Black Holes from Stars to Galaxies – Across the Range of Masses
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Radiation hydrodynamic simulations of super-Eddington accretion flows

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Abstract. We perform the two-dimensional radiation-hydrodynamic simulations to study the radiation pressure-dominated accretion flows around a black hole (BH). Our simulations show that the highly supercritical accretion flow (mass accretion rate is much larger than the critical value) is composed of the disk region and the outflow region above the disk.

The radiation force supports the thick disk and drives the outflow. The photon trapping plays an important role within the disk, reducing the disk luminosity. On the other hand, in the case that mass accretion rate moderately exceeds the critical value, we find that the disk is unstable and exhibits the limit-cycle oscillations. The disk oscillations in our simulations nicely fit to the variation amplitude and duration of quasi-periodic luminosity variations observed in the GRS 1915+105 microquasar.

Keywords. Accretion, accretion disks – black hole physics

1. Introduction

Recent observations have discovered very bright objects which may undergo supercritical (or super-Eddington) accretion flows. Ultraluminous X-ray sources (ULXs; Fabbiano 1989; Ebisawa *et al.* 2003) and narrow-line Seyfert 1 galaxies (NLS1s; see Boller 2004 for a review) are good examples. Although the ULXs might be powered by the sub-critical accretion onto the intermediate mass BHs (Makishima *et al.* 2000), a piece of evidence of the supercritical flow is reported (Vierdayanti *et al.* 2006). On the other hand, NLS1s have in general large Eddington ratios (luminosity over Eddington luminosity) and some of them seem to fall in the supercritical accretion regimes (Mineshige *et al.* 2000).

The supercritical accretion onto the central BH is thought to play important roles for the evolution of their host galaxies. King (2003), as well as Silk & Rees (1998), suggested that the strong outflow from the supercritical accretion flow regulates the evolution of the supermassive BH and its host galaxy, leading to the correlation between the velocity dispersion of the bulge stars ($\sigma_\star$) and the BH mass ($M - \sigma_\star$ relation; Gebhardt *et al.* 2000; Ferrarese & Merritt 2000). Despite growing evidence indicating the existence of supercritical accretion flows in the universe, theoretical understanding is far from being complete.

What makes the supercritical accretion flows distinct from the standard disk type flow is the presence of photon trapping (Begelman 1978; Ohsuga *et al.* 2002). By the photon trapping, photons generated via the viscous process are advected inward with accreting gas without being radiated away. In addition, the multi-dimensional gas motion, such as convective or large-scale circulation, would occur in the supercritical disk accretion flows. Strong outflow might also be generated due to the strong radiation force. We thus need at least two-dimensional treatment to investigate the supercritical disk accretion flows.

When the advective cooling is predominant over the radiative cooling, the disks are stabilised. But, the supercritical disks are not always stable. If the mass accretion rate is comparable to or moderately exceeds the critical value, thermal and secular instability is though to arise in the radiation-pressure dominant region (Lightman & Eardley 1974; Shibazaki & Hōshi 1975).

In this paper, we investigate the steady structure of the stable supercritical accretion flows and time evolution of the unstable supercritical accretion disks by performing the two-dimensional radiation hydrodynamic (RHD) simulations.

2. Highly supercritical flows; stable disks

We solve the full set of RHD equations including the viscosity term with using an explicit-implicit finite difference scheme on the Eulerian grids. Our viscosity model is basically the same as the α prescription of the viscosity proposed by Shakura & Sunyaev (1973) The matter is added continuously from the outer disk boundary to the initially (nearly) empty space at the rate of $10^3 L_{\rm E}/c^2$. The RHD equations and our methods are shown in Ohsuga *et al.* (2005) and Ohsuga (2006) in detail.

By performing long-term numerical calculations, we for the first time succeed in reproducing the quasi-steady state of the supercritical accretion flows. Although the research history of such simulations stems back to the late 1980's, when Eggum *et al.* (1987) for the first time performed numerical simulations, their calculations were restricted to the first few sec (see also Kley 1989; Okuda *et al.* 1997).

Figure 1 displays the cross-sectional view of the density distributions (colors), overlaid with the velocity vectors (arrows) in the quasi-steady state. We find that the flow structure is divided into two regions: the disk region around the equatorial plane (orange) and the outflow region above the inflow region (blue). The disk is geometrically and optically thick, and it is supported by the radiation force. We find a number of cavities

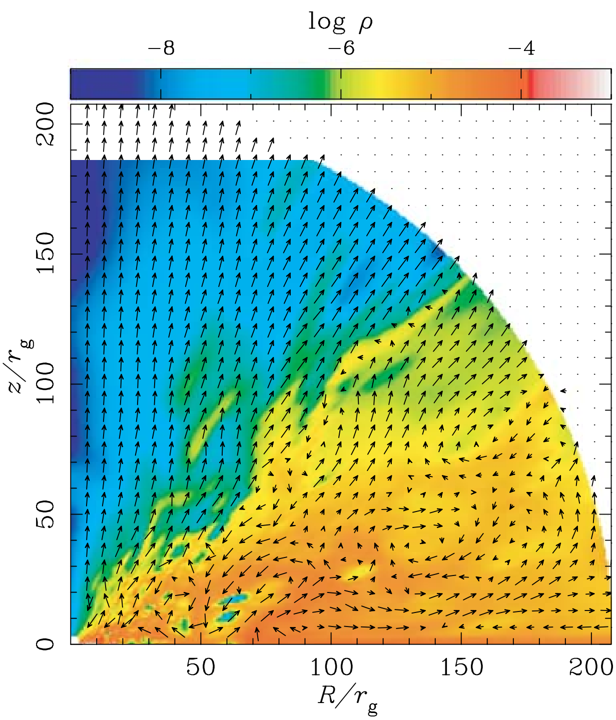

Figure 1. The density distribution in the quasi-steady state overlaid with the velocity vectors. Here, we set the mass input rate to be $10^3 L_{\rm E}/c^2$ and the mass of the BH to be $10 M_\odot$.

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and the circular motion in the disk region. The radiatively-driven outflow appears along the rotation axis. The Kelvin-Helmholtz instability is caused around the disk surface.

In the quasi-steady state, the mass accretion rate onto the BH is $\sim 10^2 L_E/c^2$. In other words, only 10% of the inflowing material is finally swallowed by the BH; i.e., 90% of the mass input rate gets stuck in the dense, disk-like structure around the equatorial plane, or transform into the known collimated high-velocity outflows perpendicular to the equatorial plane or into the low-velocity outflows with wider opening angles, respectively.

The resulting luminosity is about three times larger than the Eddington luminosity. Thus, the energy conversion efficiency, ~ 0.03, is much smaller than the prediction of the standard disk theory, ~ 0.1. This is because the large amount of photons generated inside the disk is swallowed by the BH without being radiated away. This is so-called photon trapping effects. Since the slim-disk model (Abramowicz *et al.* 1988) does not fully consider the photon trapping effects, this model overestimates the disk luminosity.

Since the supercritical disk is geometrically and optically thick, its emission is mildly collimated. Although the disk luminosity is $\sim 3L_E$, the apparent luminosity exceeds $10L_E$ in the face-on view. It implies that the large luminosities of the ULXs are explained by the supercritical accretion onto the stellar-mass BHs.

3. Moderately supercritical flows; unstable disks

Here, we set the mass input rate to be $10^2 L_E/c^2$, although we assume it to be $10^3 L_E/c^2$ in the previous simulation. In this case, the disk is unstable and exhibits quasi-periodic state transitions. Figure 2 represents the time evolution of the mass accretion rate onto the BH, $\dot{M}_{acc}$ (blue), the outflow rate, $\dot{M}_{out}$ (magenta), the disk luminosity, L (red), and the trapped luminosity, L_{trap} (green). As shown in this figure, the mass accretion rate onto the BH ($\dot{M}_{acc}$) drastically varies. It suddenly rises, retains high value for about 40 s, and then decays. Such time variation of the mass accretion rate causes the quasi-periodic luminosity changes. Whereas the luminosity (L) is not more than $0.3L_E$ in the low-luminosity state, it reaches around $2L_E$ in the high-luminosity state. The burst duration is also about 40 s. The physical mechanism of such limit-cycle oscillations is the disk instability in the radiation-pressure dominant region.

Resulting light curve in our simulations gives a nice fit to the time variation of the luminosity of GRS 1915+105. Based on the analysis of the data of GRS 1915+105 taken by

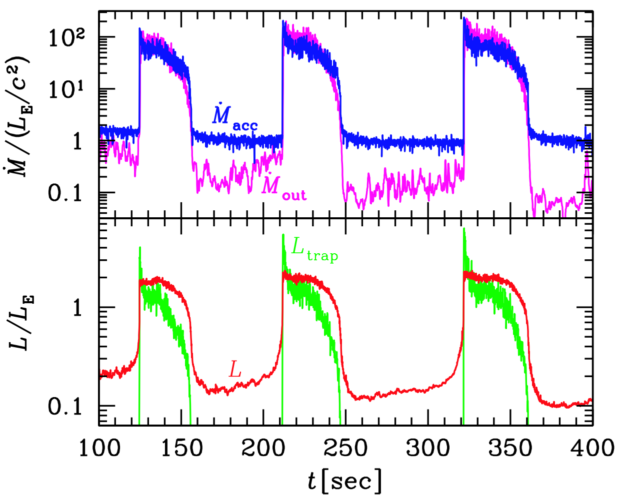

Figure 2. The time evolution of the mass accretion rate (blue), outflow rate (magenta), the luminosity (red), and trapped luminosity (green). Here, we set the mass input rate to be $10^2 L_E/c^2$.

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RXTE and ASCA, Yamaoka *et al.* (2001) have produced the light curve. The luminosity is several times higher in the high-luminosity state than in the low-luminosity state. The duration of the high-luminosity state is about $30-50$ s, and there is sharp edge between the high and low states. Our numerical results succeed in reproducing these observed features.

In Figure 2, the outflow rate ($\dot{M}_{\rm out}$) suddenly rises and decays with the luminosity. It implies that the radiately-driven outflow forms intermittently. The typical velocity of the outflow is 30% of the light speed. The photon-trapping effects appear during the high-luminosity state. It is found that the trapped luminosity ($L_{\rm trap}$), which means the radiation energy swallowed by the BH per unit time, is comparable to the luminosity in the high-luminosity state. The energy conversion efficiency is around 0.03 in the high-luminosity state, although it is ~ 0.1 in the low-luminosity state. We stress that the multi-dimensional effects, e.g., outflow and photon trapping, are significant in the high-luminosity state.

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Suzy Collin: Is it possible to scale your model to larger masses, i.e. to active galactic nuclei?

Ken Ohsuga: The instability mechanism does not depend on the black hole mass. However, there is some dependency because the size of the radiation pressure dominated region depends slightly on the black hole mass, so the timescale changes accordingly.

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