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Disk modelling by radiation-magnetohydrodynamic simulations

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Abstract. Historically, various accretion models have been discussed under radially one-zone approximations. In such one-zone models, however, dynamical aspects of the accretion flow, such as internal circulation and outflows, have been totally neglected. Further, the disk viscosity is usually described by the phenomenological α-viscosity model. We, here, elucidate the theory of accretion flows and outflows based on our global, two-dimensional radiation-magnetohydrodynamic simulations, not relying on the α model. We have succeeded in producing three distinct states of accretion flow by controling only one parameter, a density normalization. Of particular importance is the presence of outflows in all three states. Several noteworthy features of the supercritical (or super-Eddington) accretion flows are found; that is, relativistic, collimated outflows (jets), and low-velocity, uncollimated outflows with clumpy structure. Observational implications are briefly discussed.

1. INTRODUCTION

Accretion onto compact objects can produce enormous energy in forms of radiation and matter and thus have great influence on its environments. To understand how accretion occurs, it is important to build reliable accretion disk (or flow) models. Various types of accretion disk models have been discussed already for more than four decades (see [1] for an extensive review). Historically, disk models have been constructed and discussed under radially one-zone approximations. Good examples are the standard disk model, the slim disk model, and the ADAF (advection-dominated accretion flow) model proposed for the accretion disk (or flow) with moderate, high, and low luminosities, respectively [2–5].

Those models have had success to some extent; e.g., in reproducing basic spectral features, however, a number of limitations and difficulties have become clear. For examples, they are radially one-dimensional models so that they cannot treat multi-dimensional motion, such as outflow, convection, and global circulation. Viscosity, the most important key ingredient in the accretion disk theory, is prescribed by the phenomenological α-viscosity model, although its physical basis was not clear. In addition, complex coupling between radiation, magnetic fields, and matters is not properly solved, either.

Since the realistic disk viscosity is thought to be of magnetic origin [6], and since multi-dimensional motion should be considered, global, two- or three-dimensional magneto-hydrodynamical (MHD) simulations are being rather extensively performed in this century as a model for the disks with low luminosities (see [1] and references therein). There are also attempts to incorporate radiative cooling effects in MHD simulations.

Here, we focus our discussion on the supercritical case, since it is expected in tidal disruption events, and since subcritical case can be more or less understood by the one-dimensional models. It is well known that there is a stringent limit to the luminosities of spherically accreting objects, the Eddington luminosity, $L_{\rm E}$. This is because above the Eddington luminosity strong radiation-pressure force does not allow material to accrete towards a central object. It may be possible to exceed the Eddington luminosity, however, in the case of disk accretion, since the main direction of the radiation output and mass input differ in the disk geometry [2].

In particular, we address the following critical questions: How high luminosities can be achieved by supercritical accretion? What physical processes are essential there? What are their observational signatures? These are fundamental questions addressed already over several decades, yet no clear answers have been obtained, mainly because for considering complex matter-radiation interactions we need to rely on radiation-hydrodynamical (RHD) simulations.

Since the 1980's several groups performed global, two-dimensional (2-D) RHD simulations of luminous accretion flow [7–9]. Those simulations did not consider -MHD processes, however. Hence, they were obliged to utilize the phenomenological α-viscosity model. In the 2000's multi-dimensional radiation-MHD simulations were started (e.g. [10]) but under the shearing-box approximations. The global coupling of magnetic fields is artificially quenched there.

Recently, Ohsuga et al. [11] presented a new type of accretion flow simulations; that is, global, 2-D radiation-MHD simulations. They solved the accretion flow and outflow structure from the first principle; i.e., not relying on the α-viscosity model. The following basic processes in the accretion flow and jets are considered: the transport of angular momentum induced via the magnetic torque, leading to the accreting motion, the conversion of the mechanical energy to the thermal energy via MHD processes, dissipation of thermal energy, radiative transfer, and radiation-pressure and Lorentz forces which play important roles in launching outflows and supporting the disks in the vertical direction.

In this proceeding paper, we examine the complex physical processes occurring in high-luminosity accretion flow based on our global radiation-MHD simulations and provide basic information specifically on the observable signatures of supercritical accretion flow.

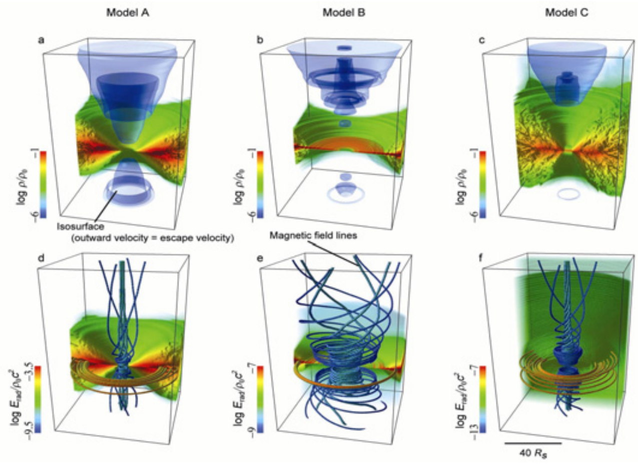

Figure 1. Perspective view of inflow and outflow patterns for Models A, B, and C, from left to right, respectively. Normalized density distributions (center) are overlaid with isosurfaces (above and below), at which the outward velocity equals to the escape velocity in the upper panels, while distribution of radiation energy density is overlaid with magnetic field lines in the lower panels. For more details, see [11].

2. GLOBAL RADIATION-MHD SIMULATIONS

Here, we show the main results of our radiation-MHD simulations. The precise numerical procedures and more detailed results have been published elsewhere [11, 12].

2.1. Overview

Our radiation-MHD simulations are performed by employing the flux-limited diffusion approximation for the radiation field. The calculations are performed in Newtonian dynamics, which may influence the limiting velocity attainable in the jet region.

We start simulations from a torus threaded with weak toroidal magnetic fields (with plasma $\beta = 100$) around a non-spinning black hole of $10\,M_{\rm sun}$. There is only one model parameter, a density normalization (density at the center of the initial torus). We calculate three models, in total (see Table 1). Since radiation emissivity sensitively depends on the density of gas, three distinct regimes of accretion flow can be reproduced by controlling this density normalization. When it is small, radiative cooling is not efficient (Model C). When it is moderate, radiative cooling turns on but radiation pressure is never dominant (Model B). When it is large enough, radiation pressure dominates over gas pressure (Model A).

Figure 1 is a perspective views of three simulated accretion flows. The (color) contours in the upper panels, which indicate the distributions of normalized density, clearly visualizes distinct flow patterns among three models. Especially, we find that accretion flows are geometrically thick in Models A and C, whereas it is geometrically thin in Model B. Therefore, the flows at high and low luminosities look apparently similar, though it is optically very thick in the former, while very thin in the latter.

Table 1. Three types of flow modes simulated by global radiation-MHD simulations.

	classical flow models	density normalization	Properties
Model A	supercritical flow	$10^0\,{\rm g\,cm^{-3}}$	thick disk with strong outflow
Model B	standard disk	$10^{-4}\,{\rm g\,cm^{-3}}$	thin disk with weak outflow
Model C	radiatively inefficent flow (RIAF)	$10^{-8}\,{\rm g\,cm^{-3}}$	thick disk with strong outflow.

The reasons for these differences can be understood in the following way: In Model A, gas density is so high that large amount of radiation must be produced, asserting strong radiation-pressure force to thicken the accretion flow. In Model B, density is moderately high so that radiative cooling can be effective. The disk is supported by gas pressure. The temperature is moderately low due to radiative loss, and so is the pressure scale-height small. A standard-type thin disk thus forms. In Model C, density is too low for radiative cooling to be effective. The flow temperature is highest among the three models, so is the pressure scale-height. Hence, a geometrically thick, optically thin disk forms. Table 1 gives a summary of the three calculated models.

The outflow regions are also indicated in the upper panels of figure 1. We find ubiquitous outflow from every mode of accretion flow, which was not always anticipated. Among the three models Model A records the largest outflow rate and such strong outflow will inevitably affect the environments of the flow (discussed later).

It is also important to note that the r-φ component of the shear-stress tensor is shown by our simulations to be roughly proportional to the local pressure in the time averaged sense. Although such a proportionality relation was assumed in the α-viscosity model and has been widely used since the 1970's, there was no proof for this. We for the first time have proven it by the global radiation-MHD simulations.

2.2. Radiation-MHD jet

From now on, we focus on Model A, the 2-D radiation-MHD version of the supercritical flow. The accretion disk in Model A is geometrically thick, as shown in figure 1, and is supported by the radiation-pressure force.

The accretion rate onto the black hole is $\sim 50\,L_{\rm E}/c^2$, much larger than the critical value, and the luminosity exceeds the Eddington luminosity, $L_{\rm ph} \sim 1.7\,L_{\rm E}$. Note that in the calculations of the photon luminosity of Model A we only consider the radiative energy released from the inner disk surface ($R < 25\,R_{\rm S}$) per unit time to avoid possible influence from the initial torus. [Here, we used the cylindrical coordinates, (R, θ, z).] So the actual photon luminosity might be higher, if we add the radiative flux at the outer disk surface ($R > 25\,R_{\rm S}$).

Figure 1 also shows that the matter goes outward above and below the disk. The mass-outflow rate is a few percent

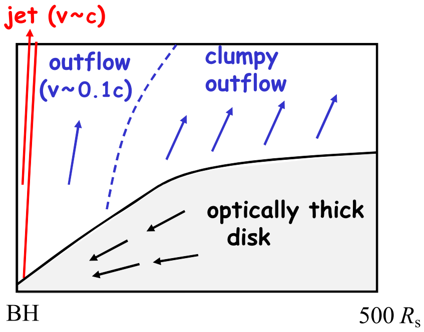

Figure 2. Schematic picture of supercritical accretion flow and associated outflow composed of a collimated, high-velocity jet and surrounding uncollimated, low-velocity outflows. The latter exhibit clumpy structure at distant regions.

of the mass accretion rate. We also find kinetic luminosity of $L_{\rm kin} \sim 0.1\,L_{\rm ph}$; that is, the supercritical flows release energy via radiation rather than via outflows.

A part of gas elements emerges and accelerates close to the photosphere in the inner region of accretion flows in which the radiation pressure dominates over gas pressure in the vertical direction. Radiation-pressure driven outflows thus arise. Within supercritical accretion flows, by contrast, rough force balance is achieved between the gravity force and the radiation force.

The outflow is composed of the inner, relativistic, collimated ($<$ 10 degree) jet along the disk rotation axis and the outer, uncollimated, low-speed ($< 0.1\,c$) outflow emerging over a wide angle (see figure 2).

To see what force is responsible for the acceleration and collimation of the jet, we evaluate the time-averaged strengths of the vertical components of the gravitational force, the gas-pressure force, the radiation-pressure force, and the Lorentz force [13]. The result is that the jet is accelerated by the radiation-pressure force, while the Lorentz force contributes much to the collimation. The latter was not expected, since the radiation energy density greatly exceeds the magnetic energy density, typically, by more than one order of magnitude. The key to understanding this magnetic collimation is the formation of a magnetic tower structure [14].

The magnetic tower structure is created by the inflation of the toroidal component of magnetic fields accumulating around the black hole [15]. There should be something which prevents the magnetic tower structure from expansion. The agent that works could be an uncollimated outflow surrounding the jet (see sec. 2.3).

The observed flux from supercritical flow is highly dependent on the viewing angle. For a face-on observer, the maximum apparent (isotropic) luminosities of $L_{\rm iso} \sim 22\,L_{\rm E}$ is achieved for the mass accretion rate of $\sim 50\,L_{\rm E}/c^2$. (The maximum apparent luminosity is higher than that found by the radiation-MHD simulations, indicating that the beaming effects are enhanced by magnetic collimation.) Even higher luminosities are also feasible, if we increase mass accretion rate. Note, however, Compton cooling should be very effective for the cases with higher mass accretion rates, which may lead to a suppression of the photon luminosities [16].

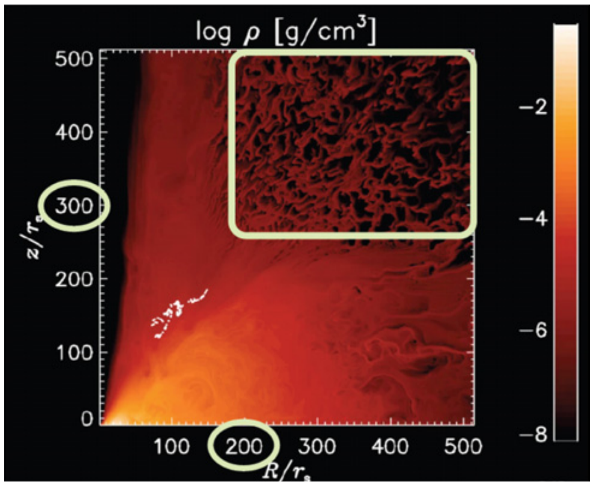

Figure 3. Clumpy outflow structure shown in the density contours. The clumps appear in the distant regions from the central black hole. The clump size is typically $\sim 10\,R_{\rm s}$ or one optical depth.

For an edge-on observer, by contrast, the apparent luminosity will be much less because emission is mildly beamed and the innermost bright part of the disk is obscured by the outer part (see [17]). We can thus expect large ratios of the kinetic luminosity ($L_{\rm kin} \sim 0.1\,L_{\rm E}$) to the isotropoic luminosity ($L_{\rm iso} \ll L_{\rm E}$) for edge-on observers. The large kinetic luminosity may account for the large ($100 \sim 500$ pc) ionizing nebulae around ultra-luminoux X-ray sources (ULXs) and/or microquasars (e.g. [18]).

2.3. Clumpy outflow

In order to examine large-scale behavior of the outflow, we run another simulation by significantly expanding the simulation box to be $(R_{\rm max}, z_{\rm max}) = (500R_{\rm s}, 500R_{\rm s})$. As a result, we found clumpy structure in the distant outflow region at $R > 200\,R_{\rm s}$ and $z > 250\,R_{\rm s}$ (see figure 3) [19]. Gas clumps with gas mass density of $\sim 10^{-6}\,{\rm g\,cm^{-3}}$ and velocity of $\sim 0.1\,c$ are blown away over wide angles.

To quantify the clumpy structure, we have performed auto-correlation function (ACF) analyses for the density distribution. We confirm a sharp peak in the ACF for the density distribution above $z > 250\,R_{\rm s}$. The width of the central peak (i.e, the typical clump size) is $\sim 5\,R_{\rm s}$, which roughly corresponds to one optical depth. We should note that the layer where clumps are formed (at $z \sim 250\,R_{\rm s}$) approximately coincides with the 'photosphere' of the flow; i.e., the average optical depth to this layer is unity. These facts indicate some kind of radiation-related instability being responsible for clump formation.

We, next, performed cross-correlation function (CCF) analysis, finding a clear anti-correlation between the gas mass density and the perpendicular component of the radiation force to the velocity vector in the clumpy outflow region. That is, the radiative flux avoids dense regions (i.e., clumps) and instead selectively passes through low-density channels between the clumps, pushing aside gas in the channel towards the clumps. Clumps thus grow until their optical depth becomes unity.

Shaviv [20] made a linear stability analysis for the optically thick, radiation dominated atmospheres of the super-Eddinton wind from stars. He has clearly shown that perturbations with wavelengths on the order of one scale-height grow on dynamical timescales under a fixed temperature condition at the bottom. This is a radiation hydrodynamic instability and is expected to create inhomogeneous density structure in the atmosphere. This is exactly the situation which we encounter here.

The directivity of radiation force (or radiation flux) is fundamental in this radiation hydrodynamic instability. The instability does not occur in the optically thick limit due to synchronization between matter and radiation field. It does not occur in the optically thin limit, either, since radiation cannot push material effectively but just passes through it. Further, this instability only occurs in the optically thick outflow from supercritical flows.

The outflow will produce several observable features. Photons from the underlying disk will be Compton up-scattered by hot plasmas in the outflow, which will create Compton-dominated spectra. Further, clumpy outflow structure will produce significant time variability in the photon luminosities. Those features are actually observed in ULXs (e.g., [21]).

Finally, we have made a number of approximations in our simulations; axisymmetry, Newtonian dynamics, and the employment of the flux-limited diffusion. These points will be improved in future simulations.

3. CONCLUSIONS

We here summarize our current theoretical understanding supercritical accretion flow.

1. We performed global, 2-D radiation-MHD simulations. We could reproduce three distinct regimes of accretion flow (supercritical flow, standard disk, and RIAF) with one code by varying the density of the flow.
2. Supercritical accretion flow exhibits mild beaming effects. For a face-on observer the isotropic (apparent) luminosity can be as large as $L_{\rm iso} \sim 22\, L_{\rm E}$ for a mass supply rate of $\sim\ 50\, L_{\rm E}/c^2$, though the real luminosity is $\sim 1.7\, L_{\rm E}$. For an edge-on observer, conversely the isotropic luminosity is much less and the ratio to the kinetic luminosity ($L_{\rm kin}\ \sim\ 0.1\, L_{\rm E}$) should be very large.
3. Supercritical accretion flow accompanies large-scale outflows at rates over $\sim 10\, L_{\rm E}/c^2$. The outflows are composed of the inner, relativistic, collimated ($<\ 10$ degree) jets and the outer, relatively low-speed ($\sim\ 0.1\, c$) uncollimated outflows emerging over a wide angle. The jets are accelerated by the radiation-pressure force and is collimated by the Lorentz force.
4. We expect a number of observational features in the supercritical outflow. Hot materials in the outflow will Compton up-scatter soft photons emitted from the underlying disk surface, thus producing Compton-dominated spectra. The clumpy structure, which is created by a radiation-hydrodynamic instability, will produce significant time variability.

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