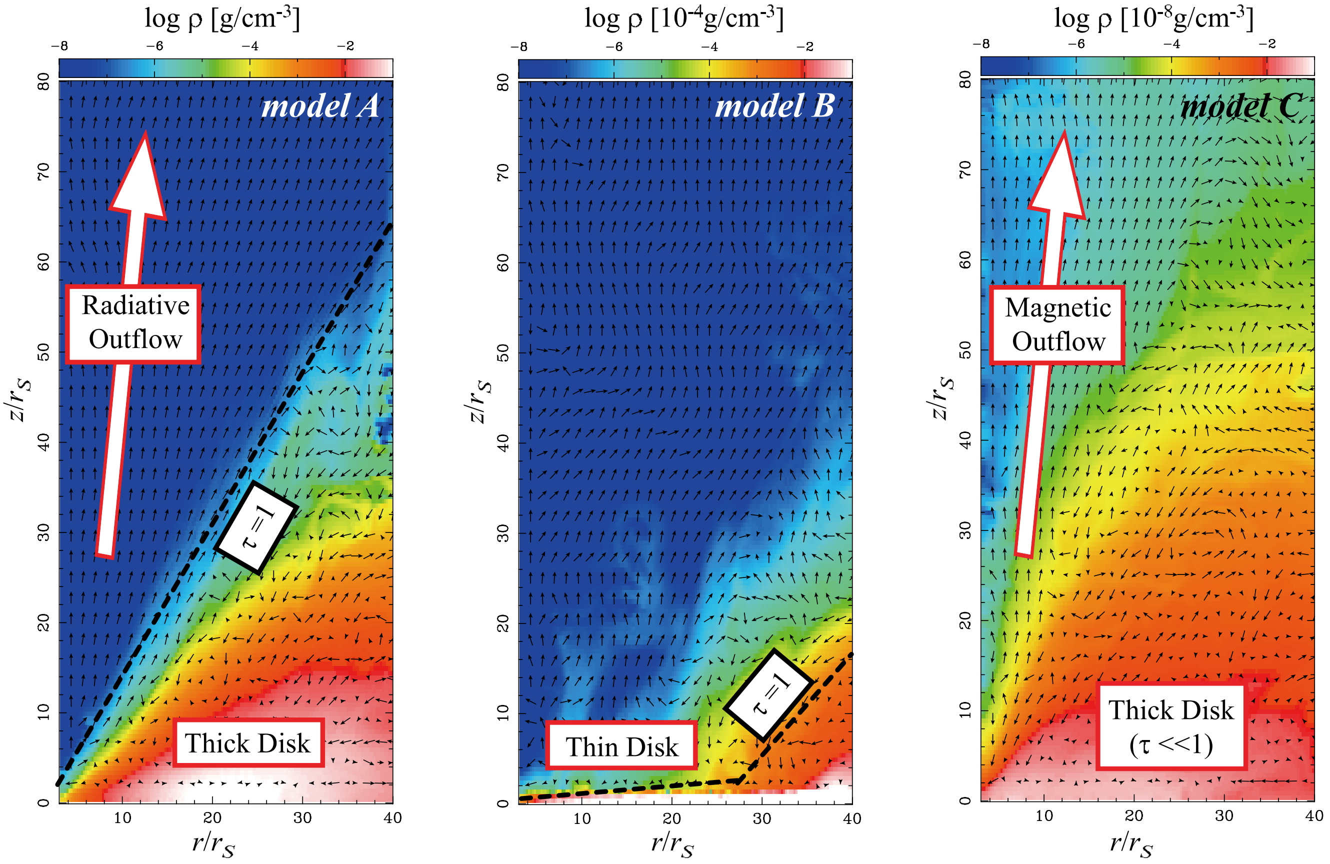

Fig. 2. Density distributions (color) overlaid with velocity vectors around the black holes. The dotted line indicates the photosphere, at which the optical thickness measured from the upper boundary is unity. The geometrically and optically thick disk forms in model A. The disk in model B is optically thick but geometrically thin. We find the geometrically thick but optically thin disk in model C. The radiation pressure force drives the outflow above the disk in model A, while the powerful outflow is generated via the magnetic pressure force in model C. The magnetic pressure also drives the outflow in model B, though it is not powerful.

We find that the strong radiation pressure force drives high-velocity outflow, whose typical velocity is around 0.25*c*. Therefore, the supercritical accretion objects have the blueshifted absorption lines by the highly ionized ions. Such blueshifted absorption lines was observed in the UV and X-ray spectra of quasars (Becker et al. 2000 Pounds et al. 2003, Reeves, O'Brien, & Ward 2003). On the other hand, the inflow velocity is much smaller than the free-fall velocity, since the sum of the radiation and centrifugal forces is nearly balanced with the gravitational force (Ohsuga & Mineshige 2007).

3. Radiation Magnetohydrodynamic (RMHD) Simulations

One big issue associated with our global RHD simulations is that the alpha model is employed (see previous section), since the magnetic fields are not solved. The disk viscosity should be calculated in a self-consistent fashion based on magnetohydrodynamics. Hence, the RMHD simulations are needed.

Three-dimensional RMHD simulations have been performed with using the shearing-box approximation (Turner et al. 2003). However, global multi-dimensional RMHD simulations, which are essential to establish a realistic picture of accretion disks, have not been attempted so far. Thus, we perform global two-dimensional RMHD simulations.

We start calculations with a rotating torus at $40r_S$ embedded in non-rotating isothermal corona. We assign the density parameter, the density at the center of the torus in the initial state, as $1\mathrm{g/cm^3}$ (model A), $10^{-4}\mathrm{g/cm^3}$ (model B), and $10^{-8}\mathrm{g/cm^3}$ (model C).

Figure 2 represent the density distributions (color) and velocity fields (vector) of three models, models A, B, and C from the left to the right, respectively.

In model A, the mass accretion rate exceeds the critical rate. The luminosity is comparable to or slightly exceeds the Eddington luminosity. The disk is optically and geometrically thick. It is supported by radiation pressure, which is predominant over the gas and magnetic pressures. The magnetic energy density is two times as large as the gas energy density. We find that the quasi-steady outflow launches from the disk surface via the strong radiation pressure force. The outflow velocity exceeds the escape velocity. The magnetic field lines stretch out within the outflow region, thus being almost parallel to the rotation axis, while the toroidal component of the magnetic fields is dominant over other components of that in the disk region. Recent radio observations revealed that the magnetic field lines are along the jet axis (Giroletti et al. 2008).

The disk in model B is also optically thick. However, it is geometrical thin, since the radiative cooling is efficient, and since the radiation pressure does not support the disk. The mass accretion rate is about 1% of the critical rate and the disk luminosity is about $10^{-3}L_{\rm E}$. Magnetic energy is about 30% of the gas energy in the disk region. The disk wind, associated with helical magnetic fields, sometimes emerges via the magnetic pressure force. This result would resolve the problem, by which the black hole binaries exhibit the absorption lines, implying the wind outflow from the disc in moderate luminosity state (Miller et al. 2006, Kubota et al. 2007).

In model C, the density is too low for radiative cooling and radiation pressure to be important. Thus, the disk consists of hot rarefied plasma. It is geometrically thick but optically thin. Our simulations reveal that the magnetic energy is around 20% of the gas energy, and the radiation energy is negligible. The mass accretion rate is smaller than 0.01% of the critical rate. We find that the vertical component of the magnetic fields is dominant over the radial component near the rotation axis, which is surrounded by the regions with strong toroidal magnetic fields. It is so-called magnetic tower jet (see also Kato, Mineshige & Shibata 2004). In contrast with models A and B, the kinetic energy output rate via the outflows exceeds the disk luminosity.

4. Conclusions

We have performed long-term two-dimensional radiation hydrodynamic (RHD) simulations of supercritical accretion flow. They for the first time reveal that the steady supercritical accretion is feasible in the case of disk geometry. The emission is mildly collimated so that the apparent luminosity can exceed the Eddington luminosity by a factor of ~ 10 in the face-on view. The strong radiation pressure force drives high-velocity ($\sim 0.25c$) outflow above the disk.

By performing two-dimensional radiation magnetohydrodynamic (RMHD) simulations, we can basically reproduce three distinct regimes of accretion flow (supercritical, standard, and radiatively inefficient flow) with one code but with different density normalization. The outflows are generated via the radiation pressure for the dense disk and via the magnetic pressure for the less dense disk.

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