Modeling Super-Eddington Accretion Flow

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Abstract. Super-Eddington (or supercritical) accretion flow seems to be realized in many astrophysical situations, such as ultra-luminous X-ray sources. We first discuss several noteworthy observable features of the supercritical accretion flow based on the framework of (1) one-dimensional, slim disk model. We expect flatter temperature profile, if the accretion rate exceeds the critical rate, and we find such a signature in the X-ray data of some ULXs. We then examine the data of (2) multi-dimensional, global radiation-hydrodynamic (RHD) simulations of disk accretion. Effects of relativistic beaming and gas outflow are particularly stressed there. Finally, we present our most recent results of (3) global, radiation-magnetohydrodynamic (RMHD) simulations of accretion flow. This model could for the first time reproduce the three different regimes of accretion (supercritical, standard-type, and radiatively inefficient accretion flow) with the same code by varying the density normalization.

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1. INTRODUCTION

Binary black holes (X-ray binaries containing stellar-mass black holes) show distinct spectral states, probably depending on the mass accretion rates (or luminosities). The so-called high/soft state appears in the moderate luminosity range, typically a few percent of the Eddington luminosity, while at lower luminosities the spectra become significantly harder and the system lies in the low-hard state. Now we have a good theory why it occurs. When there exists sufficient material in a disk, emission from the disk is so efficient that the disk should be in the standard-disk regimes [1]. The standard disk model perfectly reproduces not only the observed (blackbody) spectral shape but also the color temperature characterizing the spectra. If there is not sufficient material to cause efficient radiative loss, the disk flow is in a radiatively inefficient accretion flow (RIAF) regime and the disk gas gets significantly hotter. Except for some minor problems, we thus have a rough understanding of such luminosity-dependent spectral behavior.

Then, a next question will be: (1) what happens at high accretion rate and (2) what physical processes are important there?

It is well known that there is a limit on the luminosities of spherically accreting objects, known as the Eddington luminosity, above which a strong radiation pressure force does not allow material to accrete towards a central object. The situation may totally change, however, if the accreting material possesses angular momentum with respect to the central gravitating objects; i.e., super-Eddington (or supercritical) accretion may be feasible in disk accretion cases. This is because most of the radiation can escape from the system in the perpendicular direction to the disk plane, whereas gas can accrete through the disk plane. If radiation pressure forces in the direction parallel to the disk plane are attenuated a great deal, being blocked by large amounts of disk material, disk gas can accrete. Such a possibility and its consequence have been discussed already in the classical Shakura-Sunyaev paper [2], being followed by many authors [3–5].

Here, we take three independent, but complementary approaches to study the supercritical accretion flow. In section 2 we first carefully study the emission properties of the supercritical flow based on the one-dimensional model (the slim disk model) and fit the observed spectra to prove the existence of supercritical accretion flow in some ULXs. We, next, in sections 3 and 4 present our results of radiation Hydrodynamical (RHD) and radiation-Magnetohydrodynamical (RMHD) simulations, respectively, and discuss physics underlying the supercritical accretion flow.

2. SLIM DISK MODEL FOR ULXS

It is quite useful if one can build up a simple model of supercritical accretion flow as an extension of the standard disk model. The slim disk model was proposed for this purpose by Abramowicz et al. [3]. One of the notable effects in the super-critical flow is photon trapping; i.e., because of large Thompson optical depth photons generated deep inside the disk are trapped within the disk flow and swallowed by a black hole, without being emitted away. This occurs when the photon diffusion time (in the perpendicular direction to the disk plane) exceeds the accretion timescale. This condition defines the trapping radius,

$$r_{\rm trap} \sim (\dot{M}c^2 / L_{\rm E})\, r_{\rm S}, \tag{1}$$

where $\dot{M}$ is the mass accretion rate, $L_{\rm E}$ is the Eddington luminosity and $r_{\rm S} = 2GM/c^2$ is the Schwarzschild radius. In the slim-disk approach, this effect is incorporated within the one-dimensional model as photon entropy advection. A set of the basic equations is solved numerically for given appropriate boundary conditions (for details, see a textbook by [6], see also [7,8]). We find two remarkable features which appear when the luminosity is around the Eddington luminosities: a small innermost radius and a flatter temperature profile [8–10]. In the case of accretion onto a non-rotating (Schwarzschild) black hole, for example, we find

$$r_{\rm in} \sim 3\, r_{\rm S},\ T_{\rm eff} \propto r^{-3/4} \quad \text{at } L < L_{\rm E} \tag{2a}$$

while

$$r_{\rm in} \sim r_{\rm S},\ T_{\rm eff} \propto r^{-1/2} \quad \text{at } L >\sim L_{\rm E} \tag{2b}$$

Here we focus our discussion on the second features, since the first feature totally depends on the black hole mass estimations and inclination angle, whereas the latter ones not.

The reason why the temperature profiles differ with each other can be understood in the following way. In the standard disk, a constant fraction of gravitational energy is released at each radius; namely, have

$$2\pi r^2 F = 2\pi r^2 \sigma T_{\rm eff}^4 \propto \frac{GM\dot{M}}{r} \Rightarrow T_{\rm eff} \propto r^{-3/4}. \tag{3a}$$

In the slim disk, in contrast, the fraction of radiation which can leave from the surface of the flow decreases inward in proportion to $\sim r$ (see [6]). We, therefore, find

$$2\pi r^2 F = 2\pi r^2 \sigma T_{\rm eff}^4 \propto \frac{GM\dot{M}}{r} r \propto r^0 \Rightarrow T_{\rm eff} \propto r^{-1/2}. \tag{3b}$$

Different effective temperature profiles produce different spectral slopes in the energy band below the spectral peak. We can thus basically distinguish two types of flow by inspecting spectral slopes in soft X-ray ranges (at < 1 keV). This can be done by using the "extended disk-blackbody model" (or p-free model), in which the effective temperature profile is set to be $T_{\rm eff} \propto r^{-p}$ with p being a fitting parameter [11]. Note that for such temperature profile, we find $F_\nu \propto \nu^{3-(2/p)}$.

Ultra-luminous X-ray sources (ULXs) are X-ray bright compact sources successively found in off-center regions of nearby galaxies [12, 13]. Their luminosities largely exceed the Eddington luminosities of neutron stars, posing two possibilities: sub-critical accretion onto intermediate-mass black holes (with mass of $M > 100\,M_{\rm sun}$) or supercritical accretion onto stellar-mass black holes (with $M = 3 \sim 40\,M_{\rm sun}$). We have attempted spectral fitting to several ULX data with the extended disk-blackbody model, finding that the temperature slope (p) is always less than 0.75 and close to 0.5 and that the estimated black hole masses are below $\sim 40 M_{\rm sun}$ for all the sources we analyzed, thereby proving that supercritical accretion onto stellar-mass black holes power those ULXs ([14], see also [2]). Figure 1 clearly demonstrates this conclusion. Note that several authors claim through spectral fitting to the ULXs with the conventional spectral model (with disk blackbody plus power-law) that they prove sub-critical accretion onto intermediate-mass black holes, however, their conclusions are not reliable, since the power-law components always dominate over the disk blackbody component; we cannot trust results derived solely from minor spectral components.

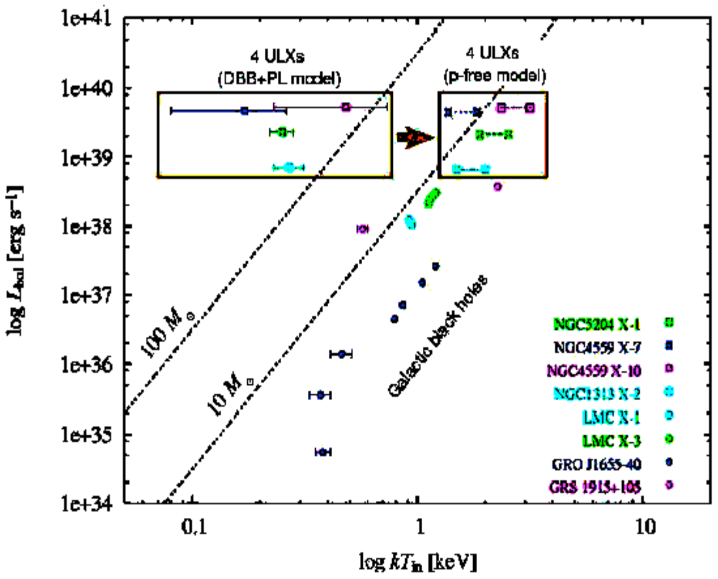

FIGURE 1. Luminosity-temperature diagram of some ULXs. From the fitting we find that all the ULXs which we analyzed fall on the ranges of stellar-mass black holes [14].

There is one important process totally missing in the slim-disk approach; that is wind mass loss. If we assume that local luminosity (defined below) does not exceed the Eddington luminosity, we find that the mass accretion rate in the disk decreases inward;

$$L(r) \equiv 2\pi r^2 F(r) = L_{\rm E} \Rightarrow \dot{M} \propto r \ \ (\because \ F \propto GM\dot{M}/r). \tag{4}$$

Hence, we have the same temperature profile as that of the slim disk model (see Eq. 3b). Moreover, the radius at which the accretion rate starts to decrease is approximately the trapping radius (Eq. 1). Therefore, we cannot distinguish the photon trapping effects and disk outflow effects through the spectral fitting. Certainly, we need more study (cf. [15]).

3. GLOBAL RHD SIMULATIONS OF SUPERCRITICAL FLOW

Such simple models as the slim disk model are quite useful, but at the same time we admit model limitations. Multi-dimensional motion, such as convection (or large-scale circulation) and outflows are not easy to treat. Hence, a distinct approach by using numerical techniques is also desirable to make progress in the study of supercritical accretion flow. Since intrinsic radiation properties are essential here, we need global radiation hydrodynamic (RHD) simulations, which were initiated already back in the 1970's [4], followed by several authors [5, 6]. However, those simulations were computational-time limited and could not follow quasi-steady state of accretion. Ohsuga et al. [16] were the first to clarify the structure of supercritical accretion flow in quasi-steady regimes.

They started simulations with an initially empty place and through the outer boundary at $500\,r_{\mathrm{S}}$, continuously add mass with angular momentum, which is 0.45 times Keplerian angular momentum at the outer boundary. The corresponding mass-input rate is $\dot{M} = 1000\,L_{\mathrm{E}}/c^2$ and black hole mass is $M = 10\,M_{\mathrm{sun}}$. To simplify the radiation processes and to save computational time, they adopted the flux-limited diffusion. The viscosity is given based on the alpha disk model

Figure 2a shows the snapshot of the density contours with velocity vectors of super-critical accretion flow. Two flow patterns (slow disk accretion flow and fast outflow) are evident in this figure. In fact, steady, super-critical accretion flow is realized!! The simulation also shows super-Eddington luminosity, significant radiation anisotropy (beaming), large-scale circulation flow, and high-speed (~0.1c) outflow. Especially, the disk luminosity can be as large as $\sim 10\,L_{\mathrm{E}}$!!

To understand why super-critical accretion is feasible, we check how much radiation energy is contained within the flow (see figure 2b). We find that the radiation energy density exceeds the Eddington radiation energy density defined by $E_{\mathrm{E}}(r) \equiv L_{\mathrm{E}}/4\pi r^2 c$ by more than 2 orders of magnitudes. We thus understand that there is much radiation inside the disk. Why then can gas accrete? The reason is that radiation flux (and so radiation pressure force) is attenuated by flat radiation energy density profile (recall $F \propto (\kappa\rho)^{-1}\nabla E_{\mathrm{rad}}$ with E_{rad} being radiation energy density). In addition, photon trapping works to reduce the radiation pressure force.

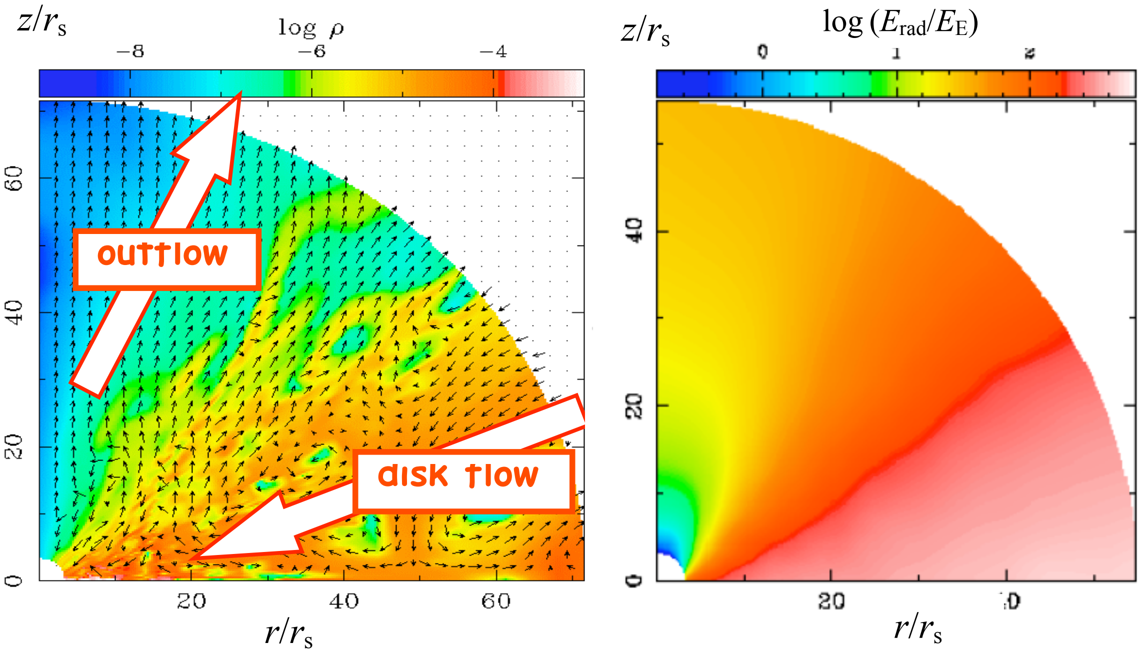

FIGURE 2. (Left) Density contours (color) and velocity vectors of supercritical accretion flow [16]. (Right) Color contours of the ratio of the radiation energy flux to the Eddington radiation energy (see text for definition) [17].

4. RMHD SIMULATIONS OF VARIOUS TYPES OF FLOW

One big issue associated with our global RHD simulations is that the magnetic fields are not solved. As for the disk viscosity, the alpha model was employed in the RHD simulations, though the disk viscosity should be calculated in a self-consistent fashion based on magnetohydrodynamics (MHD). Hence, we need the global radiation magnetohydrodynamic (RMHD) simulations. We have recently succeeded in performing global RMHD simulations of three types of accretion flows (supercritical flow, standard disk, and radiatively inefficient accretion flow).

We start calculations with a rotating torus at 40 r_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 ρ_0=1 g cm^{-3} (model A), 10^{-4} g cm^{-3} (model B), 10^{-8} g cm^{-3} (model C).

Figure 3 represents 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. We find that the strong radiation pressure force drives the quasi-steady outflows, whose velocity exceeds the escape velocity, above the disk.

In model B, the geometrically thin disk forms, since the radiative cooling is efficient, and since the radiation pressure does not support the disk. The disk is optically thick. The mass accretion rate is about 1% of the critical rate and the disk luminosity is about 10$^{-3}L_{\mathrm{E}}$. Magnetic energy is about 30% of the gas energy in the disk region. The disk wind sometimes appears.

In model C, the mass accretion rate is smaller than 0.01% of the critical rate. In this case, radiative cooling and radiation pressure do not play important roles. The disk consists of hot rarefied plasma. It is geometrically thick but optically thin. The matter is blown away near the rotation axis. In contrast with models A and B, the kinetic energy output rate via the outflows exceeds the disk luminosity. Our simulations reveal that the magnetic energy is around 20% of the gas energy, and the radiation energy is negligible.

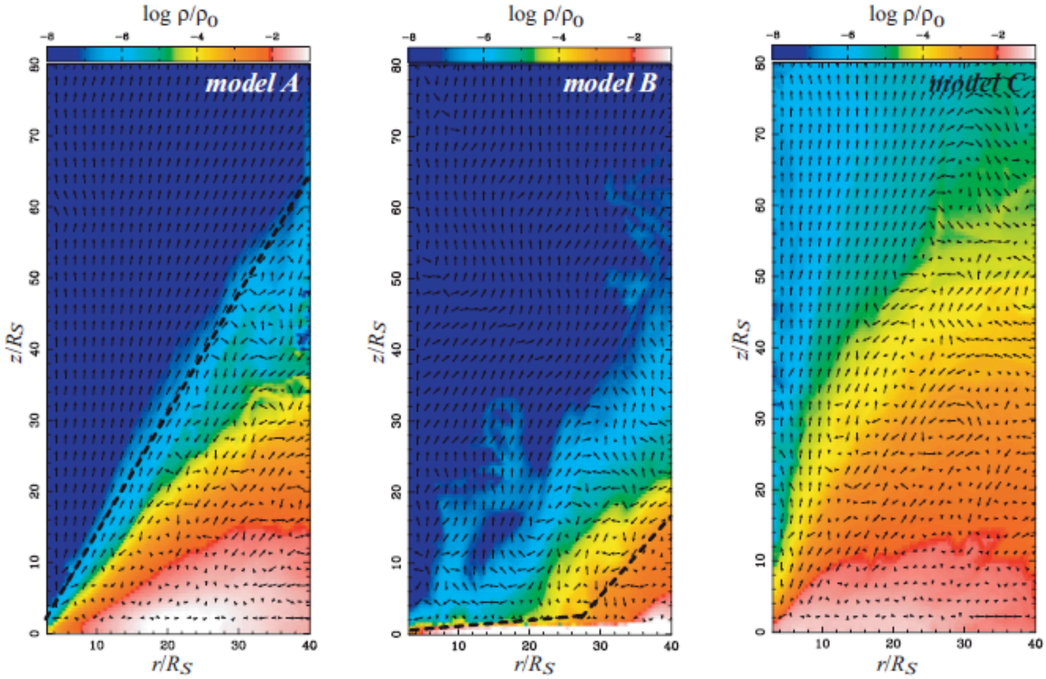

FIGURE 3. Normalized Density contours (color) and velocity vectors in models A (left), B (center), and C (right). The dotted lines represent the place of the photosphere, where the optical depth measured form the upper boundary becomes unity. Since the disk in model C is optically thin, dotted line does not appear.

TABLE 1. Basic properties of simulated accretion flow in three regimes.

Model	Density and temperature	Energetics
A (supercritical accretion flow)	$\rho \sim 10^{-2}$ g cm^{-3}, $T \sim 10^{8}$ K	*E*rad >> *E*mag >~ *E*gas
B (standard type disk)	$\rho \sim 10^{-5}$ g cm^{-3}, $T \sim 10^{6}$ K	*E*gas ~ *E*mag ~ *E*rad
C (radiatively inefficient flow)	$\rho \sim 10^{-10}$ g cm^{-3}, $T \sim 10^{9}$ K	*E*gas >~ *E*mag >> *E*rad

The results are summarized in Table 1. It is important to stress that by changing density normalizations we could reproduce three distinct regimes of accretion with the same code. It is also important to note that the disk viscosity in the simulations is shown to be roughly proportional to the pressure. Although such a relation has been assumed in the alpha viscosity model since the 1970's, we for the first time confirm it by the global RMHD simulations.

CONCLUSIONS

We here summarize our current knowledge regarding supercritical accretion flow in various astrophysical contexts.

- Near- or supercritical accretion flows seem to occur in some systems like ULXs and others.
- Slim disk model predicts flatter temperature profile. Spectral fitting with variable p (temperature gradient) proves the presence of supercritical accretion in some ULXs.
- We have performed long-term two-dimensional radiation-hydrodynamic (RHD) simulations of supercritical flow. They show super-Eddington luminosity, significant radiation anisotropy (beaming), high-speed (~0.1c) outflow, and so on. Especially, the disk luminosity can be as large as $\sim 10\,L_{\rm E}$!!
- Two-dimensional radiation-magnetohydrodynamic (RMHD) simulations are in progress. We can basically reproduce three distinct regimes of accretion flow (supercritical, standard, and radiatively inefficient flow) with one code but with different density normalization.

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